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Solar energy technologies: Photovoltaics, thermal systems, and emerging innovations

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Abstract

Solar energy technologies have emerged as central pillars in the transition to sustainable and low-carbon energy systems. Photovoltaic (PV) systems convert sunlight directly into electricity, while solar thermal systems transform solar radiation into heat for residential, industrial, and large-scale power applications. Both approaches continue to advance through innovations in materials, system design, and energy storage. Recent breakthroughs such as perovskite solar cells, bifacial panels, floating solar farms, and AI-driven optimization strategies have enhanced efficiency, reduced costs, and expanded deployment potential. Despite these advantages, challenges such as intermittency, high upfront costs, and policy uncertainty remain barriers to large-scale adoption. This paper reviews the principles, applications, benefits, and limitations of PV and solar thermal technologies, alongside emerging innovations shaping the global renewable energy landscape. It highlights the transformative role of solar energy in achieving climate goals, improving energy security, and fostering sustainable development.

Keywords: Solar energy, photovoltaic systems, solar thermal systems, renewable energy, perovskite cells and bifacial panels

Introduction

The solar technologies landscape has changed considerably due to the fast-growing role of innovations in established and newly emerging renewable energy solutions. Among the various approaches to utilize solar energy, photovoltaics and thermal systems remain central. While both methods exploit sunlight as an unlimited resource, they differ in operation and practicality. With the increasing demand for renewable, clean energy, existing and innovative solar technology solutions have become paramount. The operation of photovoltaic systems and solar thermal continues to advance to all of their potential benefits and difficulties, in some cases, together. Furthermore, novel solar technologies continue to develop and spin-off promising further room for energy and resource efficiency in the immediate future.

Photovoltaic Systems

Among the main technologies related to solar energy conversion, photovoltaic systems or cells represent a prominent approach, being able to convert sunlight directly into electrical energy. The principle of operation of photovoltaic systems is based on semiconducting materials with the photovoltaic effect: light absorption leads to the excitation of electrons (and the formation of charged carriers), generating an electric current with no moving parts or heat processes involved (Amin, 2022) [3]. A photovoltaic cell is generally designed to optimize light absorption and is composed of different layers that ensure the effective separation and flow of the charge carriers. Small off-grid cells and larger decentralized systems are available for different types of applications, with relative differences in performance and operation (Abou Jieb & Hossain, 2022) [1]. This technology, evolving for decades through scientific research, is a driving force for the promotion and development of renewable energy systems around the globe.

Additionally, the functionality of photovoltaic systems depends on the integration of essential components that work harmoniously to facilitate energy conversion and utilization. Solar panels, composed of interconnected photovoltaic cells, serve as the primary interface for capturing solar radiation, while inverters are critical to converting the direct current generated by these panels into alternating current compatible with standard electrical grids. Modern systems frequently incorporate energy storage solutions, such as batteries, enabling the retention and subsequent use of excess energy during periods of reduced sunlight (Hernández-Callejo *et al*., 2019) [8]. Optimal system design not only addresses the seamless interaction of these components but also considers factors like power conditioning and protective devices to maintain operational reliability and longevity. Thorough attention to the arrangement and maintenance of solar panels, inverters, and storage technologies fundamentally shapes the efficiency and resilience of photovoltaic installations, setting the stage for ongoing technical advancements and broader adoption.

Furthermore, the photovoltaics landscape saw significant development, especially with innovations impacting its reliability and cost reduction. New materials engineering breakthroughs (for instance, perovskite and tandem photovoltaics cells) have greatly multiplied the conversion efficiencies and opened cost-competitive production techniques (Ogundipe *et al*., 2024) [12]. Production innovations (such as thin-film deposition and roll-to-roll printing) have cut both manufacturing costs and scalability potential (Panagoda *et al*., 2023) [13]. The reduced PV energy price per watt realized today both boosts its competitiveness with traditional power generation and allows prospective use alongside complementary energy storage and management technologies. Recent innovations, thus, mark a continued evolution of photovoltaics technologies toward higher efficiency, reliability, and adaptability; ultimately accelerating the technologies' use across various energy systems.

Moreover, photovoltaic applications can be found in a social aspect, from residential to commercial and industrial use.

Domestic use involves the installation of solar panels on roofs to supply energy to buildings. In turn, business establishments produce electricity through a massive installation of solar panels on roofs or in their warehouses to reduce their operational costs, promote sustainability, and comply with environmental regulations (Marques Lameirinhas *et al*., 2022) [10]. Photovoltaic systems can be set up in factories, warehouses, and other structures to stabilize energy supply and support electricity-intensive activities. Therefore, these technologies provide various functions that could serve distinct purposes, yet help achieve the goals of affordable clean energy, sustainable infrastructure, and climate action at once (Marques Lameirinhas *et al*., 2022) [10].

Also, it should be stressed that photovoltaic systems bring a broad spectrum of positive effects that highlight their increasing role in the context of energy plans worldwide. The most important of such effects is the renewable nature of the unique approach to electricity generation offered by photovoltaic systems. Their fundamental principle lies in the fact that the solar energy is abundant and does not diminish with time. Its exploitation helps reduce the use of fossil fuels, which are limited and deplete with time, ensuring sustainability for future generations to come. The adoption of photovoltaic systems stands as a significant step towards ensuring that energy source secures reduced greenhouse gases emissions, given that the energy coming from photovoltaics does not emit any carbon dioxide or other pollutants into the atmosphere during facilities operation. Such a feature brings enormous ecological benefits that bolder efforts to build an energy system capable of producing “carbon-free energy” and “fighting climate change through clean energy” (Dambhare *et al*., 2021) [5]. Moreover, the continual developments in terms of both cell materials and production technologies have increased the efficiency and photovoltaic systems as well as their practicality, validating their secure position as the promising source of ‘emissions-free power’.

In spite of the several advantages associated with photovoltaic systems, their continued implementation and performance are still being impacted by numerous constraints. The foremost limiting factor is the dependence on sunlight, which means energy can only be produced to a significant extent at particular times and locations (weather conditions). This variability of PV systems may require human systems to be coupled with other means of storing energy for sustenance, or produce other energy during periods of non-generation, especially in areas where the solar energy harnessing resource is not consistent. Additionally, the costs of installation of the photovoltaic plant or systems (panels, inverters, and other installation components) is still high, even with the decreasing market price of the modules (Abou Jieb & Hossain, 2022) [1]. Costs, along with operational factors, make it necessary to advance curtailed research towards not only enhancing efficiency but reducing cost of initial installation and the effect of atmospheric factors on energy collection.

Solar Thermal Systems

Solar thermal technologies, unlike photovoltaic systems, are designed from the outset to recover the energy of the sun, which converts solar radiation into thermal energy directly for heating or electricity generation. These systems primarily rely on solar collectors such as flat-plate or evacuated tube collectors that absorb and transduce solar radiation to increase the temperature of a heat transfer working fluid that is usually pumped into a closed-loop circuit (Duffie *et al*., 2020) [6]. This fluid, typically water or an antifreeze mixture, transfers the collected thermal energy to end-uses that can include residential water heating, space heating, or conditioning and industrial processes. More complex systems can also rely on concentrating solar power (CSP) technologies, which usually employ mirrors or lenses that focus sunlight onto smaller, more efficient solar absorbers, yielding even higher operating temperatures that can be employed for electricity generation in steam turbines. These mechanisms and more complex systems make solar thermal technologies a robust and efficient option for the conversion of solar resources into end-users for both direct thermal applications and as a large-scale energy production technology (Duffie *et al*., 2020) [6].

Likewise, solar thermal systems consist of several key parts that enable optimal collection, transfer, and storage of solar energy to provide energy for its subsequent end-use purposes. The solar collector acts as the main exposure point for the system towards sunlight, capturing the radiation, and converting it to heat, which is then transferred to a circulating working fluid. The heated working fluid then travels through heat exchangers that enable the transfer of thermal energy to the potable water supplies, building spaces, or process systems according to the application (Duffie *et al*., 2020) [6]. Storage tanks are also used in the system to provide a constant supply of the heated working fluid even during days without sufficient sunlight or during peak demand hours. By connecting these components in both simple and complex arrangements, solar thermal systems can deliver dependable and consistent heating solutions that satisfy various residential, commercial, and industrial applications while helping them achieve optimal energy efficiencies overall (Duffie *et al*., 2020) [6].

Similarly, the advancement of state-of-the-art materials and novel concepts for heat storage achieved remarkable progress in the domain of solar thermal systems. A promising approach lies in incorporating silver nanoparticle-functionalized graphene nanosheets in polyethylene glycol-based phase change materials, which studies showed to substantially increase solar-to-thermal conversion efficiency (Zhang *et al*., 2019) [15]. Composites based on such materials demonstrate high performance in terms of thermal energy harvesting and storage, with efficiency levels exceeding 92 percent, excellent thermal conductivity, and stable phase-change behavior. With elevated energy storage densities above 166.1 J/g, these materials are especially beneficial for applications that require steady and prolonged heat supply, where both residential and industrial facilities can benefit. Due to the utilizing of such high-performance storage materials, solar thermal systems are capable of solving existing intermittency issues and enhancing their functionality as a tool for clean-energy use (Zhang *et al*., 2019) [15]. Solar energy technologies present a dual narrative of significant opportunities alongside notable challenges. As shown in Table 1, photovoltaic systems, solar thermal applications, and emerging innovations such as perovskite cells, bifacial panels, floating solar farms, and AI-driven optimization offer clean, flexible, and increasingly cost-effective solutions for electricity and heat generation. These technologies not only reduce greenhouse gas emissions but also enhance energy security, create jobs, and contribute to sustainable development goals.

Table 1: Advantages and Opportunities of Solar Energy Technologies

Technology /Innovation	Key Advantages	Explanation / Implications
Photovoltaic (PV) Systems	Direct electricity generation	Converts sunlight into electricity without moving parts, enabling clean and scalable power.
	Modular and flexible design	PV panels can be used in small rooftop systems or large solar farms, adaptable to different scales.
	Declining costs	Advances in manufacturing, thin-film deposition, and economies of scale have significantly reduced cost per watt.
	Emission-free operation	No greenhouse gases during operation, contributing to climate mitigation goals.
Solar Thermal Systems	Reliable heating applications	Provides hot water, space heating, and industrial heat, reducing fossil fuel dependency.
	Concentrating Solar Power (CSP)	Generates electricity by producing steam for turbines, suitable for large-scale grid supply.
	Energy storage potential	Thermal storage tanks allow use even during cloudy days or at night, improving reliability.
Emerging Innovations	Perovskite solar cells	High efficiency, lightweight, low-cost potential, and improved flexibility for diverse applications.
	Bifacial solar panels	Capture sunlight on both sides, increasing output, especially in high-reflectivity environments.
	Floating solar farms	Save land space, reduce water evaporation, and improve PV efficiency due to cooling effects.
	AI and Machine Learning integration	Optimize material design, predict performance, and manage system efficiency in real-time.
	Solar-powered transport	Solar cars, buses, and charging stations enable sustainable mobility and reduced grid dependency.
Societal Benefits	Energy security	Reduces reliance on imported fossil fuels, ensuring stable and local energy supply.
	Job creation	Manufacturing, installation, and maintenance industries generate employment opportunities.
	Climate and sustainability goals	Supports national and international commitments to net-zero targets and clean energy transitions.

Furthermore, solar thermal systems offer functional versatility as seen in the various applications where these are utilized. In water heating, both household and industrial-scale solar collectors are used to heat water to moderate temperatures for day-to-day applications. With this, the effects of conventional heating techniques, such as burning fossil fuels, electric heating, and direct solar use, are commonly reduced. In space heating, solar thermal systems circulate heat- carrying fluids into radiators, underfloor heating pipes, and air exchangers to heat buildings. This application promotes stable heating in households and commercial infrastructures, ensuring comfort day and night, and season after season (Duffie *et al*., 2020) [6]. On an even larger scale, solar thermal systems are used to generate electricity. Concentrating solar power technologies utilize high- temperature solar heating to create steam used to turn turbines for electricity production. These applications alone prove how solar thermal systems contribute to expansion in renewable energy use through its functional versatility, and its integral role in the shift toward low- carbon infrastructures (Duffie *et al*., 2020) [6].

Similarly, it can also be seen how solar thermal systems introduce significant benefits in their use as an alternative solution for heating systems. Since these systems are capable of utilizing the abundant resource of solar energy, they can positively yield significant cost benefits in the long run due to their potential to minimize the dependency on fossil fuels and, hence, all the costs involved in fuel acquisition and use. As production costs become lower, investments in the use of advanced materials can be sustained in the long run, such as the use of Ag–graphene/polyethylene glycol composites to improve the performance of thermal energy storage and systems further (Zhang *et al*., 2019) [15]. These materials are found to be highly efficient due to their high conversion and storage rates, allowing further progress in efficiency on the use of resources while maintaining better compatibility with the environment. In this sense, such potential serves to strengthen the appeal for more widespread adoption of solar thermal systems into current practices to enable more sustainable energy consumption with less dependency on non-renewable energy sources in response to the need for transition to low-carbon energy infrastructure.

Solar thermal systems, on the other hand, also bring some limitations that can compromise their viability and performability in certain contexts. One key issue lies in the dependence of their energy production on weather conditions and the amount of solar irradiation received at each location, as cloudy days or prolonged periods of low sunlight exposure can significantly affect thermal performance (Duffie *et al*., 2020) [6]. As a result, the exposure variability associated with solar thermal energy presents ongoing challenges to areas that experience unstable or poor sunshine, compromising system reliability and usability throughout the year. In addition, the available space for the installation of collectors and related equipment can become considerable when applied to high heat load applications such as multistory buildings or industrial applications. Therefore, sizing and site selection are heavily influenced by the available land to maximize sunshine exposure and the consequent collector configuration, which can further limit the system's implementation to certain terrains and landscapes at the expense of colonized or urbanized areas (Duffie *et al*., 2020) [6].

Emerging Innovations – The boom of novel research directions to further advance the capabilities of solar energy technologies has led to them being dubbed as “emerging innovations” from the industry standpoint. One architectural innovation is the progress in the various configurations of solar cells based on the perovskite structure. The promising structure has led to numerous architectural frameworks such as the Interdigitated Back Contact, Lateral Configuration, Fiber-Shaped, Substrate-Configuration architectures and others (Miglani *et al*., 2025) [11]. Each unique perovskite architecture is aimed at tapping new performance dimensions characterized by efficiency, flexibility, lightweight, and ease of integration with existing and upcoming application environments. Targeted engineering at the material level and structural design aspects holds the potential for optimizations in charge transportation, durability, and manufacturability at scale. Such unique characteristics of the various architectural innovations open new possibilities that are beyond the state-of-the-art with respect to deployment commonality and convenience as well. Continued advancements in perovskite technologies, when coupled with the case-specific targets from their architectural frameworks, can be expected to eventually overcome the challenges that affect their current performance (Miglani *et al*., 2025) [11].

As an example, perovskite solar cells disrupt the solar technology landscape due to their efficiency and low-cost potential. Recent advances have focused on both the material optimization - including carbon-based and inorganic cesium lead iodide perovskites - and the in-vacuum deposition processes for stable and low-cost production (Alberti *et al*., 2022) [2]. These developments help attaining low-cost and sustainable composition while those also enable sustainable device architecture for the solar landscape. Similarly, machine learning methods have allowed the precised estimate of fundamental material properties such as bandgaps which help optimize and design high-performance perovskite cells (Kumar *et al*., 2023) [9]. As these trends converge, perovskite technologies are set to provide solar panels that break efficiency and low-cost barriers to current applications, attracting a much wider audience to solar technology for the high number of potential implementations.

Bifacial solar panels are also an innovative technology that has great potential in photovoltaics. Bifacial modules can absorb solar radiation on both sides of the surface. Bifacial surfaces can take advantage of the reflected light due to the reflective surfaces below (ground or near building or facilities). It provides great overall energy yield relative to standard panels (Ogundipe *et al*., 2024) [12]. Many times, the installation height is above reflective surfaces which is beneficial to its power output, making it preferable in high albedo areas. Bifacial modules also perform better in diffuse light and provide more electricity in less ideal sunlight. Such effects brought about by the flexible installation capabilities of bifacial panels and easier energy harvesting makes it an attractive choice for maximizing footprints and further increasing the productivity of solar farms (Ogundipe *et al*., 2024) [12].

On a different note, floating solar farms have come into play due to their innovative use of water bodies as locations for photovoltaic development and energy generation. Floating solar farms minimize the pressure on land in highly urbanized areas or regions with significant farmland, as solar panels are installed on top of lakes, reservoirs, or artificial ponds. With water situated under the solar panels, the photovoltaic modules are also presumed to work more efficiently, as a lower ambient module temperature is correlated with a higher energy yield and possibly a slower rate of degeneration of the solar panels (Gagliano *et al*., 2019) [7]. Marginally, floating solar farms could also cut down evaporation from the water body, thereby resulting in additional water savings for drought-stricken or water-scarce areas. Overall, floating solar farms are seen as a scalable and feasible alternative to renewable energy development for integrating photovoltaic generation systems into a range of different contexts, growing the footprint of sustainable energy sources and developments in conjunction with terrestrial solar innovations (Gagliano *et al*., 2019) [7].

Sustainable mobility solutions are further demonstrated by the emergence of solar-based transport technology, which highlights the flexibility of photovoltaic (PV) devices and the growing reach of renewables beyond stationary settings. Vehicles using solar power, such as experimental solar cars and buses, utilize solar panels installed onto the vehicle itself to either enhance or fully power their electric drivetrain, which shares certain aspects of low-carbon solutions for mobility designed for short-distance movement and certain other specific applications. Solar charging stations are also developed and located in public areas or along certain transport routes, enabling more widespread use of electric vehicles through direct and decentralized charging from solar electricity and reduced dependency on grid electricity that is generated from fossil fuels (Tabassum *et al*., 2021) [14]. These charging with supporting monitoring and controlling technologies are also often employed to ensure effective energy supply and response to the changing level of sunshine and, within the stability and reliability required for transport systems. Provided that continuing cost reductions due to technological progress and policies encouraging the use of renewables online, powered transport technologies are expected to contribute to the mobility of integrated energy systems.

Similarly, the integration of artificial intelligence and machine learning is revolutionizing the optimization of solar energy systems by facilitating their design and operations. With state-of-the-art computational techniques, vast amounts of data and algorithms allow researchers and engineers to analyze, predict material properties, and optimize solar cell architecture much faster and accurately. Machine learning models are capable of predicting the bandgaps of ABX3-type perovskites, which is critical for determining energy conversion efficiency and applicability in various photovoltaic uses (Kumar *et al*., 2023) [9]. The derived information provides researchers with insights that will lead to the faster development of technologically advanced and efficient perovskite solar cells. Improved efficiency further offers a more directed device-optimization method rather than the traditional experimental course of action. The integration of artificial intelligence facilitates continued development and guides material selection decisions in optimizing systems for highest efficiency, energy capture, and stability amid dynamic energy environments (Kumar *et al*., 2023) [9].

Therefore, the process of innovation with state-of-the-art solar technology continues to have a monumental impact on energy at a global level, driving further development for climate and sustainability goals. With innovation maturity—high-efficiency PV materials or smart energy management, for example—the potential to reduce carbon footprints and provide energy access in numerous socio-economic scenarios encourages adherence to climate targets as proposed by the nations involved in the international policy climate agreement. On a global scale, the potential for these innovations to be deployed at scale drives a reduced reliance on fossil fuels and encourages emerging economies and developed nations to switch to cleaner technologies (Bouich *et al*., 2023) [4]. Inclusive policy and markets remain pivotal to ensure that state-of-the-art solar technology continues to be deployed at scale and price-points that encourage economic growth and climate action. But, as innovative design and applications increasingly become the norm, the impact of solar technologies on energy equity and climate adaptation will drive a significant proportion of the continued progress towards these wider goals in energy access (Bouich *et al*., 2023) [4].

Despite the promising advantages, however, there remain significant barriers to the deployment and widespread implementation of solar energy technologies in energy sectors. The primary barrier lies in the technological challenges related to the solar resources' intermittency, high efficiency of energy conversion, and energy storage under various environmental conditions (Tabassum *et al*., 2021) [14]. Economic barriers are also present due to the high upfront costs of the technologies and unequal access to financial incentives. The instability of policies regarding rules and regulations, and the sustainability of subsidies or tax credits, lead to a lack of investors' confidence in the growth and development of clean energy sectors (Tabassum *et al*., 2021) [14]. All these barriers need a coordinated effort in terms of research and development, legislative support, and market intervention to address the financial burden and overcome the existing issues for a successful transition to clean energy scenarios.

Table 2: Challenges and Barriers of Solar Energy Technologies

Category	Key Challenges	Explanation / Implications
Technological	Intermittency and variability	Solar generation depends on weather and daylight, requiring backup storage or hybrid systems.
	Efficiency limits	Despite advances, PV and thermal systems still face conversion losses and degradation over time.
	Storage integration	Battery and thermal storage solutions increase costs and require additional infrastructure.
Economic	High upfront investment	Installation costs for PV panels, inverters, collectors, and storage remain a financial barrier.
	Maintenance costs	Cleaning, repair, and replacement of components can add to lifecycle expenses.
	Unequal cost competitiveness	In some regions, fossil fuels remain cheaper due to subsidies, slowing adoption.
Policy / Market	Regulatory instability	Uncertain policies, changing tax incentives, or subsidy withdrawal discourage long-term investments.
	Financing barriers	Limited access to credit and green financing in developing countries reduces adoption potential.
	Market competition	Competing renewable technologies (wind, hydro, biomass) may receive priority in certain regions.
Practical / Social	Land and space requirements	Large-scale PV or solar thermal plants demand significant land, affecting agriculture/urban planning.
	Environmental impact	Large installations may affect ecosystems (water shading in floating PV, desert land use for CSP).
	Skilled workforce	Lack of trained personnel in installation and maintenance limits reliable deployment.
	Social acceptance	Communities may resist large solar farms due to visual, cultural, or land-use concerns.

However, as summarized in Table 2, barriers remain in the form of technological limitations like intermittency and storage needs, high upfront and maintenance costs, unstable policy frameworks, financing difficulties, and land-use or social acceptance issues. Together, these tables highlight that while solar energy holds transformative potential in reshaping the global energy landscape, realizing its full benefits requires addressing existing constraints through innovation, supportive policies, and integrated planning. Ultimately, the future of solar energy appears dependent mainly on technological innovation, government intervention and the collaboration of countries. The expected growth of solar energy in the future is facilitated by innovations and improvements to solar photovoltaic and thermal technologies that promise better conversion efficiencies, lower investment costs, and increased versatility. As countries at all levels seek to decarbonize their economies and energy supply, solar technologies provide a means to deliver inexpensive, scalable and sustainable energy to a growing global population (Bouich *et al*., 2023) [4]. Access to existing and emerging solar technologies could be enhanced through the collective action of countries to implement market and intervention policies, such as subsidy programs, designed to reduce the entry costs of less developed countries. Given additional investments in research and development, favourable regulatory regime, and international collaboration, the development and expansion of solar technologies are expected to play a significant role in satisfying the future global energy demands and achieving long-term climate goals (Bouich *et al*., 2023) [4].

Conclusion

The role of the photovoltaic and solar thermal technologies is explained through the presented discussion. These core technologies enable the widespread utilization of solar energy around the globe. While photovoltaic technologies convert sunlight into electrical energy with improving efficiencies, solar thermal systems use the heat produced by solar radiation for various applications. The performance and economic viability of photovoltaic and solar thermal technologies have been reinforced through recent advanced materials, system configurations, and smart optimization breakthroughs. Furthermore, the breakthrough technologies such as perovskite technology, bifacial technology, and floating technologies validate the ability of the existing photovoltaic and solar thermal systems to evolve and improve. Finally, all discussed points underline the solar energy systems' ability to overcome environmental issues, improve energy autonomy, and facilitate the shift towards a sustainable energy pathway and power systems all over the world.

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