

Sustainable Electricity Generation through Solar Power Technologies: A Review

Arun Kr Yadav^{1*}, Sibbi Chaurasia²

Abstract

Fossil fuels are burned to create the bulk of the energy produced globally, which depletes fossil fuel reserves and releases carbon dioxide into the atmosphere. The continued volatility of fuel prices has sparked serious concerns about the sustainable use of fuel for future energy needs. Energy use can be made sustainable and clean by minimizing the use of renewable energy resources as opposed to the damaging gases generated during the energy production process that affect the environment. The utilisation of naturally existing solar energy has increased significantly in response to the increasing demand for renewable power. Solar energy technology is now advancing in several ways. To maximize the benefits of the solar energy system, Making the most of a solar power system requires an understanding of the technology and how well it suits the needs and kind of usage. This article examines several solar power methods that can be applied globally to provide electricity sustainably. There has been a lot of excitement in solar photovoltaic (PV) and concentrated solar power (CSP) techniques. We've talked about their types, mechanisms, costs, and efficiency. While solar PV is a better developed and economically viable technology, it may be used for both small and large-scale applications. It has been observed that although CSP technology is more expensive, it offers bigger economic returns and is more fit for large-scale applications.

Keyword: Solar energy solar photovoltaic, concentrated solar power, renewable energy resources, sustainable electricity

INTRODUCTION

The need for renewable and sustainable energy sources has increased recently due to worries about energy security, environmental deterioration, and climate change. One of the most promising and swiftly evolving sources of renewable energy for sustainably generating electricity is solar power. Solar power, which harnesses the sun's limitless and unlimited energy, provides a clean, dependable, and affordable way to fulfill the world's growing energy needs while reducing the negative effects of reliance on fossil fuels. Photovoltaic (PV) panels and solar thermal systems are the mainstays of solar power technology, which uses sunlight to directly produce electricity [1]. PV panels are made up of silicon and other semiconductor-based linked solar cells that collect photons from sunshine and convert them into an electric current. In contrast, solar thermal systems focus sunlight using mirrors or lenses onto a receiver, where it is transformed into heat and steam, which powers turbines that are connected to generators to produce energy.

*Author for Correspondence

Arun Kr Yadav
E-mail: dr.arunkumaryadavee@gmail.com

¹Associate Professor, Department of Electrical Engineering
Bansal Institute of Engineering and Technology Lucknow,
Uttar Pradesh, India

²Student, Department of Electrical Engineering Bansal Institute
of Engineering and Technology, Lucknow, Uttar Pradesh, India

Received Date: April 25, 2024

Accepted Date: May 30, 2024

Published Date: June 02, 2024

Citation: Arun Kr Yadav. AReview On: Sustainable Electricity Generation Through Solar Power Technologies. Journal of Power Electronics & Power Systems. 2024; 14(1): 28–36p.

Improvements in technology and a growing public consciousness of environmental challenges. As a result, solar energy is now more competitively priced than traditional energy sources in many areas, drawing large investments and encouraging broad usage Scalability and adaptability are two of the main benefits of solar power technology. Solar power is useful for both centralized and

decentralized electricity generation since it may be mounted on a range of surfaces, such as rooftops, building facades, and open land. Furthermore, developments in PV technology have produced more robust and efficient solar panels, which lower costs and increase energy output. In conclusion, solar power technology has a great deal of promise as a green and sustainable way to produce electricity [2]. Solar energy is positioned to play a major part in the worldwide shift towards a cleaner, more sustainable energy future with continued improvements and policies that support it. By using the sun's energy, we can open up a nearly endless supply of clean energy and open the door to a more robust and sustainable energy system for future generations [3].

Photovoltaic (PV) Cells

Material & Method for Solar Power Technology

- **Materials:** PV cells are typically made from semiconductor materials, most commonly crystalline silicon, but also thin-film materials such as cadmium telluride (CdTe) or copper indium gallium selenide (CIGS).
- **Method:** PV cells use the photovoltaic effect to directly turn sunlight into electricity. Photons from sunlight cause electrons in the semiconductor material to break free, which results in an electric current. This current is then captured and directed for use as electrical power [4-5].

Solar Panels

- **Materials:** Solar panels consist of multiple PV cells interconnected and encapsulated within a protective, typically made of glass, tempered glass, or specialized plastics.
- **Method:** PV cells are interconnected to form modules, layers which are then assembled into panels. These solar panels are made to effectively collect sunlight and transform it into electrical power.
- They are installed on rooftops, ground-mounted structures, or integrated into building facades to maximize exposure to sunlight [6].

Inverters

- **Materials:** Inverters are electronic devices made from semiconductor components, capacitors, and other electronic components.
- **Method:** The direct current (DC) electricity produced by the solar panels is transformed into alternating current (AC) electricity by inverters so that it may be used in buildings, commercial spaces, and the electrical grid. Additionally, they manage voltage levels and maximize power output to maximize the efficiency of the solar energy system [7].

Mounting Structures and Racking Systems

- **Materials:** Mounting structures and racking systems are typically made from aluminium, steel, or other metals.
- **Method:** These structures provide support for solar panels and ensure proper orientation and tilt angle for optimal sunlight exposure. They are made to withstand weather-related conditions like wind, snowy conditions, and rain while firmly securing the solar array in position [8].

Balance of System Components

- **Materials:** Balance of system components include wiring, connectors, junction boxes, combiner boxes, and other electrical and mechanical components.
- **Method:** These components facilitate the safe and efficient operation of the solar power system, connecting the PV modules to the inverter and electrical grid. They also include safety features such as overcurrent protection, grounding systems, and surge protection to prevent damage to equipment and ensure compliance with electrical codes and standards [9].

Energy Storage Systems (Optional)

- **Materials:** Energy storage systems may include batteries, capacitors, or other storage devices.

- *Method:* To use the additional electricity produced by the solar power system during times when there is less sunlight or a high demand for electricity, energy storage devices are required.
- They enhance the reliability and resilience of the solar power system by providing backup power and enabling grid-independent operation in off-grid or remote locations [10].

Monitoring and Control Systems

- *Materials:* Monitoring and control systems consist of sensors, meters, data loggers, and communication devices [11].
- *Method:* These systems monitor the performance and efficiency of the solar power system in real-time, collecting data on energy production, consumption, and system health. They provide valuable insights for the system.

Optimization, maintenance, and troubleshooting, ensuring maximum energy yield and long-term reliability. An overall workflow of the adopted methodology is presented in Figure 1 [12].



Figure 1. An overall workflow of the adopted methodology.

LITERATURE STUDIES ON SOLAR POWER TECHNOLOGY

1. *Solar Cell Technologies:* Literature explores various types of solar cell technologies, such as silicon-based photovoltaics, thin-film solar cells, organic photovoltaics, and emerging concepts like perovskite solar cells. Studies focus on improving efficiency, durability, and cost-effectiveness of solar cells [13].
2. *Solar Energy Conversion Systems:* Research investigates different solar energy conversion systems, including photovoltaic systems for electricity generation and concentrating solar power (CSP) systems for thermal energy production. Studies evaluate performance, scalability, and integration with energy storage technologies [14].
3. *Integration and Grid Management:* Literature examines the challenges and opportunities associated with integrating solar power into existing electricity grids. Topics include grid stability, power quality, demand-side management, and grid-scale energy storage solutions [15].
4. *Environmental Impacts and Life Cycle Assessment:* Research evaluates solar power the relationship of technology environmental effects at every stage of its life cycle, from extraction of raw materials and production to installation, use, and decommissioning. Studies evaluate factors such as greenhouse gas emissions, water usage, land use, and waste generation [16].
5. *Economic Analysis and Market Dynamics:* Literature studies the economics of solar power, including levelized cost of electricity (LCOE), financial incentives, subsidies, and market trends. Research also examines the socio-economic implications of widespread solar adoption, such as job creation, energy access, and energy equity [17].
6. *Policy and Regulatory Frameworks:* Studies analyze policies, regulations, and incentives aimed at promoting the deployment of solar power technology. Topics include feed-in tariffs, net metering, renewable portfolio standards, tax credits, and regulatory barriers to solar energy adoption [17].
7. *Socio-Cultural Acceptance and Adoption:* Research explores public perceptions, attitudes, and behaviours towards solar power technology. Studies examine factors influencing adoption decisions, including cultural norms, social networks, trust in technology, and awareness campaigns.

8. *Techno-Economic Analysis and Optimization*: Literature employs techno-economic models and optimization techniques to assess the performance and cost-effectiveness of solar power systems under different scenarios, such as varying solar irradiance, financing mechanisms, and policy environments [17].
9. *Prospects and Emerging Trends*: Research investigates emerging trends and innovations in solar power technology, such as building-integrated photovoltaics (BIPV), solar-powered desalination, solar microgrids, and floating solar farms. Studies also explore the potential of solar energy in addressing global energy challenges and achieving sustainability goals [18].

DIFFERENT TYPE OF SOLAR POWER TECHNOLOGY

The technology known as concentrated solar power (CSP) uses mirrors or lenses to focus a lot of sunlight onto a tiny area, usually onto a receiver, which turns the solar energy into heat [19]. This heat can be used directly or converted into electricity through various means such as steam turbines or Stirling engines as shown in Figure 2.

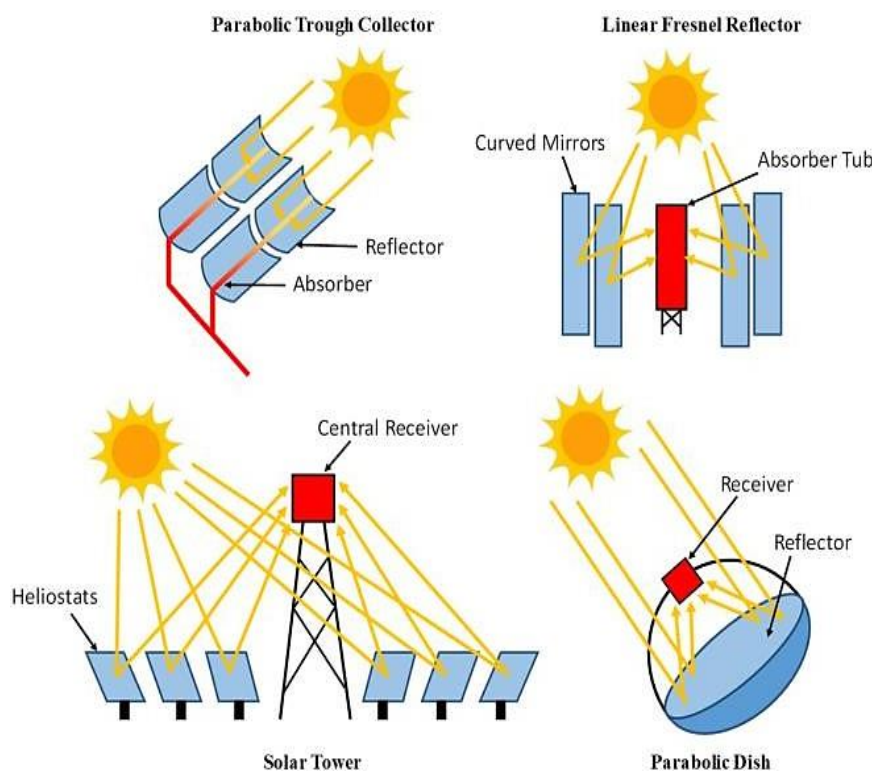


Figure 2. Four main CSP technology sources.

The Key Components of a CSP System Typically Include:

1. *Solar Collectors*: These are the glasses or reflectors that focus sunlight onto a receiving device.
2. *Receiver*: The focused sunlight is absorbed by the receiver and is transformed into heat. This heat transfer fluid can then be used to generate steam or drive a heat engine to produce electricity.
3. *Thermal Energy Storage*: Certain CSP systems include thermal energy storage built to store extra heat produced in sunny spells, enabling the production of electricity in overcast or nocturnal situations.
4. *Power Block*: This is the system that converts the heat into electricity. It can include steam turbines, Stirling engines, or other types of heat engines.

CSP Technology Offers Several Advantages, Including

- *Dispatchable Power*: CSP with thermal energy storage can provide electricity even when the sun isn't shining, allowing for more reliable and consistent power generation.

- *Scalability*: CSP systems can be adjusted in size to accommodate different energy requirements.
- *Grid Stability*: CSP plants can provide grid stability by providing on-demand power and helping to balance fluctuations in renewable energy sources like wind and solar photovoltaic.
- *Minimal Environmental Impact*: CSP plants generate power without releasing greenhouse gases or other pollutants linked to the burning of fossil fuels. Despite these advantages, CSP also faces challenges such as high upfront costs, land requirements, and intermittency of sunlight. Continuing investigation and development, however, seeks to raise the CSP the relationship of technology effectiveness and affordability [19].

Photovoltaic (PV) Technology

The idea of photoelectric effect serves as the foundation for photovoltaic (PV) technology, which converts incident solar energy directly into electrical energy [20]. PV technology is suitable for places with both high and low direct solar exposure since it takes advantage of the scattered portions of incoming light as shown in Figure 3.

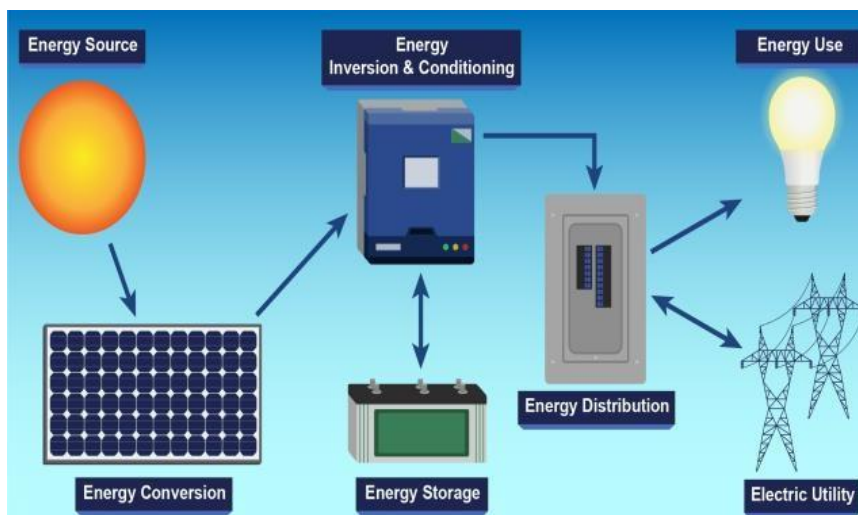


Figure 3. Photovoltaic (PV)Technology.

PV technology uses solar panels, which are composed of different photovoltaic materials, to generate electricity. The most often used materials are mono and polycrystalline silicon, cadmium telluride (Cadet), gallium arsenide (GaAs), and Indium gallium phosphide (In Gap)-based triple-junction solar cells [21]. A solar cell is, in general, a small device that produces electricity. Several solar cells are connected to form modules, which are then built to generate power on a larger scale. Photovoltaic technology (PV) converts incident solar energy directly into electrical energy using the principle of photoelectric effect. It utilizes inbound, distributed components. As a result, PV technology is applicable in areas with high and low levels of direct sun exposure. Solar panels, which are made of various photovoltaic substances, are used to generate electricity using solar energy generation. Among the most widely used materials are Indium gallium phosphide (InGaP) triple- junction solar cells, gallium arsenide (GaAs), cadmium telluride (CdTe), and mono and polycrystalline silicon. A solar cell is generally speaking a small device that generates power. To generate more electricity, solar cells are built into modules that consist of many cells. These modules are then assembled [22].

GENERATION OF PHOTOVOLTAIC TECHNOLOGY

Solar photovoltaics, or photovoltaic (PV) technology, is a technique for utilising semiconducting substances to convert sunlight into electrical power. Over the years, several generations of PV technology have emerged, each with its own advancements and improvements. Here's a brief overview of the generations of photovoltaic technology in Figure 4.

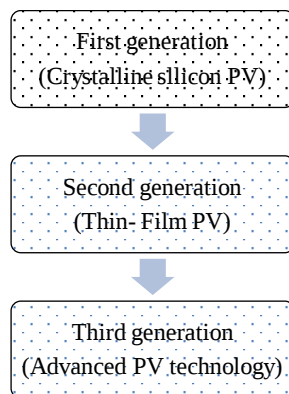


Figure 4. Solar Photovoltaic generation.

1. *First Generation (Crystalline Silicon PV)*: Silicon wafers are used to create crystalline silicon solar panels, which make up the majority of first-generation PV technology. This generation can be divided into two categories:
 - *Monocrystalline silicon*: produced more costlyly due to its great efficiency and use of single-crystal silicon.
 - *Polycrystalline silicon*: Made from multiple silicon crystals, relatively lower in efficiency compared to monocrystalline but cheaper to manufacture.
2. *Second Generation (Thin-Film PV)*: Second-generation PV technology involves thin-film solar cells that use materials other than crystalline silicon. thin film Usually, flexible materials or glass are used as substrates for solar cell deposition. Typical materials for thin-film technology consist of:
 - Amorphous silicon (a-Si)
 - Cadmium telluride (CdTe)
 - Copper indium gallium selenide (CIGS)

Thin-film PV cells are lighter, more flexible, and cheaper to produce than crystalline silicon cells. However, they usually have lower efficiency.

3. *Third Generation (Advanced PV Technologies)*: The third generation of PV technologies includes various advanced concepts and materials aimed at achieving higher efficiency and lower production costs. Some of these technologies include:
 - *Multijunction solar cells*: these kinds of solar cells increase efficiency by capturing a wider spectrum of sunlight through the use of many layers of semiconductors.
 - *Organic photovoltaics (OPV)*: OPV cells use organic (carbon-based) materials to generate electricity. They are lightweight, flexible, and potentially low-cost, suitable for applications like building-integrated photovoltaics (BIPV) and wearable electronics [23].

Comparison of CSP And PV Technology

Perovskite solar cells: Perovskite-based solar panels have drawn a lot of interest because of the opportunity for low production costs and quick efficiency gains. They use perovskite-structured materials, often in combination with other materials, to convert sunlight into electricity. Comparing Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies involves evaluating various factors, including efficiency, cost, scalability, land use, reliability, and applications [25]. Here's a comparison between CSP and PV technologies:

Principle of Operation

- *CSP*: Concentrated Solar Power systems use mirrors or lenses to focus sunlight onto a tiny area, usually a receiver, in order to produce heat. After that, the heat is converted to steam, which powers a turbine that is connected to a generator to generate energy.

- **PV:** Photovoltaic systems use semiconductor materials (like silicon) that produce a voltage when exposed to light to directly convert sunshine into power [25].

Efficiency

- **CSP:** CSP systems typically have higher efficiency in converting sunlight into electricity in areas with high direct solar radiation. However, elements like the architecture of the system and the weather may have an impact on how effective they are.
- **PV:** PV systems have lower efficiency compared to CSP systems but have the advantage of being able to generate electricity even under diffuse sunlight conditions. PV efficiency is also improving over time with advancements in materials and technology [26].

Cost

- **CSP:** CSP systems often require higher initial capital investment due to the complexity of the technology, including mirrors, tracking systems, and thermal storage. However, as technology has advanced and economies of scale have been realised, the cost of CSP has been declining.
- **PV:** PV systems generally have lower initial capital costs compared to CSP systems, especially for residential and commercial installations. PV technology is now among the most affordable renewable energy sources due to its considerable cost reductions over time.

Scalability

- **CSP:** Large-scale installations appropriate for utility-scale energy production are frequently CSP systems. They require significant land area and are typically built in regions with high direct solar radiation [26].
- **PV:** PV systems are highly scalable and can be installed in various sizes, from small rooftop installations to utility-scale solar farms. They can be used for dispersed as well as centralised power generation.

Land Use

- **CSP:** CSP systems require relatively more land area compared to PV systems, especially for large-scale installations with concentrated solar collectors.
- **PV:** PV systems generally require less land area per unit of electricity generated, especially for rooftop installations or ground-mounted systems with fixed tilt [26].

Reliability

- **CSP:** CSP systems with thermal storage capability can provide electricity even when there is no sunlight, offering dispatchable power generation similar to conventional power plants.
- **PV:** PV systems lack built-in energy storage and are reliant on sunshine.
- However, battery storage systems can be integrated with PV installations to enhance reliability and provide backup power.

Applications

- **CSP:** CSP systems are well-suited for large-scale utility power generation and are often used in regions with high direct solar radiation for grid-connected electricity production [26].
- **PV:** PV systems are versatile and can be used for various applications, including residential, commercial, industrial, and off-grid power generation, as well as for small-scale applications like portable electronics and solar-powered water pumps [26].

DISCUSSION AND CONCLUSION

The development of solar power technology, there has been a steady increase in the use of CSP and PV systems for green energy. In contrast to conventional energy sources, solar power technologies have garnered significant attention and developed into a competitive sustainable energy alternative in recent times. As a result, customers' ever-increasing interest has spurred a technological revolution

and important developments in the form of higher solar power system efficiencies. More sophisticated technology is becoming less expensive for businesses. The advancements in this field of technology have led to the commercial maturity of solar power technologies [27]. There is frequently some overlap between these technological developments and CSP and PV applications. Utilizing various methods and applications, CSP and PV technologies both make use of the sun's inherent energy to generate green energy. Since the two solar power technologies, PV and CSP, have different underlying principles, their cohabitation has not been characterized by competition but rather by cooperation in order to fulfill the world's expanding energy needs and reduce carbon emissions. This research project has reviewed a number of solar power technologies. Their variety, efficacy, cost implications, and environmental impact have all been discussed [28]. According to this analysis, the CSP plant generates more energy than the PV plant for the same nominal output power, indicating that there may be financial benefits. However, the initial cost of installing a CSP plant is significantly higher than that of a comparable PV unit. Every solar power technology has benefits and drawbacks of its own, and as the best option depends only on usage patterns and environmental conditions, it is hard to identify which is better [29]. This review paper has outlined some of the most crucial considerations that must be made when deciding whether solar power technology is appropriate for a given circumstance [30]. In today's world, solar energy is becoming a top green energy source as sustainability and mitigating climate change become worldwide concerns [31].

REFERENCES

1. <https://energy.sais.jhu.edu/articles/renewable-energy-vs-sustainable-energy/>
2. <https://www.energy.gov/eere/why-clean-energy-matters>
3. <https://energy.sais.jhu.edu/articles/renewable-energy-vs-sustainable-energy/>
4. <https://www.open.edu/openlearn/nature-environment/environmental-studies/introduction-sustainable-energy/content-section-2>
5. MakaAO, O'Donovan TS. Transient thermal-electrical performance modelling of solar concentrating photovoltaic (CPV) receiver. *Solar Energy*, 2020, 211:897–907.
6. https://en.wikipedia.org/wiki/Solar_cell#cite_ref-IEA_roadmap-PV-2014_6-0
7. Variath R.C., Andersen M.A.E., Nielsen O.N. *et al.*: 'A review of module inverter topologies suitable for photovoltaic systems'. *Proc. Conf. Int. Symp. on Parameterized and Exact Computation (IPEC)*, Singapore, 2010, pp. 310–316
8. Jinxin Cao, Akihito Yoshida, Proshit Kumar Saha, Yukio Tamura, "Wind loading characteristics Vol.3, Page No. 214-255, 2013
9. <https://solarsena.com/balance-of-system-bos-equipment-photovoltaic-system/>
10. J. Hunt, B. Zakeri, W. Filho, et al., Swimming pool thermal energy storage, an alternative for distributed cooling energy storage, *Energy Convers. Manag.* 230 (2021).
11. Sharma, N.; Chakraborty, A.K. Implementation of Dynamic Controls for Grid-Tied-Inverters through Next-Generation Smart Meters and Its Application in Modernized Grid. *Energies* 2022, 15, 988.
12. Balwani, M.R.; Thirumala, K.; Mohan, V.; Bu, S.; Thomas, M.S. Development of a Smart Meter for Power Quality-Based Tariff Implementation in a Smart Grid. *Energies* 2021, 14, 6171.
13. Giuliano, G., A. Bonasera, G. Arrabito, and B. Pignataro. 2021. Semitransparent perovskite solar cells for building integration and tandem photovoltaics: Design strategies and challenges. *Solar RRL* 5 (12): 2100702.
14. Chakravarthi, B. N. C. V., & Siva Krishna Rao, G. V. (2020a). A high gain novel double-boost converter for DC microgrid applications. <https://doi.org/10.1142/S0218126620502461>
15. <https://doi.org/10.1201/b19138>
16. de Baan L, Alkemade R, Koellner T (2013) Land use impacts on biodiversity in LCA: a global approach. *Int J Life Cycle Assess* 18(6):1216–1230
17. Policies and regulations for renewable energy mini-grids (irena.org)
18. Fu, J.; Mao, X.; Siyal, A.A.; Liu, Y.; Ao, W.; Liu, G.; Dai, J. Pyrolysis of furfural residue pellets: Physicochemical characteristics of pyrolytic pellets and pyrolysis kinetics. *Renew. Energy* 2021, 179, 2136–2146.

19. “Concentrated solar power: technology, economy analysis, and policy implications in China”
20. https://en.wikipedia.org/wiki/Photovoltaics#cite_refSolar_Power_for_the_World:_What_You_Wanted_to_Know_about_Photovoltaics_3-0
21. How Do Solar Cells Work? Photovoltaic Cells Explained | EnergySage
22. Solar Photovoltaic Technology Basics | Department of Energy
23. Green, M. A. Radiative efficiency of state-of-the-art photovoltaic cells. *Prog. Photovolt.* 20, 472–476 (2012).
24. <https://www.solarfeeds.com/mag/csp-and-pv-differences-comparison/>
25. <https://ijcrt.org/papers/IJCRT2312108.pdf>
26. <https://solarmagazine.com/solarpanels/perovskite-solar-cells/>
27. UNFCCC. *The Paris Agreement*. Archived from the original on 19 March 2021. Retrieved 18 September 2021. <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement> (2 February 2022, date last accessed).
28. IRENA. Solar Energy—International Renewable Energy Agency. 2021. www.irena.org/solar (2 February 2022, date last accessed).
29. McIntosh, K.R., Shaw, N.C. and Cotter, J.E., 2004, June. Light trapping in sunpower’s A-300 solar cells. In *Proceedings of the 19th European Photovoltaic Solar Energy Conference* (pp. 844-7)
30. Sarkin, A.S., Ekren, N. and Sağlam, Ş. (2020) ‘A review of anti-reflection and self-cleaning coatings on photovoltaic panels’, *Solar Energy*, 199, pp. 63–73. doi:10.1016/j.solener.2020.01.084.
31. y Storage Systems’, *Energy Reports*, 9, pp. 380–387. doi:10.1016/j.egyr.2023.05.157.