

Next Generation Photovoltaics: Trends in Materials and Systems

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Abstract: Photovoltaic (PV) materials are at the heart of solar energy conversion technologies and show an important role in the evolution toward sustainable energy systems. Various researchers proposed countless methods for harnessing energy from the constant solar radiation through solar panels. However, relatively low efficiency is the primary challenge with solar panels, which is influenced by the temperature of the panel, the solar cell type, the panel orientation, and the solar irradiance level. As the promote to reduce carbon emissions grows stronger, it is most important to produce and utilize solar panels in the most efficient manner. This is possible by enhancing their power generation and performance. Additionally, a significant challenge for panel installations is the availability of land or space. Numerous studies have examined the evolution of technologies used in the production of photovoltaic (PV) cells and their designs. However, there remains a gap in the field, particularly when it comes to integrating the latest PV technologies and architectural advancements concentrate on improving the efficiency of PV applications. This paper reviews the current state of PV materials, which include traditional silicon-based cells in addition, emerging materials such as perovskites, organic photovoltaic, quantum dots, and thin-film technologies. Emphasis is placed on material properties, device performance, fabrication methods, environmental impact, and future research directions. This paper also searches the tasks associated with commercialization of next-generation PV materials, scales and stability. The integration challenges of solar panels and potential areas for future research are also examined. This work offers useful insights for both readers and researchers, providing a foundation for understanding the factors influencing solar panel efficiency. It also discusses approaches to improving efficiency and outlines the obstacles that need to be addressed to ensure the successful implementation of these systems.

Keywords: Photovoltaic Materials, Solar Energy, Thin-Film Photovoltaic, Renewable Energy, Power Conversion Efficiency.

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I. INTRODUCTION

The demand for growing global energy and the urgent requirement of reducing greenhouse gas emissions have boost the search for renewable energy sources. In this, solar energy is wealthy and potential because direct electricity is generated by using photovoltaic (PV) technologies [1]. The efficiency and cost- effectiveness of PV devices are largely depending on the materials used in their construction. This paper provides a comprehensive overview of the performance, evolution and visions of photovoltaic materials in solar energy harvesting. Environmental issues are among the most critical global challenges today. These problems

primarily occur from the necessity of replacing the harmful emissions generated by fossil fuel combustion. These emissions lead to environmental pollution and the greenhouse effect. In contrast, renewable energy sources present a more sustainable and cleaner alternative [2]. The evolution to renewable energy must occur in collaboration with the increasing global energy demand and the needs of increasing energy in developing nations. Non-renewable energy sources cannot meet this growing demand because they are finite and limited sources [3]. The foundation of photovoltaic technology is done in the early 19th period, with explorers by conducting experiments on the photovoltaic technology. Albert Einstein further advanced

this understanding by publishing his theory. Through the lens of quantum mechanics, he explained the phenomenon. The first functional silicon-based solar cell was successfully developed in the 1950s. This solar cell had an efficiency of approximately 6% [4]. Over the succeeding decades, photovoltaic technology has been continuously improving. This improvement is particularly in terms of cell consistency, efficiency and cost reduction. Investment in photovoltaic research and development is increased due to the crisis of oil in 1970s [5]. In the 19th decade, photovoltaic technology began to see wider commercial use. Photovoltaic technology widely used in remote regions where access to conventional power sources was limited [6]. By the 20th century, rapid growth is experienced driven by government incentives, technological innovations and decreasing production costs.

Despite the potential, the energy converted by current systems may be insufficient for consumption. By producing fuel from water and carbon dioxide, efficiency can be improved. For this, bio stimulated nanoscale assemblies are used. This technique inspired by photosynthetic processes. These systems can be enhanced by new structures and genetic engineering to encourage production of biomass [7]. Matching the irregular energy production with unstable demand is one of the key challenges in photovoltaic (PV) [8]. A possible solution to match such demand is to build a storing component to manage these irregular energy causes more effectively [9]. Additionally, batteries can be used to improve problems of irregular energy demand [10,11]. The photosynthesis process typically has conversion efficiency between 5% to 10% but photovoltaic cells offer significantly higher efficiency around 23% [12]. There are various technologies aimed at improving the capability of photovoltaic systems when affected by fluctuations of temperature. Methods to improve panel performance include the cooling techniques by water and partial materials change [13, 14]. In addition, transparent coatings of photonic crystal cooling and forced air circulation provided to photovoltaic panels to improve performance [15].

This review explores the recent advancements in novel material resources for solar photovoltaic system. The focus of recent advancement is on emerging technologies like perovskite solar cells, Organic Photovoltaic (OPVs),

Quantum Dot Solar Cells, Thin- Film Technologies. It assesses the efficiency and durability of various material generations used in solar photovoltaic strategies and relates them to old materials. The review also examines the scalability and cost- effectiveness of producing these innovative materials, identifying the key challenges and opportunities associated with their development and implementation. Key challenges include issues of toxicity, permanence and profitability. Hence, the review proposes strategies to address existing limitations and facilitate the adoption of environmentally friendly energy systems. However, further research and development are necessary to overcome current barriers and enable large-scale implementation.

II. PHOTOVOLTAIC ENERGY SYSTEMS: DESIGN AND

A. Operation

Fundamentally, solar energy is harnessed in two primary ways. First through the solar thermal route, which utilizes solar collectors, heaters, dryers, and similar devices. The other is through the solar electricity route, which uses solar photovoltaic systems. Second method is illustrated in figure 1. A typical photovoltaic system consists of arrangements of photovoltaic panels, batteries, meter, breaker and inverter depending on the system's size [16]. In this technology, sunlight is directly converted into electricity without any conversion process. It operates without producing pollutants, strong and straightforward design. This technology helps to mitigate global warming. Additionally, it is modular and has lower operational costs. It requires minimum maintenance, and it can produce power ranging from microwatt to megawatt. When we compare it to other renewable energy technologies, photovoltaic systems offer the highest power density [17].

The solar panels performance can have influenced by several environmental factors and characteristics. These factors include the position of photon incidence, orientation of panel, photovoltaic module conductivity, the material used in solar cells and the time for measuring the sun's direction. As a result, a significant amount of measurement data is required before implementing tracker systems [19].

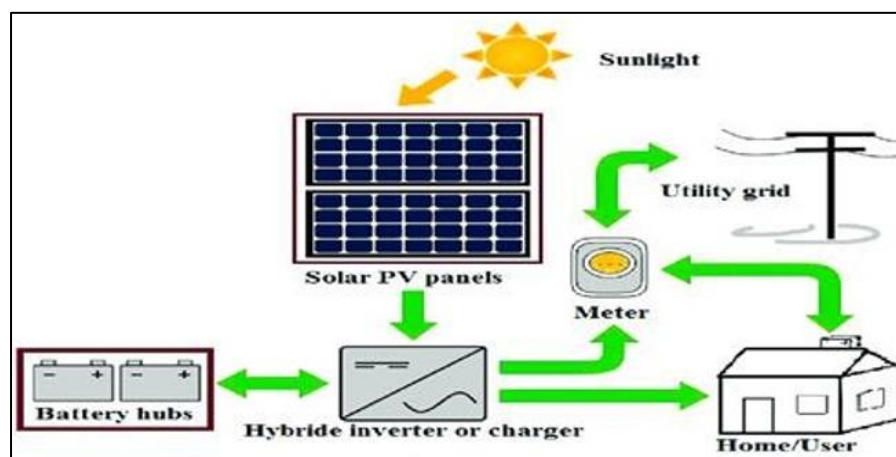


Fig 1: Plan Diagram of the Solar Photovoltaic Systems

Fig 1: Plan diagram of the solar photovoltaic systems [18] Active and passive are two types of tracking systems. Active tracking systems use motors and gear mechanisms to move solar panels toward the sun. The passive tracking systems depend on compressed gas within canisters, which is activated by solar heat. This compressed gas has a low boiling point. The main disadvantage of passive tracking systems is dependence on weather conditions. Another disadvantage is the challenge of selecting the appropriate gas and glass to ensure efficiency. The glass's absorption capabilities are influenced by its color, strength, and chemical properties. On the other hand, the disadvantage of active solar tracking systems are they requiring higher maintenance and may experience a reduction in power productivity if the panel and sun is not directly aligned [20]. Photovoltaic systems are versatile and scalable making them ideal for applications in homes, businesses, and large-scale utilities. For this, power capacities of photovoltaic system ranging from 1 kilowatt to 300 megawatts. One of the major advantages of PV technology is its environmental friendliness. PV technology does not emit harmful gases like carbon dioxide (CO₂), carbon monoxide (CO), or nitrogen oxides (NO_x) during operation. These systems also offer the benefit of low operating and maintenance expenses. [21] However, they do have some limitations, like High upfront installation costs. Photovoltaic system gives Variable power output depending on weather and sunlight availability. There is a requirement for energy storage solutions to enhance consistency and performance.

III. MATERIALS AND METHODS

This section elaborates the Solar photovoltaic materials adopted for the present research study.

A. Materials

When exposed to sunlight, solar photovoltaic materials absorb sun light and convert the solar energy into electrical energy. Generally, photovoltaic systems predominantly depend on inorganic materials. These systems often need expensive and energy concentrated processing methods. Additionally, materials like cadmium telluride can be toxic and have inadequate natural abundance. These issues can be addressed by utilizing organic photovoltaic. The efficiency of photovoltaic cells with organic based is still significantly lower than that of conventional inorganic based systems. Photovoltaic devices typically consume semiconductor, which consist silicon-based solar cells to generate energy. These include crystalline silicon solar cells, which is available in both single crystalline and multi crystalline forms. The main components of solar energy systems are PV modules, which can operate effectively in unflavored environments and provide high energy for powering electronic loads. Silicon based photovoltaic cells remain the most common type, representing over 90% of the global photovoltaic market [22].

High quality polycrystalline technologies, which increase the performance of monocrystalline cells. These systems are more cost effective than traditional methods.

The high efficiency and low concentration module technologies are used to further reduction of the overall cost of photovoltaic (PV) systems [23]. Recent studies have explored silicon heterojunction solar cells, which have high efficiency and considered as the next generation of silicon cells. It is also found that, by increasing the short circuit current and maintaining a high circuit voltage, efficiency limits can be achieved. It is important to minimize the use of indium and silver for large-scale production [22]. Low cost hybrid polymer semiconductor materials are currently in use. This material absorbs photons with energy, which result formation of bound electron-hole pairs. These pairs are typically ranging from 5 nm to 15 nm. These exactions diffuse through the material. They may either isolate into separate charge carriers or recombine, releasing energy in the process [24]

B. Exploring Breakthroughs in Cell Type Technologies

There are notable advancements in photovoltaic (PV) technology including the development of solar cells. That advancement increases absorption and cost effectiveness. Also, well organized perovskite solar cells and bifacial solar panels captures the sunlight from both sides. Additionally, transparent solar cells are combined with surfaces, while perovskite cells and silicon cells work together to boost efficiency. Developed light harvesting techniques using nanomaterials are also making an impact. Roll-to-roll printing methods are helping to lower manufacture costs. The integration of artificial intelligence and machine learning (AIML) is being applied to enhance performance and lightweight flexible solar panels based on thin film technologies are enabling more flexible installations on alternative surfaces [25]

➤ Crystalline Silicon:

It is the most widely used material in photovoltaic technology. These cells are known for their high efficiency and consistency. They come in two main forms:

- Monocrystalline silicon: It is made from a single crystal structure. It offers high effectiveness (15–22%) and longevity.
- Polycrystalline/multicrystalline silicon: It is made from various silicon crystals. It shows low efficiency (13–17%) but it is more affordable.
- Breakthroughs: In 2020, these solar cells reached a highest efficiency about 27%, with ongoing investigation focused on decreasing manufacture costs and enhancing stability.
- Research Trend: c-Si continues to be the most researched and invested technology, boasting a high Research Trend score, indicating sustained interest and development.
- Efficiency Range: It shows efficiency between 15– 20%, with reliability. [26]
- Advantages: The main advantages of these materials are High efficiency, long lifespan, proven technology.
- Disadvantages: The limitation of material is Energy-intensive manufacturing process and rigid structure.

➤ *Thin Film Cells:*

Thin film solar cells are created by putting thin layers of semiconductor materials onto plastic or glass. These cells are flexible and lightweight compared to other cells. They are suitable for diverse applications due to Lightweight and flexible nature.

They come in three main forms

- Cadmium Telluride (CdTe): It offers relatively efficiency (9–16%). It is widely used in large-scale installations.
- Copper Indium Gallium Selenide: It is Flexible and lightweight; it offers efficiency around 13–17%.
- Amorphous Silicon (a-Si): It offers less efficiency compared to others (6–10%). It is often used in calculators and small devices.
- Breakthroughs: in 2020, thin film solar cells attained efficiencies of up to 24%, with study focusing on enhancing stability and exploring fresh materials [27].
- Research Trend: Research interest and investment in thin film solar cells have decreased, as indicated by a low RT5 score, reflecting fewer breakthroughs in the field.
- Advantages: Advantages of materials are Lightweight, flexible, cheaper to produce.
- Disadvantages: Drawbacks of material are Lower efficiency and shorter lifespan than crystalline silicon.

➤ *Organic Solar Cells:*

They are made from carbon-based materials such as polymers or molecules. These materials are still in research and development, but they show low-cost, flexible, and transparent solar cells.

- Breakthroughs: in 2020, these cells showed efficiencies of 18.3%, with study concentrated on refining stability and evolving novel materials.
- Research Trend: as reflected by a high RT5, Organic solar cells have experienced a stable growth in research interest and investment, suggesting continuous breakthroughs in the area [28].
- Efficiency: Currently It offers efficiency of 6–18% in

labs but lower in real-world conditions.

- Advantages: It shows advantages like Lightweight, easy to manufacture, can be printed on various surfaces.
- Disadvantages: Drawbacks of materials are Lower efficiency and durability. Considering the disadvantages, they are not yet commercialized on a large scale

➤ *Hybrid Perovskite Solar Cells:*

These cells combine photovoltaic technology with other energy sources like wind or hydro to enhance overall energy generation [27].

- Breakthroughs: These cells achieved efficiencies up to 29% in 2020, with study efforts of improving stability and evolving innovative materials.
- Research Trend: These cells have seen a significant growth in exploration interest and investment, indicating a rapidly growing field [28].
- Advantages: It shows advantages such as High efficiency and low cost manufacturing.
- Disadvantages: Drawbacks of these cells are Stability issues and use of toxic materials like lead are still being addressed

➤ *Dye-Sensitized Solar Cells (DSSC):*

They copy natural photosynthesis process. They use dye to absorb sunlight and generate electricity. A transparent conducting oxide coated with titanium oxide. A light weight dye absorbed on to titanium surface.

- Breakthroughs: Dye sensitized solar cells shown efficiencies of up to 14% in 2020, with study focused on enhancing strength and discovering new materials.
- Research Trend: These cells have experienced a failure in exploration interest and investment indicating a reduction in breakthroughs [29].
- Advantages: It shows advantages such as low-cost production. It can work in low light condition.
- Disadvantages: Drawbacks of these cells are Stability issues and low efficiency compared to others.

Table 1 — Different Solar Photovoltaic Material

Material Type	Efficiency Range	Flexibility	Commercial Use
Monocrystalline Si	15–22%	No	Yes
Polycrystalline Si	13–17%	No	Yes
CdTe (Thin-Film)	9–16%	Some	Yes
CIGS (Thin-Film)	13–17%	Yes	Yes
Organic PV	6–18%	Yes	Limited
Perovskite	20–25%+ (lab)	Yes	Emerging

It is important to recognize that these trends are continually growing, with new breakthroughs emerging frequently. This overview provides a snapshot of the current state of investigation in photovoltaic technology.

IV. FUTURE SCOPE IN SOLAR TECHNOLOGY

In recent years, solar technology has made remarkable advancements by establishing itself as a crucial renewable energy source. However, there remains significant potential for further investigation and improvement in this field. Below are several key areas where future scope could drive

improvements and innovations in solar technology:

➤ *Energy Storage*

The primary challenge with solar energy is its intermittency. Reason is solar power is available only when the sun is available. To enhance the reliability and stability of solar energy, significant research into better energy storage solutions is necessary. Areas of focus could include:

- Advances in battery technology for more efficient and long-lasting storage. For this, Lithium batteries, Sodium batteries, potassium batteries can be used.
- The development of thermal storage and hydrogen storage systems, which could provide alternatives to traditional battery storage and help store solar energy for use when sunlight is not available [30].
- For high storage energy storage, super capacitors can be used. Ongoing research aims to improve density by using advanced electrode materials like Graphene.

➤ *Efficiency*

Generally, efficiency in photovoltaic system refers to the ability of converting sunlight into usable electrical energy. Future research could explore:

- Fresh materials such as perovskite solar cells that could increase the energy conversion efficiency of solar panels.
- For improving energy output, it is necessary to exploring the use of nanotechnology, quantum dots, and multi-junction cells that absorb a broader spectrum of light. [31].

➤ *Durability*

For long term performance of solar system durability is most important. Solar panels are generally designed to work for a long period, but they can be weak to damage from extreme weather, UV exposure, temperature fluctuation and other environmental factors. Future study could focus on:

- Manufacturing more durable materials that are resistant to wear, UV radiation, and corrosion.
- Designing solar panels that are better equipped to handle harsh weather conditions and that have longer lifespans, reducing the need for replacements and maintenance [32].

➤ *Integration with Other Technologies*

Solar energy is not limited to standalone systems. It can be combined with a variety of other technologies to increase its utility and efficiency. Areas of research could include:

- Electric vehicles (EVs) are in demand now days. More research is required into how solar power could be used for charging stations or even directly integrated into the vehicles themselves.
- Integration with smart homes, allowing for optimized energy usage and smooth management of solar power systems.
- Solar energy can be stored in Micro grids and distributed to local communities more efficiently, ensuring reliable and decentralized energy access [33].

➤ *Large-Scale Deployment*

Large-scale deployment is essential to harness the full potential of solar energy. Future scope could focus on:

- Reducing the solar panels cost and making solar technology cheaper for mass adoption.
- The enlargement of innovative manufacturing processes to increase production efficiency and rapidity. In that way reducing the overall cost of production and scaling up solar energy deployment [34].

➤ *Solar-Driven Water Treatment*

Solar energy has the potential to significantly affect water treatment technologies. By utilizing solar energy to power water purification processes, we can provide sustainable solutions to address water scarcity. It involves desalination, disinfection and purification process. Research could focus on:

- Evolving low cost and efficient solar driven water treatment technologies that could be used in regions where access to clean drinking water is limited [35].

➤ *Artificial Intelligence (AI) and Machine Learning*

The integration of AI and machine learning into solar energy systems has the potential to develop their performance and management. Future research could explore:

- The development of advanced algorithms that predict solar irradiance, improving the efficiency of energy generation.
- Using AI to optimize energy storage systems, ensuring that excess solar energy is efficiently stored and utilized.
- Applying AI to improve the management of micro grids, enhancing the reliability and performance of solar-powered systems [36].

V. SUSTAINABILITY IMPACT

Photovoltaic (PV) technologies convert the sunlight directly into electricity; have become a fundamental player in addressing the global demand for sustainable energy solutions. This section explores the wide-reaching sustainability impacts of PV systems across three main dimensions: environmental, economic, and social.

➤ *Environmental Impact*

The environmental benefits of PV technologies are one of the primary reasons for their growing adoption. These systems produce clean electricity with minimal direct emissions, making them a central part of strategies to mitigate climate change.

• *Reduction in Greenhouse Gas Emissions:*

PV systems generate electricity without releasing carbon dioxide (CO₂) or other harmful greenhouse gases (GHGs) during operation. Photovoltaic technology helps prevent global warming by reducing greenhouse gases. This contrasts with conventional fossil-fuel-based power generation, which is a major source of GHGs [37].

- *Energy Independence and Conservation:*

By harnessing solar energy, PV systems reduce dependence on non-renewable energy sources. In that way conserving natural resources like coal, oil, and natural gas is possible.

- *Waste and Resource Usage:*

The manufacturing and disposal of PV panels do have some environmental impact. The production process requires raw materials such as silver, silicon, and energy intensive processes. However, advancements in recycling methods and efforts to make production more efficient are reducing these impacts. Some companies are working on creating more sustainable panels that use fewer toxic materials. [38]

➤ *Economic Impact*

The economic sustainability of photovoltaic systems is a one of the key factor in their global adoption. PV technologies contribute positively to both local economies and global markets, creating jobs and reducing energy costs over time.

- *Job Creation:*

The solar industry has created many jobs. These include jobs in installation, manufacturing, maintenance and research and development. The growth of this sector supports economies by increasing employment and stimulating related industries.

- *Cost Reduction and Financial Viability:*

The cost of PV technology has dropped intensely due to developments in manufacturing, economies of scale, and technological improvements. This makes PV systems more affordable for both consumers and businesses. In many regions, the cost of solar energy is now cheaper than traditional fossil fuels [39].

- *Energy Bill Savings and Investment:*

For residential and commercial users, installing PV systems often leads to significant savings on energy bills. In some cases, surplus electricity generated by PV panels which can be sold back to the grid for creating additional income. Over time, the upfront investment in solar energy infrastructure typically pays off through lower operational costs [40].

➤ *Social Impact*

The social dimensions of PV technologies are equally significant, especially in terms of access to energy, quality of life improvements, and the advancement of social justice.

- *Energy Access in Isolated Areas:*

One of the most transformative aspects of PV systems is their potential to provide clean, affordable energy to remote or off-grid areas. In regions without reliable electricity infrastructure, PV technology can offer an immediate solution to meet the energy needs of communities, improving living standards and supporting essential services like healthcare and education. [41]

- *Health and Well-being:*

Solar energy reduces dependence on biomass, coal, and other polluting fuels used for cooking and heating in many developing regions. This shift can lead to better air quality, reduced respiratory illnesses, and improved health outcomes for individuals who previously relied on traditional energy sources. [42]

- *Social Equity and Empowerment:*

By providing communities with the tools and resources to generate their own electricity, PV systems empower individuals, promote self-sufficiency, and enhance flexibility against energy price fluctuations. Moreover, as PV technologies become more affordable, they help reduce energy shortage and provide openings for sidelined societies to contribute in the clean energy transition.

VI. CONCLUSION

Photovoltaic technologies have developed as a favorable clarification for a more workable future by offering a renewable and resourceful source of energy. Among the various Photovoltaic technologies available, silicon based PV systems, including crystalline silicon and thin film silicon are commonly used technologies across the globe. These systems provide several advantages, making them highly effective for large-scale energy production. The potential of photovoltaic (PV) technologies is to reduce our dependence on fossil fuels and mitigate environment change. PV technologies provide a clean and renewable energy source that can play a critical role in global efforts to reduce the emissions of greenhouse gases and conversion to a more sustainable energy future.

Moreover, PV technologies have the unique ability to provide energy to the lots of people who presently live without reliable electricity, particularly in rural and remote areas. These communities often face challenges in accessing power through traditional, centralized electricity grids. However, PV systems can offer a decentralized solution, providing electricity where traditional grid infrastructure is absent or impractical. As solar technology continues to evolve and the cost of production continues to decrease, solar photovoltaic systems are expected to become even more affordable and accessible. Given this outlook, investing in Photovoltaic technologies, enhancing research and development, and implementing supportive strategies to encourage their widespread placement should be a main concern. These efforts will be crucial in ensuring that solar energy plays a central role in attaining a sustainable, reliable, and cost effective global energy future.

Recent innovations in solar photovoltaic (PV) technologies are accelerating the shift towards more efficient, affordable, and versatile solar energy solutions. Key advancements include the exploration of new materials, cutting-edge manufacturing processes, and the emergence of innovative applications that expand the potential of solar power. The exciting development in PV technology is the use of perovskite materials, which show great potential for achieving higher efficiencies than traditional crystalline

silicon solar cells. These materials can absorb light more efficiently and are cost-effective to produce. While research is still ongoing to improve their stability and scalability, perovskites represent a promising frontier in solar technology, with the potential to transform the industry. These advancements are making solar photovoltaic (PV) technology increasingly attractive for a varied variety of presentations. As innovations in materials, design, and production continue to improve performance and reduce costs, solar PV is becoming more accessible and practical for both residential and industrial use. With the ongoing decline in installation and manufacturing costs, solar Photovoltaic is predictable to develop as the principal source of renewable energy in the near future, playing a central role in the global evolution to clean and sustainable energy.

REFERENCES

- [1]. Green, M. A., et al. (2022). Solar cell efficiency tables (Version 60). *Progress in Photovoltaics*, 30(1), 3-12.
- [2]. Gong J, Liang J, Sumathy K (2012) Review on dye-sensitized solar cells (DSSCs): fundamental concepts and novel materials. *Renew Sustain Energy Rev* 16(8):5848–5860
- [3]. Dubacheva GV, Liang CK, Bassani DM (2012) Functional monolayers from carbon nanostructures–fullerenes, carbon nanotubes, and graphene–as novel materials for solar energy conversion. *Coord Chem Rev* 256(21–22):2628–2639
- [4]. PV Status Report. 2011. Available online: http://www.ncpre.iitb.ac.in/userfiles/files/PV_Status_Report_2011.pdf (accessed on 17 August 2023).
- [5]. Ginidi, A.; Ghoneim, S.M.; Elsayed, A.; El-Sehiemy, R.; Shaheen, A.; El-Fergany, A. Gorilla troops optimizer for electrically based single and double-diode models of solar photovoltaic systems. *Sustainability* 2021, 13, 9459
- [6]. IEA—International Energy Agency. Available online: <https://www.iea.org/> (accessed on 10 April 2022).
- [7]. Gordon J, Gordon JM (eds) (2001) Solar energy: the state of the art: ISES position papers
- [8]. Sayigh AAM (ed) (2012) Solar energy engineering. Elsevier
- [9]. Xing Z, Sun D, Li Z, Zhou W (2022) Hollow semiconductor photocatalysts for solar energy conversion. *Adv Powder Mater* 1(2):100021
- [10]. Rabaia MKH, Abdelkareem MA, Sayed ET, Elsaid K, Chae KJ, Wilberforce T, Olabi AG (2021) Environmental impacts of solar energy systems: a review. *Sci Total Environ* 754:141989
- [11]. Sodikjon K, Begyor S, Aleksandr K, Farrukh D, Mukhtasar M, Akbarjon A (2022) Prospective aspects of using solar energy. *J New Century Innovat* 18(1):142–148
- [12]. Chasta G, Suthar D, Thakur A, Kannan MD, Dhaka MS (2022) Comprehensive investigation on influence of copper doping on physical properties of CdSe thin films for solar cell applications. *Mater Res Bull* 152:111845
- [13]. Ding T, Zhou Y, Ong WL, Ho GW (2021) Hybrid solar-driven interfacial evaporation systems: beyond water production towards high solar energy utilization. *Mater Today* 42:178–191
- [14]. Hoeven MVD (2015) Technology roadmap: solar photovoltaic energy. International Energy Agency, Paris, France
- [15]. Siecker J, Kusakana K, Numbi EB (2017) A review of solar photovoltaic systems cooling technologies. *Renew Sustain Energy Rev* 79:192–203
- [16]. Santbergen R, van Zolingen RC (2008) The absorption factor of crystalline silicon PV cells: a numerical and experimental study. *Sol Energy Mater Sol Cells* 92(4):432–444
- [17]. Zhao J, Xu Z, Law MK, Heidari H, Abdellatif SO, Imran MA, Ghannam R (2021) Simulation of crystalline silicon photovoltaic cells for wearable applications. *IEEE Access* 9:20868–20877
- [18]. Behura, Arun & Kumar, Dr & Rajak, Dipen & Pruncu, Catalin & Lamberti, Luciano. (2021). Towards better performances for a novel rooftop solar PV system. *Solar Energy*. 216. 518-529. 10.1016/j.solener.2021.01.045.
- [19]. Hightower M, Pierce SA (2008) The energy challenge. *Nature* 452(7185):285–286
- [20]. Nsengiyumva W, Chen SG, Hu L, Chen X (2018) Recent advancements and challenges in solar tracking systems (STS): a review. *Renew Sustain Energy Rev* 81:250–279
- [21]. Kim JH, Kang DW, Yun H, Kang M, Singh N, Kim JS, Hong CS (2022) Post synthetic modifications in porous organic polymers for biomedical and related applications. *Chem Soc Rev* 51(1):43–56
- [22]. Sun Z, Chen X, He Y, Li J, Wang J, Yan H, Zhang Y (2022) toward efficiency limits of crystalline silicon solar cells: recent progress in high-efficiency silicon heterojunction solar cells. *Adv Energy Mater* 12(23):2200015
- [23]. Santbergen R, van Zolingen RC (2008) The absorption factor of crystalline silicon PV cells: a numerical and experimental study. *Sol Energy Mater Sol Cells* 92(4):432–444
- [24]. Jamroen C, Komkum P, Kohsri S, Himananto W, Panupintu S, Unkat S (2020) A low-cost dual-axis solar tracking system based on digital logic design: Design and implementation. *Sustain Energy Technol Assessm* 37:100618
- [25]. PV Status Report. 2011. Available online: http://www.ncpre.iitb.ac.in/userfiles/files/PV_Status_Report_2011.pdf (accessed on 17 August 2023).
- [26]. Bayindir, R.; Demirbas, S.; Irmak, E.; Cetinkaya, U.; Ova, A.; Yesil, M. Effects of renewable energy sources on the power system. In *Proceedings of the 2016 IEEE International Power Electronics and Motion Control Conference (PEMC)*, Varna, Bulgaria, 25–28 September 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 388–393.
- [27]. Shah, A.; Torres, P.; Tscharnner, R.; Wyrsh, N.; Keppner, H. Photovoltaic technology: The case for thin-film solar cells. *Science* 1999, 285, 692–698.

- [28]. Shaheen, A.M.; Ginidi, A.R.; El-Sehiemy, R.A.; El-Fergany, A.; Elsayed, A.M. Optimal parameters extraction of photovoltaic triple diode model using an enhanced artificial gorilla troops optimizer. *Energy* 2023, 283, 129034.
- [29]. Kyprianou, A.; Phinikarides, A.; Makrides, G.; Georghiou, G.E. Definition and computation of the degradation rates of photovoltaic systems of different technologies with robust principal component analysis. *IEEE J. Photovolt.* 2015, 5, 1698–1705.
- [30]. Sima, C.A.; Popescu, M.O.; Popescu, C.L. Sensitivity analysis of optimal economic dispatch. *UPB Sci. Bull. Ser. C Electr. Eng. Comput. Sci.* 2020, 82, 223–236.
- [31]. Passari, L.; Susi, E. Recombination mechanisms and doping density in silicon. *J. Appl. Phys.* 1983, 54, 3935–3937.
- [32]. Al-Dahidi, S.; Ayadi, O.; Adeeb, J.; Alrbai, M.; Qawasmeh, B.R. Extreme learning machines for solar photovoltaic power predictions. *Energies* 2018, 11, 2725.
- [33]. Restuccia, D.; Spizzirri, U.G.; Luca, M.D.; Parisi, O.I.; Picci, N. Biogenic amines as quality marker in organic and fair- trade cocoa-based products. *Sustainability* 2016, 8, 856.
- [34]. Khan, H.R.; Khan, F.S.; Ahmed, S.; Akhtar, J. Smart nanomaterials and three-dimensional printing for flexible solar cell applications. In *Smart Multifunctional Nano-inks*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 389–411.
- [35]. Haffaf, A.; Lakdja, F. Feasibility and Performance Analysis of Using Solar Water Heating System in Algeria. *UPB Sci. Bull. Ser. C Electr. Eng. Comput. Sci.* 2022, 84, 271–286.
- [36]. Al-Dahidi, S.; Ayadi, O.; Adeeb, J.; Alrbai, M.; Qawasmeh, B.R. Extreme learning machines for solar photovoltaic power predictions. *Energies* 2018, 11, 2725.
- [37]. pelle, M.; Lucchi, E.; Maturi, L.; Astigarraga, A.; Causone, F. Coloured BIPV technologies: Methodological and experimental assessment for architecturally sensitive areas. *Energies* 2020, 13, 4506.
- [38]. Green, M.A. Photovoltaics: Technology overview. *Energy Policy* 2000, 28, 989–998.
- [39]. Solar Cell Central. Available online: <http://solarcellcentral.com>
- [40]. Jim, J.; Rabelo, M.; Padi, S.P.; Yousuf, H.; Cho, E.-C.; Yi, J. A review of the degradation of photovoltaic modules for life expectancy. *Energies* 2021, 14, 4278.
- [41]. Romeo, A.; Artigiani, E. CdTe-based thin film solar cells: Past, present and future. *Energies* 2021, 14, 1684.
- [42]. Ramalingam, K.; Indulkar, C. Solar energy and photovoltaic technology. In *Distributed Generation Systems*; Elsevier: Amsterdam, the Netherlands, 2017; pp. 69–147.