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Review

A Comprehensive Overview of Photovoltaic Technologies and Their Efficiency for Climate Neutrality

Alexandra Catalina Lazaroiu [1,2], Mohammed Gmal Osman [2,3,*], Cristian-Valentin Strejoiu [2,3] and Gheorghe Lazaroiu [2,3]

[1] Department of Measurements, Electrical Devices and Static Converters, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania; catalina.sima@yahoo.com
[2] University MARITIMA of Constanta, 900663 Constanta, Romania; strejoiu8@gmail.com (C.-V.S.); glazaroiu@yahoo.com (G.L.)
[3] Doctoral School of Energy Engineering, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania
* Correspondence: mohagamal123@gmail.com; Tel.: +40-729662271

Abstract: Solar photovoltaic (PV) technology is a cornerstone of the global effort to transition towards cleaner and more sustainable energy systems. This paper explores the pivotal role of PV technology in reducing greenhouse gas emissions and combatting the pressing issue of climate change. At the heart of its efficacy lies the efficiency of PV materials, which dictates the extent to which sunlight is transformed into electricity. Over the last decade, substantial advancements in PV efficiency have propelled the widespread adoption of solar PV technology on a global scale. The efficiency of PV materials is a critical factor, determining how effectively sunlight is transformed into electricity. Enhanced efficiency, achieved through a decade of progress, has driven the global expansion of solar PV. Multi-junction photovoltaic materials have now exceeded 40% efficiency in lab tests. China leads the world in solar PV installations, boasting over 253 GW of installed capacity by the end of 2021. Other prominent countries in this sector are the United States, Japan, Germany, and India. Photovoltaic (PV) cell technologies are rapidly improving, with efficiencies reaching up to 30% and costs falling below $0.50/W, making PV a competitive source of energy in many countries around the world. Solar PV technology holds immense potential for creating a cleaner, reliable, scalable, and cost-effective electricity system. To expedite its deployment and foster a more sustainable energy future, continued investment in research and development along with supportive policies and market mechanisms is essential. This paper underscores the pivotal role of solar PV technology in the global energy transition and advocates for a concerted effort to unlock its full potential in achieving a more sustainable and resilient energy future.

Keywords: greenhouse gas emissions; sustainable energy system; clean energy; sustainability

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1. Introduction

Photovoltaic technology has come a long way since its inception in the 20th century [1]. The history of photovoltaics can be traced back to the discovery of the photoelectric effect by Albert Einstein in 1905, which laid the foundation for the development of solar cells [2]. In 1954, the first practical solar cell was developed by Bell Labs, which had an efficiency of around 6%. Over the years, the efficiency of solar cells has increased significantly, with the latest commercial solar cells reaching efficiencies of over 20% [1]. The development of photovoltaic technology has been driven by the need for clean and renewable energy sources and has been supported by significant investment from governments, research institutions, and the private industry [3]. The technology has been used in a variety of applications, including residential and commercial buildings, power generation for remote areas, and spacecraft [4]. There are several different types of solar cells, each with their own advantages and disadvantages. The most common type is the silicon-based solar cell,

which is widely used due to its high efficiency, low cost, and reliability. Other types of solar cells include thin-film solar cells, organic solar cells, and dye-sensitized solar cells, each with their own unique properties [5]. One of the challenges facing the widespread adoption of photovoltaic technology is the variability of solar radiation, which can be affected by factors such as shading, temperature variation, and weather conditions [6]. Researchers have developed various techniques to mitigate these effects, including the use of maximum power point tracking (MPPT) and bypass diodes [7]. The extraction of optimal parameters for photovoltaic (PV) models is crucial for accurately simulating and predicting the performance of PV systems under various operating conditions. The triple-diode model (TDM) is a widely used PV model that incorporates the effects of three diode junctions to represent the complex electrical behavior of PV cells. However, determining the optimal parameters of the TDM can be challenging due to its nonlinear nature and the presence of multiple local minima [8].

In recent years, various optimization algorithms have been proposed for extracting the optimal parameters of the TDM. Among these, the enhanced artificial gorilla troop (EAGT) optimizer and the hunter-prey-based optimization (HPO) algorithm have emerged as promising techniques [3].

The EAGT optimizer is a metaheuristic algorithm inspired by the social behavior of gorilla troops. It incorporates various strategies, such as migration, exploration, and exploitation, to effectively search for the optimal solution. The HPO algorithm, on the other hand, mimics the hunting behavior of predators and the prey's evasive strategies to navigate the search space and converge to the optimal parameters [8].

Several studies have compared the performance of the EAGT and HPO algorithms in extracting the optimal parameters of the TDM for various PV modules. The results consistently demonstrate that both algorithms can achieve high accuracy and convergence speed, outperforming conventional optimization methods [2].

In addition to the TDM, the EAGT and HPO algorithms have also been successfully applied to extract the optimal parameters of other PV models, such as the single-diode model (SDM) and double-diode model (DDM). These models are simpler than the TDM but may not provide sufficient accuracy for certain applications.

The EAGT and HPO algorithms have proven to be effective tools for extracting the optimal parameters of various PV models. They offer significant advantages over conventional optimization methods in terms of accuracy, convergence speed, and robustness. As a result, these algorithms are becoming increasingly popular in the field of PV modeling and simulation [2,3].

Despite these challenges, the adoption of photovoltaic technology has continued to grow, with the technology becoming an increasingly important source of clean energy worldwide [9]. The technology has become a key tool in achieving the United Nations' sustainable development goals and has the potential to play a critical role in the transition to a more sustainable future [8].

The history of photovoltaic technology can be traced back to the work of scientists such as Heinrich Hertz and Alexandre Edmond Becquerel in the 19th century, who conducted experiments on the photoelectric effect [10]. In 1905, Albert Einstein published his theory of the photoelectric effect, which explained the phenomenon in terms of quantum mechanics [3]. In the 1950s, researchers at Bell Labs, including Daryl Chapin, Calvin Fuller, and Gerald Pearson, developed the first practical silicon-based solar cell. The efficiency of this cell was around 6%, which was a significant improvement over the previous design [3]. In the following decades, photovoltaic technology continued to develop, with improvements in cell efficiency, cost, and reliability. The oil crisis of the 1970s spurred interest in renewable energy sources, leading to increased investment in photovoltaic research and development [5]. In the 1980s and 1990s, the commercial use of photovoltaic technology began to grow, particularly in remote areas where traditional power sources were not available [1]. In the 2000s, the growth of the global solar industry accelerated, driven by a

combination of technological advances, government incentives, and declining production costs [3].

Today, photovoltaic technology is a major industry with applications in a wide range of sectors, including residential and commercial buildings, transportation, and power generation [5]. The continued growth of the industry is expected to play a key role in the transition to a more sustainable energy system [6]. The development of photovoltaic technology began in the mid-20th century. The first application of a solar cell as a power source was in Americus, Georgia in 1955, followed by the launch of NASA's Vanguard-I satellite with a solar system in 1958 [8]. Photovoltaic power sources were also used in the Russian space program's Sputnik-3 satellite, marking the beginning of the use of photovoltaic technology in space missions [6]. Despite early successes in space applications, the commercialization of photovoltaic technology was hindered by the high cost of production [2]. However, the oil crisis in the 1970s led to an increase in interest in photovoltaic technology, and new manufacturing processes were developed to reduce costs [2]. Mono-Si (monocrystalline silicon) was the primary material used until 1973, but thereafter, poly-Si (polycrystalline silicon) and a-Si (amorphous silicon) became popular due to their lower cost and less demanding production processes [3].

The paper aims to provide a comprehensive historical context for the development of photovoltaic (PV) technology, analyze the technological advancements that have shaped PV technology, elucidate the broad impact of PV technology across various sectors, explore the challenges hindering its adoption and innovative solutions, emphasize its global significance in the transition to sustainable energy systems, provide insights into PV cell materials, examine the commercialization of PV technology and its industry growth, highlight its role in sustainability and policy implications, and underscore the importance of ongoing research and innovation in the integration of PV technology.

The first paper to reference is "A Carrier Transport Enhancement Mechanism in Highly Efficient Antimony Selenide Thin-Film Solar Cell" by Luo, Y., Chen, G. et al., (Advanced Functional Materials) [4].

This paper represents the recent advances in perovskite solar cells, including their materials, device structures, and fabrication processes. It also discusses the challenges that need to be addressed before perovskite solar cells can be commercialized.

The second paper is "Organic solar cells: A recent study in progress and future perspectives" by Zhang, H., Lu, Y. et al., (Chemical Engineering Journal) [5].

This paper represents the recent progress in organic solar cells, including their materials, device structures, and fabrication processes. It also discusses the challenges that need to be addressed before organic solar cells can be commercialized.

The third is "Integration of photovoltaics with other energy systems: A recent study in advances and challenges" by Akhmedov, A.K., et al., (Materials) [6].

This paper represents the recent advances in the integration of PV with other energy systems, such as grid batteries and electric vehicles. It also discusses the challenges that need to be addressed before PV can be fully integrated with other energy systems.

The fourth is "Recent advances in high-efficiency solar cells" by Scarpulla, M.A. et al., (Solar Energy Materials and Solar Cells) [7].

This paper represents the recent advances in high-efficiency solar cells, including their materials, device structures, and fabrication processes. It also discusses the challenges that need to be addressed before high-efficiency solar cells can be widely deployed.

The final paper is "The future of photovoltaics: A recent study in advances and trends" by Fazal, M.A., Rubaiee, S. (Solar Energy) [9].

This paper represents the recent advance in PV technologies and the trends that are expected to shape the market in the coming years. It discusses the potential of PV to play a major role in the transition to a clean energy future.

These papers are all excellent reviews of the latest advances in PV technologies. They are essential reading for anyone who wants to understand the current state-of-the-art technology in PV research and development.

2. Global State of Solar Photovoltaic (PV) Technology

In 2017, worldwide solar cell production figures fluctuated between 18 GW and 27 GW. Since the year 2001, the total PV production has increased nearly two orders of magnitude, with annual growth rates ranging from 40% to 90% [4]. Notably, from 2001 to 2017, PV electricity system prices witnessed a substantial decrease of 40% [5]. Projections at that time suggested a global electricity consumption increase at a rate of 2.4% per year until 2030 [6]. As PV material technology advanced, the adoption of solar power worldwide experienced rapid growth year by year.

Monocrystalline and silicon materials dominated approximately 80% of the PV market, while thin-film materials were gaining ground rapidly (see Figure 1) [7]. Additionally, emerging technologies, such as polymer/organic and hybrid solar cells, were still in the research and development phases.

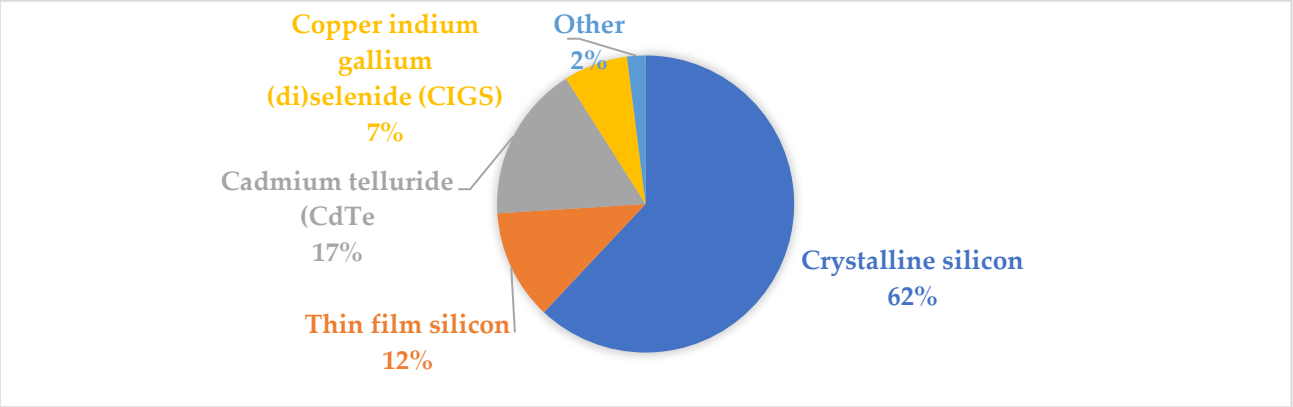


Figure 1. Solar cell materials market share in 2017 [7].

Figure 2 provides insight into PV production by different countries from 2001 to 2017, as reported by the JRCE European Commission. China emerged as the leader in solar cell production during this period. However, European countries took the lead in PV installation, boasting a combined output of 39 GW by the end of 2017 [5]. Notable PV installations in Europe included 7.4 GW in Germany, 3.9 GW in Spain, and 1.05 GW in France. Meanwhile, several developing countries in Asia and the Pacific region, such as India, Malaysia, Taiwan, Korea, and Thailand, displayed significant improvements in PV installations, driven by government financial incentives for renewable energy projects. India, in particular, demonstrated its commitment to solar energy production by launching a national solar mission with the ambitious goal of reaching 500 GW of solar power production by 2030 [9].

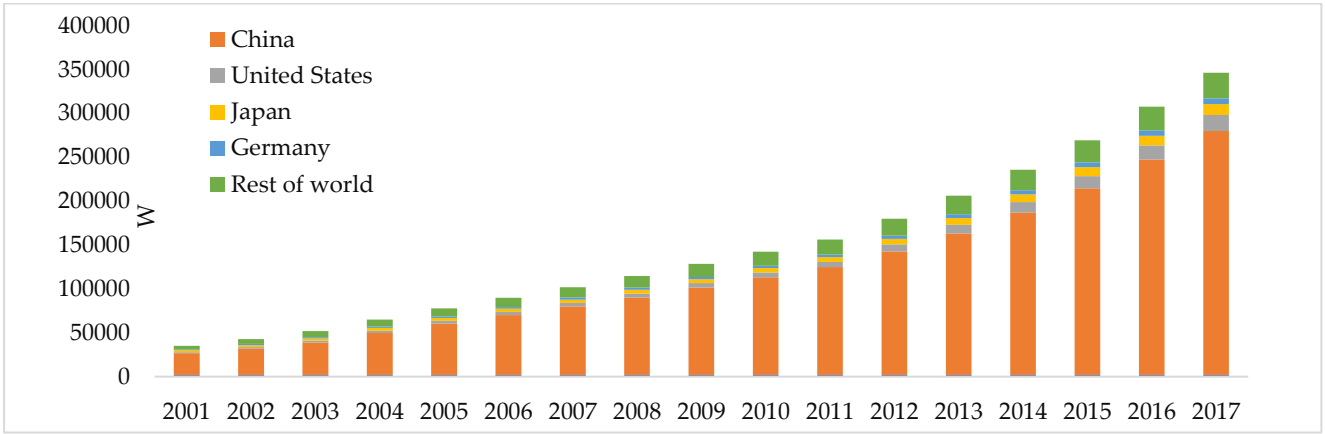


Figure 2. PV production from 2001 to 2017 [5].

Wu et al. conducted research on grid-connected PV systems in China, concluding that PV technology in China was experiencing rapid growth, partly due to government support in the form of special funds and installation policies [11].

As shown in Figure 3, PV capacity in Europe has grown rapidly in recent years, and it is now the world's largest PV market. However, the rest of the world is also catching up, and PV capacity in the rest of the world is expected to exceed PV capacity in Europe in the coming years.

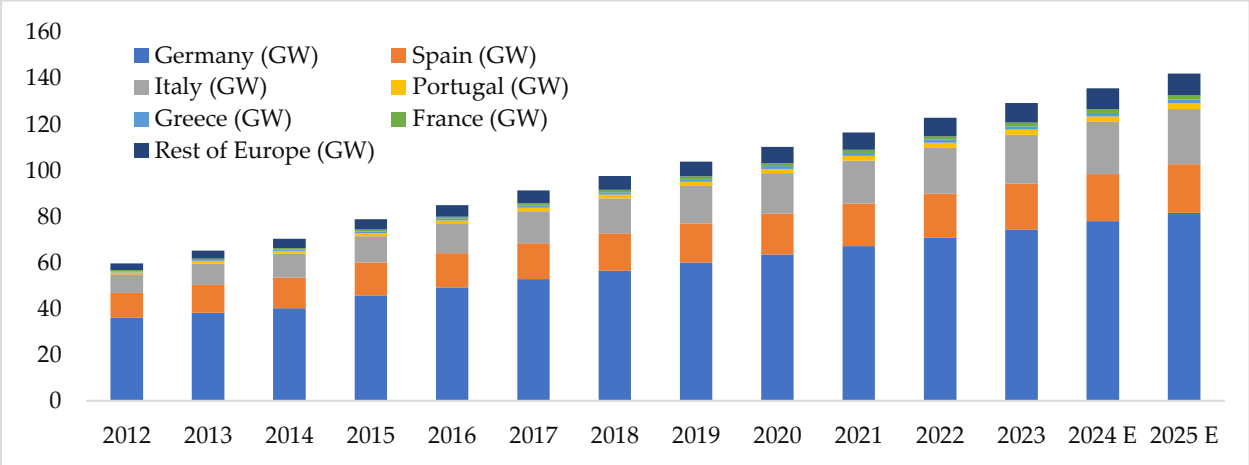


Figure 3. PV distribution in Europe [10].

Predicting future trends and directions:

The global PV market is expected to continue to grow rapidly in the coming years, driven by declining costs, government support, and increasing demand for renewable energy. Europe and the rest of the world are both expected to play a major role in this growth. Here are some other trends and directions of PV distribution in Europe and the rest of the world in the coming years:

Decentralization of PV generation: PV is increasingly being deployed in decentralized locations, such as rooftops and small businesses. This is due to several factors, including declining costs of PV technology, government support for decentralized PV generation, and the increasing availability of net metering programs.

Integration of PV with other energy systems: PV is increasingly being integrated with other energy systems, such as grid batteries and electric vehicles. This is due to the need to balance the variability of PV generation and to provide flexibility to the electricity grid.

Self-consumption of PV electricity: PV self-consumption is increasing, as more and more households and businesses are choosing to generate their own electricity from PV. This is due to a few factors, including declining costs of PV technology, government support for PV self-consumption, and the increasing awareness of the benefits of self-consumption.

Overall, the future of PV distribution in Europe and the rest of the world is very bright. The PV market is expected to continue to grow rapidly in the coming years as PV becomes more affordable and efficient. PV is expected to play a major role in the transition to a clean energy future [7].

As in Figure 4, China is the largest PV market in the world, followed by the United States and Japan. China's PV market is expected to continue to grow rapidly in the coming years, and it is expected to reach 312 GW by 2025. The United States' and Japan's PV markets are also expected to grow in the coming years but at a slower pace than China's PV market.

Predicting future trends and directions:

The PV market in China, the United States, and Japan is expected to continue to grow in the coming years, driven by declining costs, government support, and an increasing demand for renewable energy.

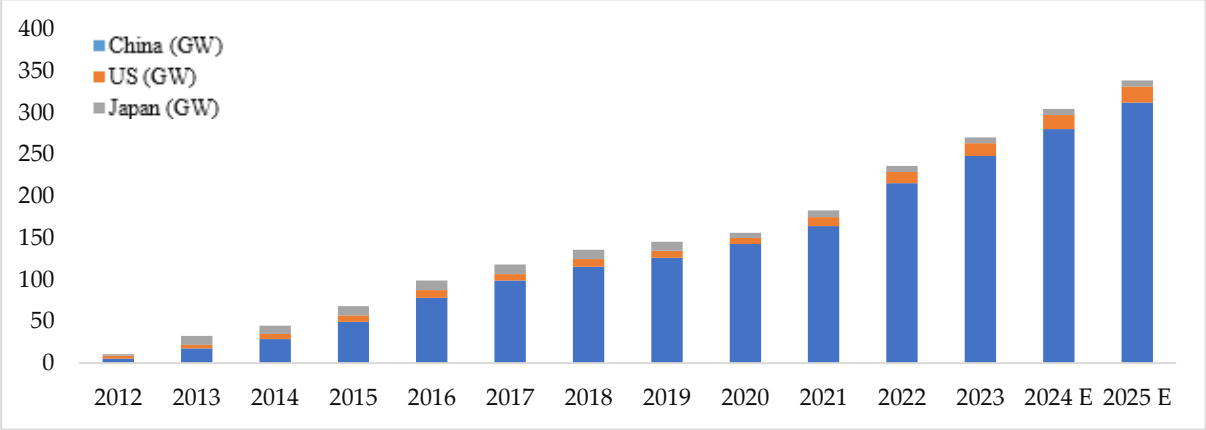


Figure 4. PV distribution worldwide [10].

Here are some other trends and directions of PV production in these countries in the coming years:

Increased focus on high-efficiency PV panels: PV manufacturers in these countries are increasingly focusing on producing high-efficiency PV panels, which can reduce the cost of PV systems.

Development of new PV technologies: New PV technologies, such as perovskite PV and organic PV, are being developed in these countries, which have the potential to further reduce the cost of PV and improve its efficiency [10].

Integration of PV with other energy systems: PV is being increasingly integrated with other energy systems, such as grid batteries and electric vehicles in these countries. This is helping to make the electricity grid more flexible and reliable.

The future of PV production in China, the United States, and Japan is very bright. The PV market in these countries is expected to continue to grow rapidly in the coming years, as PV becomes more affordable and efficient. PV is expected to play a major role in the transition to a clean energy future in these countries. At that time, numerous companies worldwide were engaged in solar cell production, with many of them situated in China. Among these, more than 100 companies specialized in polycrystalline silicon-based solar cells [2].

Figure 5 provides an overview of different material production companies for solar cells. Additionally, thin-film technology held a significant market share in PV production, with companies like Sharp and First Solar being prominent manufacturers of thin-film, technology-based solar cells.

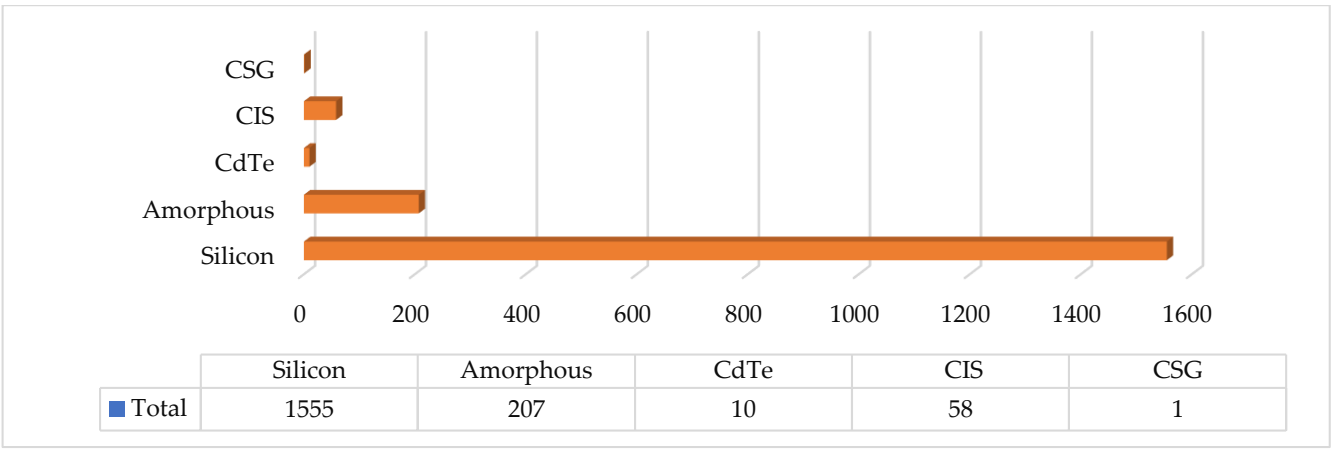


Figure 5. Material production companies for solar cell [12].

3. Current Commitments and Goals of Photovoltaic Technology

Currently, photovoltaic technology is a key player in the renewable energy sector and has become an important part of global efforts to combat climate change [6]. In line with this, the United Nations has included renewable energy in 3 of its 17 Sustainable Development Goals (SDGs) for 2030. These goals are as follows:

1. Affordable and clean energy—Ensure access to affordable, reliable, sustainable, and modern energy for all;
2. Industry, innovation, and infrastructure—Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation;
3. Climate action—Take urgent action to combat climate change and its impacts.

Many countries and organizations around the world have set ambitious targets for increasing the share of renewable energy in their energy mix, including photovoltaic technology [8]. For example, the European Union has set a target of producing at least 32% of its energy from renewable sources by 2030, while China aims to have 35% of its electricity generated by non-fossil fuel sources by 2030 [8].

In addition, many companies in the photovoltaic industry have set their own targets for achieving sustainability and reducing their carbon footprint [2]. For example, the Solar Energy Industries Association (SEIA) in the United States has set a target for the solar industry to achieve 20% of all U.S. electricity generation by 2030, while the Chinese solar panel manufacturer, Jinko Solar, has committed to achieving carbon neutrality by 2025 [2]. Photovoltaic technology is expected to continue to play a major role in the global transition to a low-carbon, sustainable energy future [10].

4. Photovoltaic Generation Technology

Photovoltaic cells can be classified into different generations based on the materials and production techniques used. The first-generation cells were made of crystalline silicon and dominated the market for many years [4]. The second generation includes thin-film cells, which are made of materials such as amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS) [12]. Third-generation cells are still under development and use materials such as organic semiconductors, dye-sensitized solar cells (DSSC), and perovskite solar cells [13]. Fourth-generation cells are being researched and developed to improve the efficiency and durability of the previous generations, with technologies like tandem solar cells, hot-carrier solar cells, and quantum dot solar cells [14].

First-generation cells have a high efficiency rate, but the production process is expensive and time-consuming. Second-generation cells have lower efficiency but are cheaper to produce, making them suitable for large-scale installations [5]. Third-generation cells have the potential to increase efficiency while reducing costs, but they are still in the experimental phase. Fourth-generation cells aim to improve on the previous generations by incorporating advanced materials and techniques, but they are still under development and not yet commercially available [15].

Photovoltaic (PV) efficiency refers to the ability of a photovoltaic device, such as a solar cell or solar panel, to convert sunlight into usable electrical energy. It is expressed as a percentage and represents the ratio of electrical power output to the amount of sunlight (solar energy) input. PV efficiency is measured by assessing the electrical power output of a solar cell or panel under standard test conditions (STC), which include a specific light intensity and temperature. The efficiency is calculated by dividing the electrical power output by the incident solar power. The resulting value is then multiplied by 100 to express it as a percentage. Several factors influence the efficiency of photovoltaic devices: material properties, cell design, temperature, solar spectrum, reflection and absorption losses, inverter efficiency, dirt, and shading [9].

Each generation of photovoltaic cells has its advantages and limitations, and research continues to improve efficiency, durability, and cost-effectiveness [11].

The adoption of solar photovoltaic (PV) technology faces challenges, such as intermittency, high-energy storage costs, land-use conflicts, resource constraints, competition

from other energy sources, initial cost barriers, integration into existing infrastructure, and environmental concerns. Addressing these challenges through research, innovation, and supportive policies is essential for the sustained growth and widespread adoption of solar PV technology [6].

The following table summarizes the Research Tendency RT and RT5 metrics for the different generations of solar cells:

Continued investment in research and development (R&D) is crucial for advancing solar PV technology. Promising areas of research include the following: tandem solar cells, perovskite solar cells, advanced materials, bifacial solar technology, energy storage solutions, transparent solar cells, nanotechnology and light trapping, AI and machine learning, flexible and lightweight solar panels, environmental impact, and recycling.

Investment in these areas holds the potential to drive breakthroughs, making solar PV technology more cost effective, efficient, and sustainable in the future [3].

Research Tendency (RT) in Table 1 is a metric used to assess the level of research interest in a specific technology or material; it is usually calculated by analyzing the number of publications, patents, and investments in a particular field over a certain period [1]. In the context of photovoltaic generations, RT can be used to evaluate the historical trend in research interest and investment for each generation of solar cells [16].

Table 1. Research Tendency RT and RT5 metrics for the different generations of solar cells.

Solar Cell Generation	RT (1954–2021)	RT5 (2016–2021)
1st Generation	High	Low
2nd Generation	Low	Moderate
3rd Generation	Moderate	High
4th Generation	Low	High

RT5 is a metric that assesses research interest and investment in a specific technology over the last 5 years. It is like the RT metric, but instead of considering the entire time frame, it focuses only on the most recent breakthroughs and developments [17]. RT5 is a useful complement to RT, as it provides a more up-to-date assessment of the current state of research and development in a particular field. By considering the rate of progress over the last 5 years, it is possible to identify trends and predict future developments in the technology [18].

As can be seen from the table, the research interest in 1st generation solar cells has remained consistently high over the years, as this is the most widely used technology for commercial applications [2]. On the other hand, 2nd generation solar cells have had a lower RT, indicating a decrease in research interest over time, but still moderate RT5, suggesting some recent breakthroughs in this technology [19]. Third generation solar cells have had a moderate RT overall but high RT5, indicating a recent increase in research interests and breakthroughs. Finally, 4th generation solar cells have had a low RT overall but high RT5, indicating that this is a relatively new and emerging field of research with increasing interest in recent years [20].

5. Breakthroughs and Research Tendencies per Cell-Type Technology

As of 2022, significant advancements in photovoltaic (PV) technology include tandem solar cells for improved absorption; cost-effective and highly efficient perovskite solar cells; bifacial solar panels capturing sunlight from both sides; transparent solar cells integrated into surfaces; silicon and perovskite tandem cells for enhanced efficiency; improved light-harvesting techniques using advanced structures and nanomaterials; innovative manufacturing techniques, such as roll-to-roll printing; the application of artificial intelligence (AI) and machine learning to optimize system performance; and the development of flexible and lightweight solar panels based on thin-film technologies for versatile installation on unconventional surfaces [10].

Here is an overview of breakthroughs and research tendencies for each of the main solar cell technologies:

i. *Crystalline Silicon (c-Si):* This is the most widely used PV technology and consists of solar cells made of crystalline silicon. These cells can be either monocrystalline or polycrystalline, and they are known for their high efficiency and reliability [21].
   - Breakthroughs: c-Si solar cells have achieved a maximum efficiency of 26.7% in 2020, with research focusing on reducing production costs and improving stability;
   - Research Tendency: c-Si solar cells have consistently been the most researched and invested-in technology, with a high RT5, indicating continued interest [14];
   - High efficiency and reliability, Efficiency range: 15–20%.

ii. *Thin-film Solar Cells:* This technology involves depositing thin layers of semiconducting materials on a substrate, such as glass or plastic [15]. Thin-film PV cells are more flexible and lightweight than crystalline silicon cells, making them suitable for a wider range of applications. However, they generally have lower efficiency than c-Si cells [22].
   - Breakthroughs: Thin-film solar cells have achieved efficiencies of up to 23.4% in 2020, with research focusing on improving stability and developing new materials;
   - Research Tendency: Thin-film solar cells have seen a decline in research interest and investment, with a low RT5, indicating a decrease in breakthroughs.

iii. *Organic Solar Cells:*
   - Breakthroughs: Organic solar cells have achieved efficiencies of up to 18.3% in 2020, with research focusing on improving stability and developing new materials;
   - Research Tendency: Organic solar cells have seen a steady increase in research interest and investment, with a high RT5, indicating growing breakthroughs [2].

iv. *Hybrid Perovskite Solar Cells:* This technology combines PV cells with other renewable energy sources, such as wind or hydro, to increase overall energy production [23].
   - Breakthroughs: Hybrid perovskite solar cells have achieved efficiencies of up to 29.1% in 2020, with research focusing on improving stability and developing new materials [24];
   - Research Tendency: Hybrid perovskite solar cells have seen a dramatic increase in research interest and investment, with an extremely high RT5, indicating a rapidly growing field [24].

v. *Dye-Sensitized Solar Cells (DSSC):*
   - Breakthroughs: DSSCs have achieved efficiencies of up to 14.1% in 2020, with research focusing on improving stability and developing new materials;
   - Research Tendency: DSSCs have seen a decline in research interest and investment, with a low RT5, indicating a decrease in breakthroughs [25].

It is worth noting that these trends are constantly evolving, and new breakthroughs are being made all the time, so this is just a snapshot of the current state of research in photovoltaic technology [26].

Here is a Table 2 summarizing some of the main comparisons between different PV technologies:

Table 2. The Main Comparisons Between Different PV Technologies [27].

Technology	Efficiency	Cost	Lifespan	Application
Monocrystalline	High	High	Long	Residential, Commercial
Polycrystalline	Moderate	Moderate	Long	Residential, Commercial
Thin Film	Low	Low	Short	Large-Scale, Commercial
Crystalline Silicon	High	Moderate	Long	Residential, Commercial
Amorphous Silicon	Low	Low	Short	Small-Scale, Portable
Concentrated PV	High	High	Long	Large-Scale, Commercial
Non-concentrated PV	Moderate	Low	Long	Residential, Small-Scale
Organic PV	Low	Low	Short	Small-Scale, Portable
Hybrid PV	Variable	Variable	Variable	Variable

Note that the efficiency, cost, lifespan, and application of each technology can vary widely depending on the specific product and manufacturer [22]. This table is intended to provide a general overview of the main differences between different types of PV technology [28].

The National Renewable Energy Laboratory (NREL) maintains a chart (Figure 6) that lists the highest independently confirmed efficiency measurements for various types of solar cells. This chart is called the Best Research-Cell Efficiency Chart and is updated regularly to reflect the latest research findings [29].

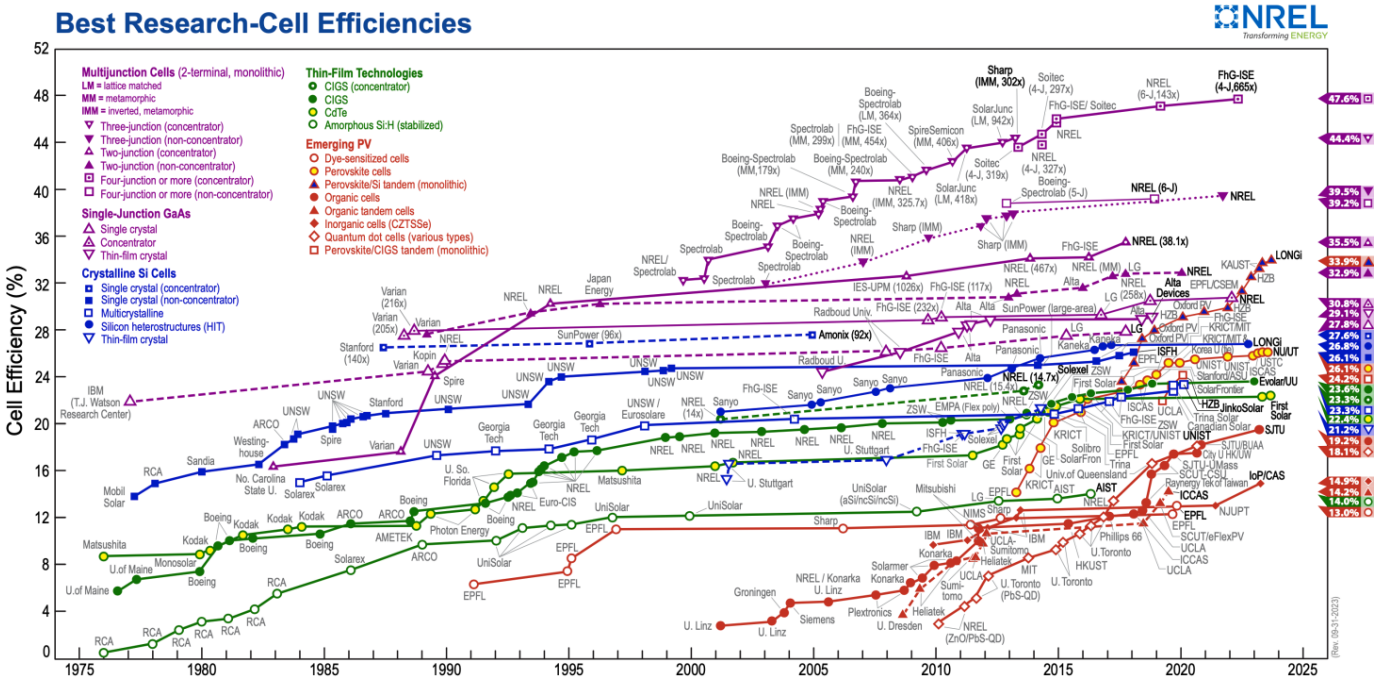


Figure 6. The Best Research-Cell Efficiency Chart [29].

Here are the current highest confirmed efficiency values for different types of solar cells, as listed on the NREL chart:

1. Multijunction Solar Cells: 47.1% (research grade);
2. Concentrator Solar Cells: 46.1% (research grade);
3. Silicon Solar Cells (single junction): 27.6% (commercial grade);
4. Tandem Perovskite/Silicon Solar Cells: 29.5% (research grade);
5. Organic Solar Cells: 18.9% (research grade).

It is important to note that these efficiency values are for research-grade solar cells and are not necessarily representative of commercial products currently available on the market [14]. Additionally, these values are not achievable in all conditions and may vary based on the specific application and location [30]. However, these values represent the cutting-edge technology of solar cell research and development and indicate the potential for continued improvements in solar energy technology, as shown in Tables 3–5 [31].

Table 3. Comparison of Crystalline Silicon (c-Si) PV Technologies [19].

Type	Efficiency	Cost	Durability
Monocrystalline	15–22%	0.40–0.80 $/W	25 years
Polycrystalline	13–18%	0.30–0.60 $/W	25 years
Bifacial	16–25%	0.50–1.00 $/W	25 years
PERC	19–22%	0.40–0.80 $/W	25 years

Table 4. Comparison of Thin-Film PV Technologies [14].

Type	Efficiency	Cost	Durability
Amorphous Silicon (a-Si)	6–10%	0.20–0.60 $/W	20–25 years
Cadmium Telluride (CdTe)	9–13%	0.20–0.40 $/W	25 years
Copper Indium Gallium Selenide (CIGS)	10–20%	0.30–0.70 $/W	20–25 years
Organic PV (OPV)	2–10%	0.20–0.60 $/W	10–15 years

Table 5. Comparison of Concentrated PV (CPV) Technologies [3].

Type	Efficiency	Cost	Durability
Hight CPV	35–40%	1.00–3.00 $/W	25–30 years
Low CPV	25–30%	0.50–1.50 $/W	25–30 years
Direct CPV	25–30%	1.00–2.00 $/W	25–30 years

Tables 6 and 7 provides a more comprehensive comparison of solar cell technologies in terms of their power output along with their respective advantages and disadvantages [32]. Monocrystalline silicon cells are known for their high efficiency and durability, but they are also the most expensive [33]. Polycrystalline cells are a more cost-effective option but have lower efficiency and require more space [34]. Thin-film cells are less expensive to produce and can be made in larger sizes, but they have lower efficiency and durability. CPV cells are the most efficient but also the most expensive and require specialized equipment [35].

Table 6. Comparing Solar Cell Technologies in Terms of their power output [36].

Solar Cell Technology	Efficiency (%)	Typical Power Output (W/m^2)	Pros	Cons
Monocrystalline Silicon	22	180–210	High efficiency, space-efficient, durable	Expensive [26]
Polycrystalline Silicon	15–20	150–180	Less expensive than monocrystalline, moderate efficiency	Less efficient, less space-efficient [30]
Thin-Film	10–15	70–120	Less expensive than crystalline silicon, can be made in larger sizes	Lower efficiency, less durable, may require more space [22]

Table 6. *Cont.*

Solar Cell Technology	Efficiency (%)	Typical Power Output (W/m^2)	Pros	Cons
Concentrated Photovoltaic	Up to 40	200–800	Highest efficiency, space-efficient	Most expensive, requires specialized equipment, limited availability [11]

Table 7. Different aspects of photovoltaic (PV) technologies.

Technology	Description
Monocrystalline	Made from a single crystal of silicon, high efficiency [18].
Polycrystalline	Made from multiple crystals, lower efficiency than mono [11].
Thin Film	Uses less silicon than crystalline, lower efficiency [16].
Crystalline Silicon	Made from a single crystal of silicon, high efficiency [32].
Amorphous Silicon	Less efficient but less expensive than crystalline [16].
Concentrated PV	Uses lenses or mirrors to focus sunlight, high efficiency [22].
Non-concentrated PV	Does not use lenses or mirrors, lower cost [23].
Organic PV	Uses organic materials, low efficiency but flexible [30].
Hybrid PV	Combines different PV technologies for optimal balance [30].

Table 8 compares the estimated operational lifetimes of different photovoltaic (PV) solar cell types, with single-junction GaAs cells having the longest projected duration at 43 years, followed closely by crystalline silicon cells at 44 years, thin-film technologies at 45 years, multijunction solar cells at 30 years, and emerging PV technologies at 28 years, signifying the expected years of efficient operation for each technology [23].

Table 8. Comparison by duration of operation.

Type	Duration of Operation (Years)
Multijunction Solar Cells	30
Single-Junction GaAs	43
Crystalline Si Cells	44
Thin-Film Technologies	45
Emerging PV	28

Trends in photovoltaic (PV) efficiency improvement include incremental advances, the emergence of tandem solar cells stacking multiple materials for enhanced efficiency, the growing prominence of perovskite solar cells due to rapid efficiency gains, and the increasing popularity of bifacial solar panels capturing sunlight from both sides. Scientific articles, such as "Recent advances in solar cell technologies and materials" and "Tandem solar cells: A review of commercialization progress and technology trends", provide insights into these advancements [12].

6. Sustainability Impact

Photovoltaic (PV) technologies have gained considerable attention due to their potential to address critical sustainability challenges. This section delves into the multifaceted sustainability impact of photovoltaic systems, encompassing environmental, economic, and social dimensions.

6.1. Environmental Considerations

Lifecycle Assessment (LCA): Photovoltaic systems undergo a rigorous lifecycle assessment, which evaluates their environmental impact from production to disposal. LCAs consistently reveal a substantial reduction in greenhouse gas emissions compared to fossil fuels. PV systems produce clean electricity, contributing significantly to climate change mitigation [37].

Manufacturing and disposing of photovoltaic (PV) materials raise environmental concerns. Key issues include energy consumption, resource extraction, toxic materials, end-of-life disposal, limited recycling infrastructure, water usage, carbon footprint, and land-use impact. Efforts involve adopting sustainable practices, cleaner manufacturing, efficient recycling, energy efficiency, alternative materials, and responsible land-use planning. Continuous research and innovation are essential for addressing these concerns and advancing the environmental sustainability of solar PV technology [30].

Environmental Benefits: Photovoltaic systems offer a range of environmental benefits, including a reduction in air pollution, decreased water usage for electricity generation, and diminished reliance on environmentally detrimental resource extraction. Solar panels require no water during operation, unlike fossil fuel-based power plants [27].

Environmental Challenges: While PV systems are generally environmentally friendly during operation, challenges exist in the manufacturing phase. This section addresses concerns related to energy-intensive manufacturing processes, material selection, and the proper disposal or recycling of solar panels at the end of their operational life.

6.2. Economic Implications

Economic Benefits: PV systems generate substantial economic benefits. They lead to lower electricity bills for consumers, reducing their energy expenditures over time. Additionally, the solar industry is a significant driver of job creation, stimulating local economies and fostering energy independence [38].

Economic Viability: The economic viability of photovoltaic technologies depends on various factors, including government incentives, subsidies, and ongoing cost reductions in PV module production. The decreasing cost of solar panels has made PV systems more accessible to a broader range of consumers and businesses.

The cost reductions in photovoltaic (PV) modules have significantly enhanced the economic viability of solar PV systems compared to fossil fuel-based power generation. Factors contributing to this competitiveness include declining module costs; decreasing levelized cost of electricity (LCOE); economies of scale in large-scale projects; financial incentives, such as tax credits and feed-in tariffs; technological advancements improving efficiency; innovative manufacturing; financing options, such as power purchase agreements (PPAs); and the achievement of grid parity in some regions. These factors, coupled with carbon pricing and environmental regulations, collectively make solar PV increasingly attractive and competitive in the energy market [14].

Return on Investment (ROI): Through case studies and financial analyses, it becomes evident that the return on investment for photovoltaic installations can be substantial. Demonstrating ROI in various sectors, such as residential, commercial, and industrial, highlights the financial attractiveness of adopting PV technologies.

6.3. Social Considerations

Energy Access: Photovoltaic technologies play a pivotal role in addressing energy access disparities, particularly in underserved or remote regions. They enable the provision of electricity to areas without a reliable grid connection, improving the quality of life and fostering economic development [13].

Social Equity: Achieving sustainability also involves addressing social equity concerns. This section explores how photovoltaic initiatives and policies aim to ensure that the benefits of clean energy are accessible to all socioeconomic groups, emphasizing energy justice as a critical component of sustainability efforts [39].

Community Engagement: Community-based photovoltaic projects have emerged as a powerful force for positive social impact. By engaging local communities in the development and ownership of solar installations, these projects create jobs, promote energy self-reliance, and strengthen social bonds.

6.4. Technological Innovations for Sustainability

Energy Storage: The integration of energy storage systems with photovoltaic installations enhances sustainability by enabling the efficient utilization of solar energy even during periods of low sunlight. Battery technology advancements have the potential to transform the reliability and flexibility of PV systems [40].

Smart Grids: Smart grid technologies are revolutionizing the way photovoltaic systems interact with the electricity grid. By optimizing energy flows, improving grid management, and facilitating demand response, smart grids enhance the overall sustainability and efficiency of PV installations.

Solar-Integrated Building Materials: Innovative solar-integrated building materials, such as solar roof tiles and solar windows, are contributing to sustainable construction practices. These technologies seamlessly blend aesthetics with energy generation, promoting the widespread adoption of PV systems in urban environments [41].

6.5. Long-Term Sustainability and Challenges

Durability and Reliability: The long-term sustainability of photovoltaic systems relies on their durability and reliability. This section discusses the importance of regular maintenance, quality assurance, and advances in materials to ensure the extended operational life of PV installations [42].

Resource Considerations: To maintain sustainability, it is crucial to examine the availability of raw materials used in photovoltaic technology. Addressing potential resource constraints and exploring alternative materials are essential aspects of long-term sustainability planning.

Environmental Mitigation: Ongoing research and strategies aimed at mitigating potential environmental impacts of photovoltaic technology production are critical. This section explores initiatives to reduce the environmental footprint of PV manufacturing, including sustainable material sourcing and recycling programs [43].

7. Implementation and Practical Considerations for Photovoltaic Installations

Implementing a photovoltaic (PV) installation can be a complex process, involving several practical considerations to ensure that the installation is safe, reliable, and cost-effective. Here are some key factors to consider when implementing a PV installation:

i. *Site Assessment:* The first step in implementing a PV installation is to conduct a thorough site assessment to evaluate the available space, shading, orientation, and other factors that can affect the performance of the system. This will help to determine the optimal design and placement of the PV modules [44].
ii. *System Design:* The system design will depend on the specific application, size, and budget of the installation. This includes selecting the appropriate PV modules, inverters, mounting structures, and other components, as well as designing the electrical and mechanical systems [45].
iii. *Permitting and Compliance:* PV installations must comply with local building and electrical codes and regulations, which may require obtaining permits and inspections from local authorities. It is important to work with experienced professionals who are familiar with local regulations and can ensure compliance [46].
iv. *Installation and Commissioning:* Once the system design and permitting are complete, the installation process can begin. This involves installing the PV modules, wiring the electrical system, and commissioning the system to ensure that it is operating correctly and safely [47].

v. *Operation and Maintenance:* PV installations require ongoing maintenance and monitoring to ensure optimal performance and longevity. This includes cleaning the modules, inspecting the electrical system, and monitoring the system output to detect any issues or inefficiencies.
vi. *Financial Considerations:* PV installations can require a significant upfront investment but can provide long-term cost savings through reduced energy bills and potential revenue from selling excess energy back to the grid. It is important to carefully consider the financial implications of a PV installation, including financing options and a potential return on investment [48].

Implementing a PV installation requires careful planning, design, and execution to ensure that the system is safe, reliable, and cost-effective. Working with experienced professionals and conducting a thorough site assessment can help to ensure a successful installation that meets the needs of the specific application [49].

8. Installation Methods of PV System and Solutions

Installation methods of photovoltaic (PV) systems can vary depending on factors, such as the size and complexity of the system, local regulations and building codes, and site-specific considerations. However, there are several common installation methods and solutions that can be used to ensure the safe and efficient operation of a PV system [50].

i. *Rooftop installation:* This is one of the most common installation methods for residential and commercial PV systems. PV modules are mounted on the roof of the building using either a flush mount or tilt mount system. The mounting system should be designed to withstand wind, snow, and other environmental factors and should be properly secured to the roof structure [51].
ii. *Ground-mounted installation:* This method is used for larger PV systems where there is sufficient available land. PV modules are mounted on a frame or structure that is anchored to the ground. The mounting system should be designed to withstand wind, snow, and other environmental factors and should be properly secured to the ground [37].
iii. *Building-integrated PV (BIPV):* This method involves integrating PV modules into the building's structure, such as into the roof or façade. BIPV systems can provide a seamless appearance and can help to offset building energy use [52].
iv. *Microinverter or power optimizer solution:* These solutions can be used to optimize the performance of a PV system by monitoring and optimizing the performance of individual modules or strings. This can help to reduce losses due to shading or mismatched modules.
v. *DC optimizers:* These devices can be used to optimize the output of individual PV modules by reducing losses due to shading or other factors. DC optimizers can be used with either string inverters or microinverters [53].
vi. *Monitoring and control:* A monitoring and control system can provide real-time data on the performance of the PV system, allowing for optimization of the system's performance and the detection of potential issues [42].

Overall, careful consideration of the installation method and associated components is essential for safe and efficient operation of a PV system. Proper installation and maintenance can help to maximize the performance and lifespan of the system and can help to ensure that the system is operating safely and reliably [34].

9. Price Trend of Crystalline-Installed PV in the World Market

The price trend of crystalline-installed PV systems in the world market has been decreasing over the past decade. This is due to a combination of factors, including advances in technology, economies of scale, and increased competition in the market [2].

According to data from the International Renewable Energy Agency (IRENA), the global weighted average price of installed crystalline PV systems decreased from $4.4/W

in 2010 to $1.2/W in 2020, representing an average annual decline of around 13%. This decrease in price has been driven by a combination of factors, including improvements in manufacturing efficiency, increased competition among PV module manufacturers, and government policies and incentives aimed at promoting the adoption of renewable energy [19].

i. *Crystalline Silicon (c-Si)*: The cost of c-Si PV modules has decreased by about 90% over the past decade, making it one of the most cost-effective PV technologies on the market. The average price of c-Si modules is currently around $0.20–$0.30 per watt.
ii. *Thin-Film PV*: The cost of thin-film PV modules has also declined significantly over the past decade, with an average price of around $0.20–$0.40 per watt. However, thin-film PV modules have lower efficiency compared to c-Si modules, which can result in higher overall system costs [45].
iii. *Concentrator PV*: Concentrator PV systems have a higher upfront cost due to the need for specialized equipment, such as lenses or mirrors, to concentrate sunlight onto the solar cells. However, their high efficiency can result in lower overall system costs over the lifetime of the system [54].
iv. *Hybrid PV:* The cost of hybrid PV systems can vary widely depending on the combination of technologies used. However, the use of multiple renewable energy sources can increase overall energy production and reduce costs in the long term [55].
v. *Organic PV and DSSCs*: Organic PV and DSSC technologies have lower costs compared to other PV technologies due to their simpler manufacturing processes and lower material costs. However, they also have lower efficiency compared to c-Si and thin-film PV technologies [56].
vi. *Perovskite solar cells*: Perovskite solar cells have the potential to be even cheaper than c-Si and thin-film PV technologies due to their low material costs and simple manufacturing process. However, the technology is still in the experimental stage, and its long-term stability and durability are not yet fully understood [12].

In addition, the cost of PV system components, such as inverters and mounting structures, has also decreased over time, contributing to the overall decrease in system prices. As a result, PV systems have become increasingly competitive with traditional fossil fuel-based energy sources and have become a cost-effective option for many applications [57]. It is worth noting that the price of installed PV systems can vary widely depending on factors such as the size and complexity of the system, local labor costs, and government policies and incentives. However, overall, the trend in the world market has been towards decreasing prices for crystalline-installed PV systems over time [44].

Breakthroughs and research tendencies per cell-type technology are shown in Figure 7; the emerging PV technologies, including emerging thin-film technologies, polycrystalline silicon, and monocrystalline silicon, are all in the early stages of development, but they have the potential to revolutionize the PV industry.

Emerging thin-film technologies are a wide range of PV technologies that use thin films of materials to convert sunlight into electricity. These technologies have the potential to be more efficient and less expensive than traditional silicon solar cells [19].

Polycrystalline silicon is a type of silicon that is made up of many small crystals. Polycrystalline silicon solar cells are less expensive than monocrystalline silicon solar cells, but they are also less efficient.

Monocrystalline silicon is a type of silicon that is made up of a single crystal. Monocrystalline silicon solar cells are the most efficient type of solar cell, but they are also the most expensive. The research tendencies in these areas are focused on improving efficiency and reducing costs. Researchers are also developing new materials and device structures that could lead to new PV technologies that are even more efficient and affordable [37].

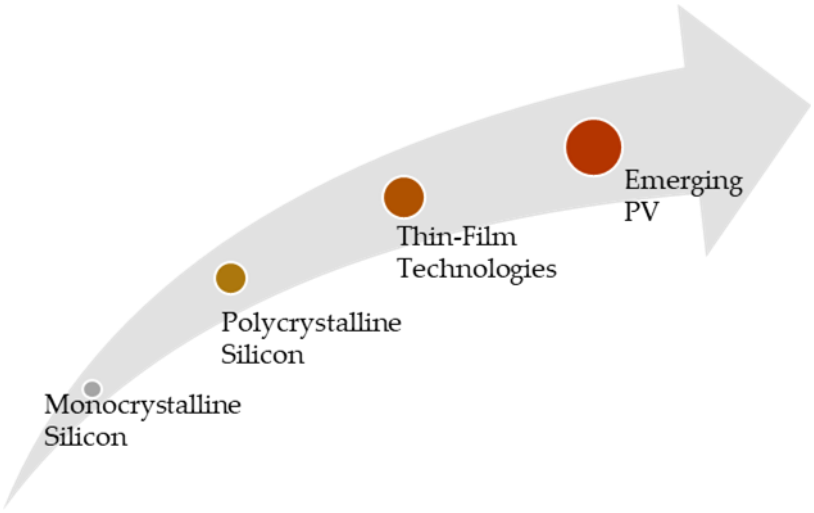


Figure 7. Breakthroughs and research tendencies per cell-type technology.

Supportive policies are crucial for fostering the adoption of solar photovoltaic (PV) technology. Key policies include Feed-in Tariffs (FiTs), Net Metering, Tax Incentives, Renewable Energy Credits (RECs), and Grants/Subsidies. These policies aim to provide a stable revenue stream, enhance economic viability, lower upfront costs, and offer additional financial incentives. Implemented together, they create a comprehensive framework aligned with renewable energy goals, accelerating the adoption of solar PV. The impact varies based on policy design, local regulations, and the maturity of the solar market in each region.

Table 9 shows the outlines key of breakthroughs and research tendencies for each cell-type technology, providing a structured and easily readable overview of advancements and trends within the field of photovoltaics.

Table 9. Breakthroughs and research tendencies.

Cell-Type Technology	Breakthroughs and Research Tendencies
Monocrystalline Silicon	1. Improved energy conversion efficiency through advanced cell designs [16].
	2. Enhanced durability and reduced degradation rates, leading to longer lifespans [56].
	3. Development of bifacial solar cells for increased energy yield [42].
Polycrystalline Silicon	1. Cost-effective manufacturing techniques, lowering the price per watt [34].
	2. Research into bifacial panels and anti-reflective coatings for efficiency gains [41].
	3. Recycling and waste reduction strategies to address end-of-life concerns [41].
Thin-Film Technologies	1. Advancements in thin-film materials, boosting efficiency, and flexibility [42].
	2. Integration into building materials, such as solar windows and facades [29].
	3. Exploration of tandem solar cells and perovskite-silicon hybrid technologies [33].
Emerging PV Technologies	1. Perovskite solar cells with potential for record-breaking efficiency [42].
	2. Organic and quantum dot PV technologies for flexibility and low-cost manufacturing.
	3. Research into tandem configurations and stability improvements for emerging PV.

As shown in Figure 8, crystalline solar panels are manufactured through a series of steps, including the production of silicon ingots; wafer slicing; surface texturing; ion implantation or diffusion for creating the P-N junction; the application of anti-reflective coating; metallization with metal electrodes; the assembly into solar modules; encapsulation for protection, framing, and junction box attachment; quality testing; and, finally, packaging for distribution and installation.

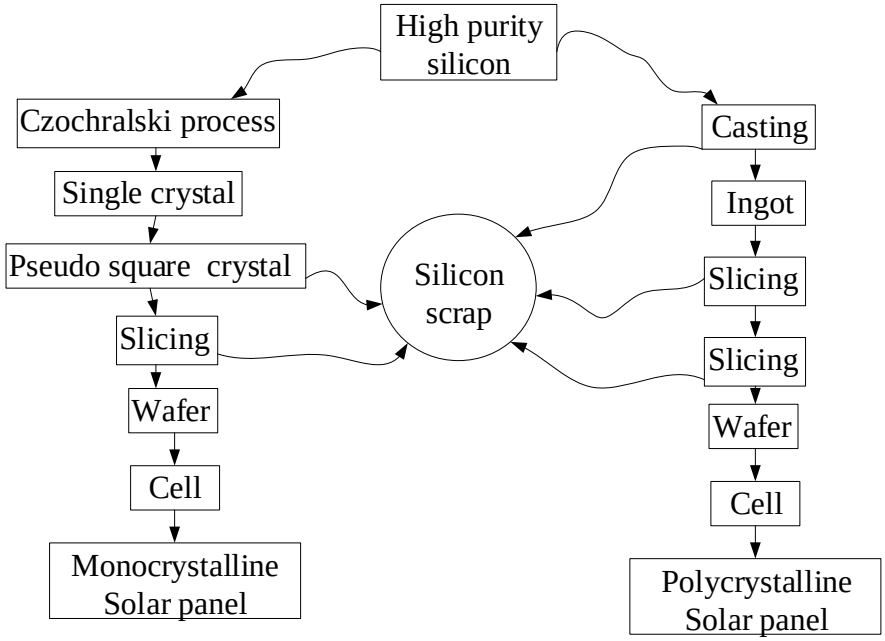
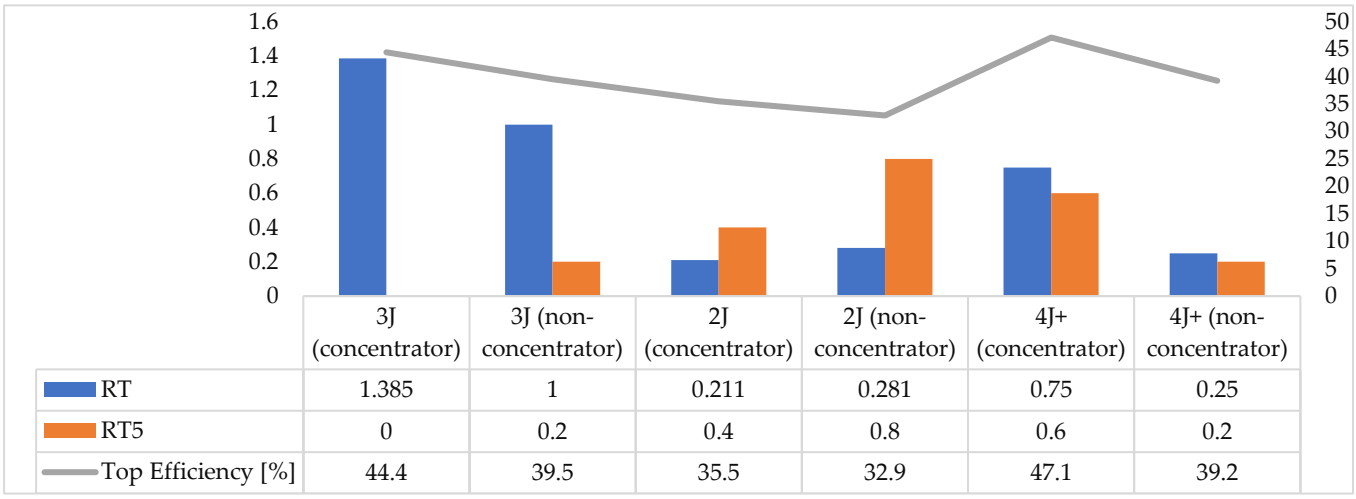


Figure 8. Process of manufacturing crystalline solar panels.

By extracting efficiency breakthroughs from the NREL chart for each specific cell type and then comparing them within a specific timeframe, we observe a discernible research tendency (RT). Typically, advancements in efficiency are closely linked with innovations in fabrication techniques, which, in turn, depend on a substantial body of research in the field [29].

However, relying solely on RT may not provide a comprehensive understanding of current research interests, as a technology may have experienced significant breakthroughs in the past but subsequently halted its progress. To address this limitation, an additional complementary metric, RT5, has been introduced. RT5 functions similarly to RT but focuses exclusively on the most recent five years, offering insights into the field's recent developments and trends [30].

Research breakthroughs in multijunction solar cells, as shown in Figure 9, have led to significant improvements in efficiency, with concentrator four-junction cells achieving top efficiencies of 47.1%, while research tendencies focus on developing new materials and improving stability and durability [30].



	3J (concentrator)	3J (non-concentrator)	2J (concentrator)	2J (non-concentrator)	4J+ (concentrator)	4J+ (non-concentrator)
RT	1.385	1	0.211	0.281	0.75	0.25
RT5	0	0.2	0.4	0.8	0.6	0.2
Top Efficiency [%]	44.4	39.5	35.5	32.9	47.1	39.2

Figure 9. Breakthroughs and research tendencies in Multijunction Cells [29].

Breakthroughs in GaAs solar cells, as shown in Figure 10, have resulted in high efficiencies of 29.1% for thin-film crystal cells and 30.5% for concentrator cells, while research tendencies focus on developing new materials and improving stability and durability.

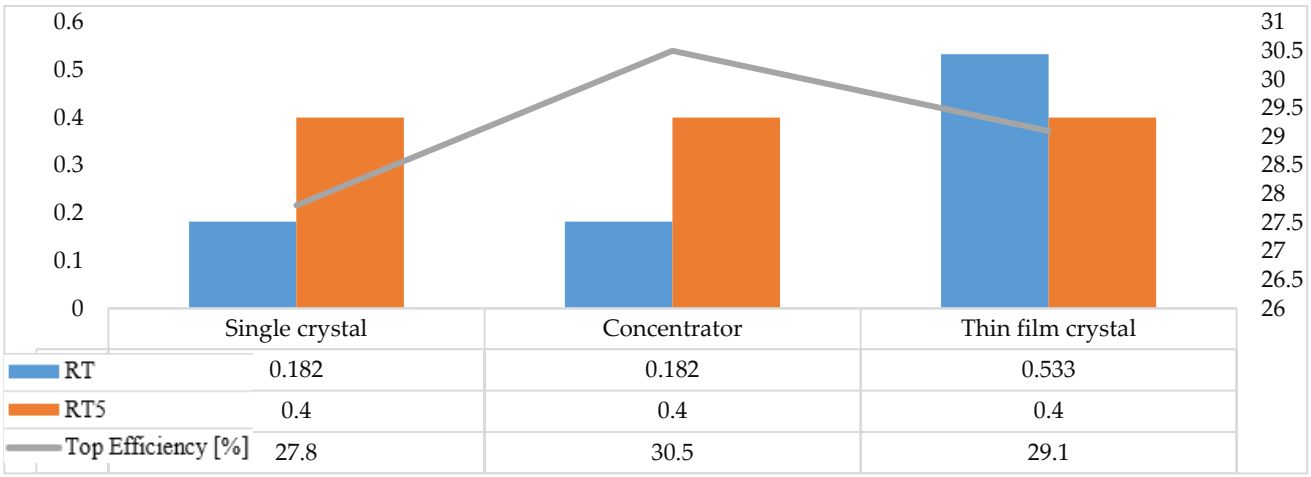


Figure 10. Breakthroughs and research tendencies in GaAs cells [29].

Breakthroughs in crystalline Si solar cells, as shown in Figure 11, have achieved efficiency records of 27.6% for single-crystal concentrator cells and 26.7% for silicon heterostructure (HIT) cells, while research tendencies focus on improving efficiency, reducing costs, and extending the lifetime of these cells [30].

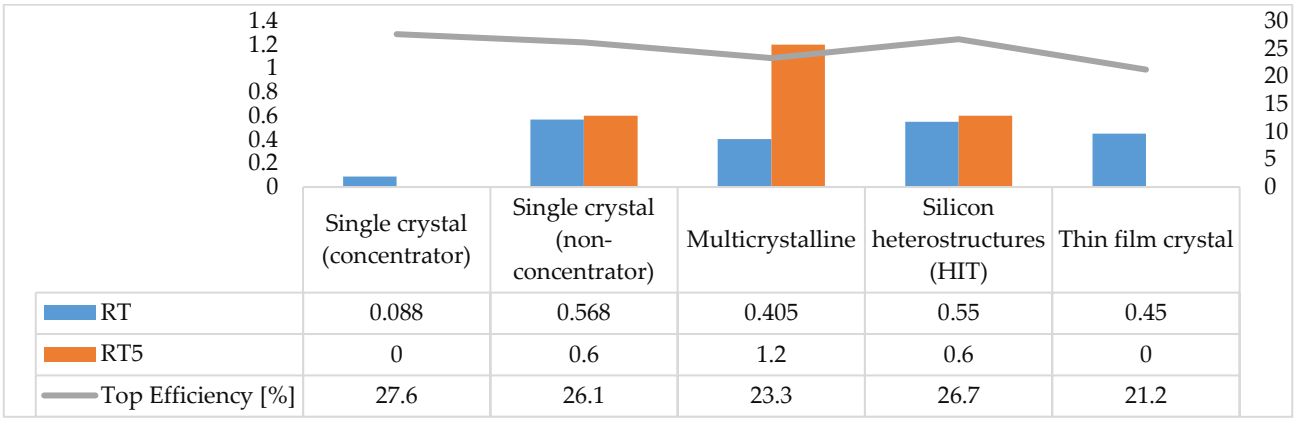


Figure 11. Breakthroughs and research tendencies in Crystalline Si cells [29].

Breakthroughs in thin-film solar cells, as shown in Figure 12, have resulted in efficiency records of 23.4% for CIGS cells and 22.1% for CdTe cells, while research trends focus on developing new materials, improving stability, and reducing costs.

Breakthroughs in emerging solar cells, as shown in Figure 13, have achieved efficiency records of 25.5% for perovskite cells, 29.5% for perovskite/Si tandem cells, and 18.2% for organic cells, while research tendencies focus on improving efficiency, stability, and scalability.

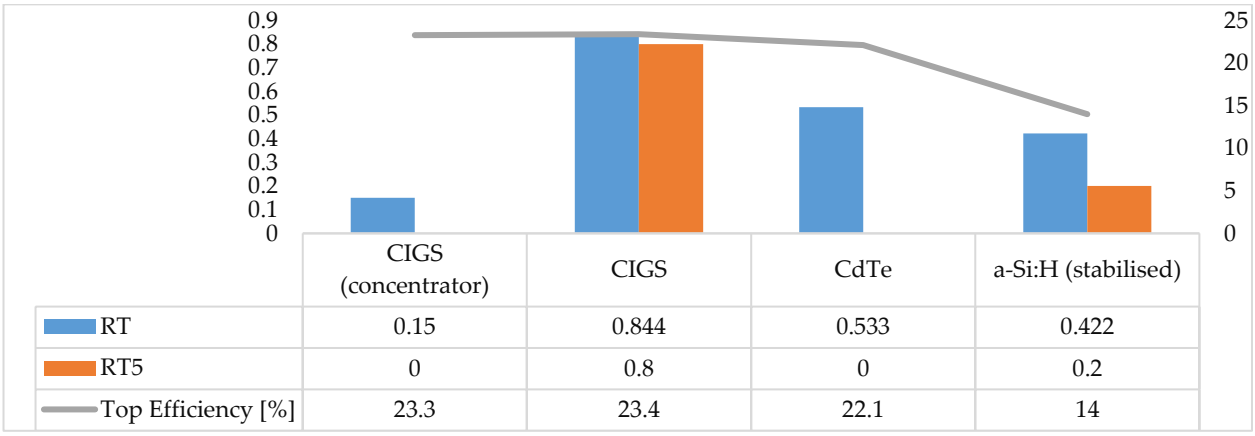


Figure 12. Breakthroughs and research tendencies in Thin-film cells [29].

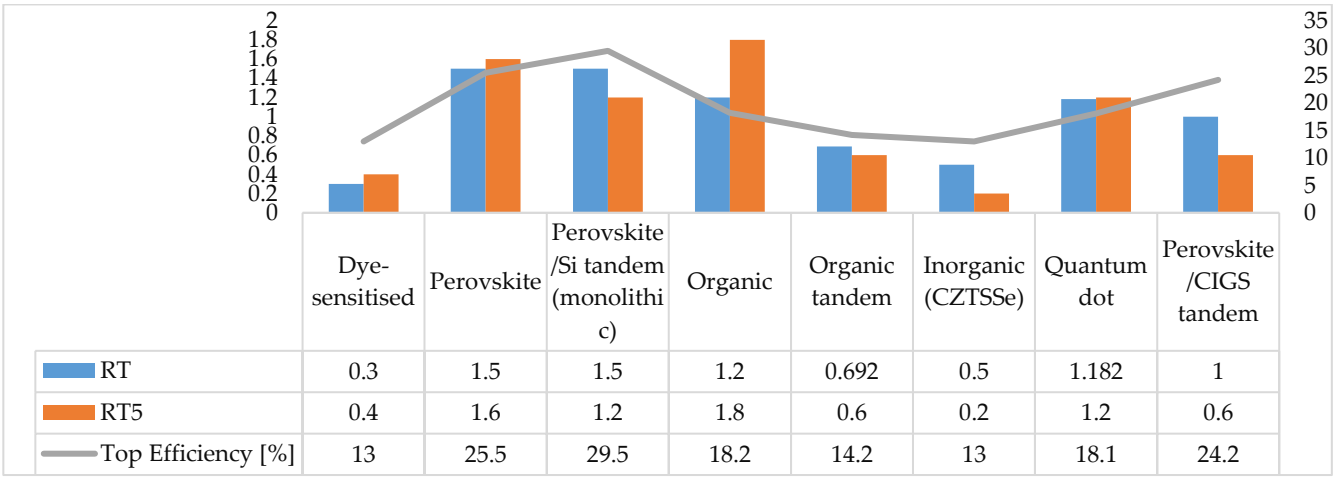


Figure 13. Breakthroughs and research tendencies in Emerging cells [29].

10. Future Research in Solar Technology

Solar technology has advanced significantly in recent years, making it an increasingly viable and important source of renewable energy. However, there is still considerable room for research and development in this field [58]. Here are some potential areas of future research in solar technology:

i. *Energy storage:* One of the biggest challenges of solar energy is that it is only available when the sun is shining. To make solar energy more reliable, research into better energy storage solutions is needed [59]. This could include advances in battery technology, as well as the development of new types of energy storage systems, such as thermal storage or hydrogen storage.

ii. *Efficiency:* Although solar panels have become more efficient in recent years, there is still considerable room for improvement. Researchers can explore new materials and technologies that can increase the efficiency of solar cells, such as perovskites or tandem cells [60].

iii. *Durability*: Solar panels are designed to last for many years, but they can be damaged by extreme weather or other environmental factors. Future research could focus on developing more durable solar materials and improving the design of solar panels to make them more resistant to damage [61].

iv. *Integration with other technologies*: Solar energy can be integrated with other technologies, such as electric vehicles, smart homes, and microgrids. Research in this area could help to improve the efficiency and reliability of these systems as well as make them more cost-effective [62].

v. *Large-scale deployment*: Solar energy has great potential to meet our energy needs, but to achieve this, it must be deployed on a much larger scale. Research can focus on ways to reduce the cost of solar panels as well as the development of new manufacturing processes that can increase the speed and efficiency of production [63].
vi. *Solar-driven water treatment*: The use of solar energy in water treatment technologies could provide a sustainable solution to provide clean drinking water. Research in this area could focus on developing low-cost and efficient solar-driven water treatment technologies [64].
vii. *Artificial Intelligence (AI) and machine learning*: The use of AI and machine learning can help optimize the efficiency of solar energy systems. Future research could focus on developing algorithms that can improve the performance of solar energy systems by predicting solar irradiance, optimizing energy storage, and improving the management of microgrids [61].

There are many exciting areas of research in solar technology that could help to make it an even more important source of renewable energy in the years to come.

11. Conclusions

Photovoltaic (PV) technologies offer a promising solution for a sustainable future by providing a clean and efficient source of energy. Silicon-based PV technologies, such as crystalline silicon and thin-film silicon, are the most widely used technologies today, and they offer high efficiency and a long lifespan. However, there are other types of PV technologies, such as cadmium telluride, copper indium gallium selenide, and organic PV, that also offer high efficiency and cost-effectiveness.

The potential of PV technologies to reduce our dependence on fossil fuels and mitigate climate change is vast. PV technologies can also provide energy access to the millions of people who currently lack it. In many parts of the world, particularly in rural areas, people lack access to reliable electricity. PV technologies can provide a decentralized source of electricity that is not reliant on centralized power grids. As technology advances and costs continue to decline, PV technologies are likely to become increasingly important in meeting our energy needs. The International Energy Agency (IEA) predicts that solar PV will be the cheapest source of electricity in most parts of the world by 2030. Therefore, investment in PV technologies, research and development, and policies that support their deployment should be a priority to achieve a sustainable and efficient energy future.

In summary, PV technologies have the potential to revolutionize the energy sector by providing a clean, efficient, and cost-effective source of electricity. As we work towards a sustainable future, it is imperative that we continue to support the development and deployment of PV technologies to realize their full potential.

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