

SOLAR ENERGY AS A DRIVER OF THE GREEN TRANSITION: THE PATH TO A SUSTAINABLE FUTURE

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Abstract: Solar energy is increasingly gaining significance as an essential part of sustainable development and the transition to cleaner forms of energy. Its application helps reduce dependence on fossil fuels, contributes to the reduction of harmful gas emissions, and offers numerous economic and ecological benefits. This paper examines the role of solar energy in creating a greener energy system, focusing on the technical, economic, and environmental aspects of its application. The paper begins by reviewing global capacities and current trends in solar energy usage, with special emphasis on technological advancements that enable greater efficiency of solar systems. It then analyzes financial aspects, including initial costs, subsidy opportunities, and the long-term profitability of investments in this technology. The ecological benefits of solar energy are also an important focus, ranging from reduced carbon dioxide emissions to preserving natural resources and improving air quality. One of the key elements of the paper is the evaluation of solar system efficiency, as precise measurement is essential for making informed decisions about their implementation and profitability. In this context, factors such as production capacity, efficiency, economic sustainability, and comparisons with other renewable energy sources are considered. The paper also addresses challenges—barriers related to infrastructure, financing, and regulatory frameworks continue to hinder the broader adoption of solar energy. Solar energy holds significant potential for transforming the energy sector toward a more sustainable model. However, to fully realize this potential, it is essential to continue the development of advanced technologies, ensure better integration of solar systems into existing grids, and enhance institutional and regulatory support. Systematic investment in innovation and strengthening international cooperation can significantly contribute to global efforts in combating climate change and ensuring energy stability.

Keywords: renewable energy sources, solar energy, energy efficiency, green transition, energy independence.

1. INTRODUCTION

In recent decades, the world has been facing growing ecological and energy challenges, necessitating an urgent transition to sustainable energy sources. Solar energy, as one of the most accessible renewable sources, plays a key role in this process[1-3]. By using sunlight to generate electricity

and thermal energy, dependence on fossil fuels is reduced, which helps mitigate climate change and decrease greenhouse gas emissions. In addition to ecological advantages, solar energy is becoming increasingly economically viable due to technological advancements and decreasing production costs. The green transition involves the gradual phasing

out of fossil fuels and the adoption of sustainable energy solutions that ensure a more environmentally friendly and secure future [4,5]. Solar energy already plays a crucial role in global energy strategies, and according to data from the International Renewable Energy Agency (IRENA), its application continues to grow year by year. Governments worldwide are implementing policies and incentives to accelerate the integration of solar systems into electrical grids, thereby reducing energy dependence and promoting local electricity generation. One of the greatest advantages of solar energy is its widespread availability—the sun knows no boundaries, meaning that solar technology can be applied in almost all parts of the world. Moreover, the development of solar technologies creates new job opportunities in production, installation, and maintenance sectors, which can have a significant positive impact on the economy. However, despite its numerous advantages, challenges remain, such as high initial investments, the need for improved energy storage technologies, and the adaptation of existing electrical grids to decentralized energy production [6-8]. The aim of this paper is to analyze how solar energy contributes to the green transition and how its efficiency can be measured in both ecological and economic contexts. Technical aspects of solar systems, their economic viability, and their positive environmental impacts will be considered. Special attention will be paid to efficiency indicators, such as production capacity, utilization factor, and long-term sustainability. Understanding the efficiency of solar energy is crucial for making informed decisions about its implementation. Technological progress offers numerous possibilities, but the efficiency of solar systems also depends on geographic, economic, and regulatory conditions [9]. Therefore, this paper will provide an overview of methods for assessing the efficiency of solar energy, analyze the challenges faced by its broader application, and outline guidelines for improving solar technologies to achieve long-term sustainability. Solar energy is not just a tool for reducing greenhouse gas emissions—it is a key element of the global energy transition that can deliver economic, social, and ecological benefits. Its broader application can significantly contribute to energy security, reduce electricity production costs, and create more resilient and environmentally friendly energy systems.

2. TRENDS IN RENEWABLE ENERGY SOURCES

2.1. Global Trends in Renewable Energy Sources

In the past decade, the world has witnessed a significant increase in energy production from renewable sources. This trend is the result of the growing need for sustainable development, the reduction of greenhouse gas emissions, and the transition from fossil fuels to more environmentally friendly energy forms [5]. Technological advancements, the decline in the cost of renewable technologies, and global political and social pressure to combat climate change have further accelerated this process.

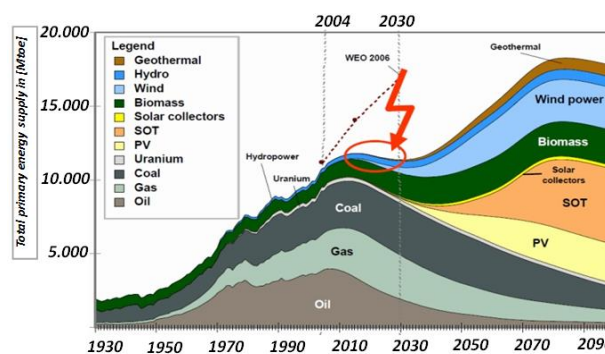


Figure 1. Comprehensive Global Energy Scenario for the Implementation of Renewable Energy Sources for the Period 1930-2100 [6,10]

Based on the scenario published in [10] (World Energy Outlook 2006), there are two extremes in the overall primary energy supply in the world: one occurring between 2004 and 2030, and the other between 2070 and 2090. In the first extreme, fossil fuels dominate energy production, with a larger share of energy coming from coal, oil, and gas. In the second extreme, renewable energy sources (geothermal, wind, solar, and biomass) take precedence in energy production. According to all the energy production scenarios presented here, as well as those in [10,11], the share of renewable energy sources in global and European Union (EU-28) energy production continues to grow, leading to a significant reduction in the share of fossil fuels by 2080. This would eliminate all the negative consequences of using fossil fuels for energy production. Consequently, climate issues and ecosystem problems will be addressed both globally and within the EU-28, and clean energy will be produced from renewable sources. The

most prevalent renewable energy sources today are solar energy, wind energy, hydropower, biomass (bio-energy), and geothermal energy. Among these, solar and wind energy have experienced the fastest growth. According to the International Renewable Energy Agency (IRENA), the total renewable energy capacity has increased from about 1,700 gigawatts (GW) in 2013 to more than 3,300 GW by the end of 2023. This represents almost a doubling of capacity in just ten years. Solar energy has recorded the highest growth among all sources. The price of solar panels has dropped by more than 80% in the past decade, enabling widespread implementation globally, especially in countries with high solar potential. In 2023, solar energy accounted for around 20% of the total newly installed capacity from renewable sources. Wind energy, both onshore and offshore, is also expanding, with China, the United States, and EU countries leading in this segment. Offshore wind farms, particularly in the North Sea and Asia, have experienced significant growth. Hydropower remains the dominant renewable energy source in terms of total electricity generation, although its growth has stagnated due to limited geographic opportunities and environmental concerns. Bioenergy, which involves the use of biomass for the production of heat and electricity, represents a significant segment of renewable energy, especially in rural areas and countries with well-developed agriculture and forestry sectors. Biomass includes wood, plant residues, organic waste, and biogas, and can also be used for biofuel production. Bioenergy is one of the few sources that can be available 24 hours a day, making it a crucial factor in energy stability. In many countries, particularly in Europe and South America, biomass constitutes a significant portion of total renewable energy consumption. Over the past decade, China has become the global leader in renewable energy installations, with the largest investments in solar and wind power. The European Union has also strongly supported renewable energy through various policies, subsidies, and targets under the Green Deal. The United States, despite occasional policy fluctuations, has accelerated its transition, particularly through private investments and state-level initiatives. Developing countries, such as India and Brazil, have also made significant progress. India, thanks to large solar projects like the “Solar Mission,” and Brazil, with its strong hydropower sector and growing interest in biomass and wind, have significantly contributed to global growth, as shown in Figure 3. The trend of renewable energy sources in the world from 2001 to 2024 is presented in

Figure 2, and global renewable energy production and expansion in 2024 is depicted in Figure 3 [12,13].

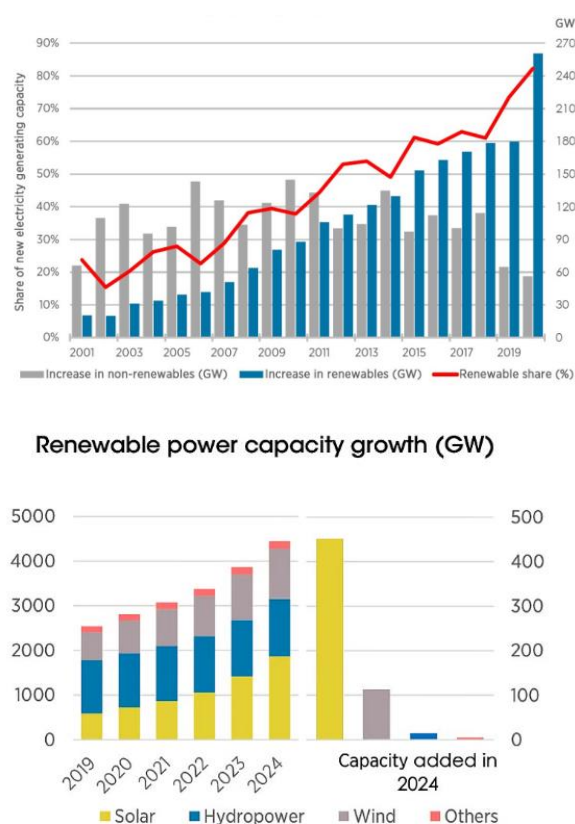


Figure 2. Trend of Renewable Energy Sources in the World from 2001 to 2024.[12,13]

An analysis of the diagram in Figure 2 leads to the conclusion that, globally, energy production from renewable sources has been increasing year by year, in other words, showing a growing trend[14-16]. However, it is important to emphasize that this growth trend remains insufficient to meet the targets set by the Paris Climate Agreement. According to data from the International Renewable Energy Agency (IRENA), renewable energy sources accounted for over 90% of global additions to electricity generation capacity in 2024, compared to 86% in 2023. The year 2024 marked another record-breaking period for renewables, with 585 gigawatts (GW) of new capacity installed, representing 92.5% of total global power expansion. Solar photovoltaic (PV) technology led this growth, contributing 451.9 GW of new capacity—an annual increase of 32.2%. Combined, solar PV and wind energy accounted for 96.6% of all net renewable energy capacity additions in 2024. Wind power capacity grew by 11.1%, adding 113 GW globally.

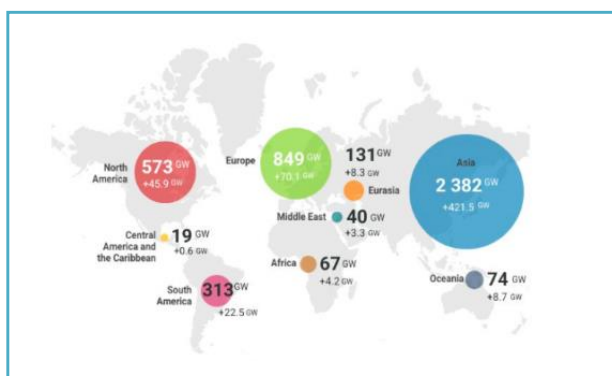


Figure 3. Diagram of Global Renewable Energy Production and Expansion in the World in 2024.[12]

China played a dominant role in solar PV deployment, installing 278 GW in 2024 alone. The total global solar PV capacity has now reached 1,865 GW, which constitutes more than three-quarters of the world's total renewable capacity of 4,448 GW. For comparison, in 2023, renewable energy accounted for 86% of the global increase in energy capacity, including 345.5 GW of newly installed solar PV. Although 2024 marked the year with the largest increase in renewable energy capacity and growth, the International Renewable Energy Agency (IRENA) highlights that regional disparities remain evident at the global level. Asia continues to dominate the global market, accounting for 64% of the global increase in renewable energy capacity[17–19]. In contrast, Central America and the Caribbean contributed the least, with only 3.2%. Renewable energy sources are increasingly displacing fossil fuels, driving job creation, lowering electricity costs, and improving air quality. Furthermore, they play a crucial role in revitalizing economies worldwide. However, for a fair and faster energy transition, it is essential that all countries have equal opportunities to fully utilize affordable, clean renewable energy. Despite impressive growth, global progress remains insufficient to achieve the target of tripling installed renewable energy capacity to 11.2 terawatts (TW) by 2030, as outlined in the Paris Climate Agreement. Current growth rates would need to accelerate to 16.6% annually by 2030, according to IRENA. In addition to progress, the renewable energy sector faces several challenges. A key issue is intermittency—the dependence of production on weather conditions—which requires significant investment in energy storage capacities and the modernization of electricity grids. Additional barriers include administrative hurdles, limited

investments in some regions, and local resistance to infrastructure projects. Despite these challenges, the future of renewable energy remains highly optimistic. In many parts of the world, renewable sources have already become the most cost-effective means of electricity generation. Technological innovations in battery systems, smart grids, and digital solutions will further enhance the efficiency, flexibility, and reliability of energy systems. The experience of the past decade demonstrates that the energy transition is not only possible but inevitable. Renewable energy sources are becoming the foundational pillars of modern energy systems worldwide, reducing dependence on fossil fuels, fostering sustainable economic growth, and contributing to environmental preservation [20–22]. If current trends continue, renewable energy is set to become the dominant form of electricity generation in the coming decades.

2.2. Trends in Renewable Energy Sources in the European Union

The European Union recognizes renewable energy sources as a cornerstone of a sustainable energy future and a key instrument in combating climate change. Within its strategic framework, the European Union is fully committed to replacing fossil fuels with renewable energy sources [23–25]. According to the report by the European Renewable Energy Federation, it is projected that by 2050, the use of renewable energy will double compared to the current level of nuclear energy production (Figure 4) [26]. The report also reveals that by introducing new technologies, we are able to maintain the sustainability of the system of renewable energy sources, which means improving energy efficiency. If this energy transition were to be achieved and supported by citizens, a large number of jobs would be created throughout the European Union. The EU strategy includes the development of a regulatory framework that encourages investments in renewable energy, reduces administrative barriers, and strengthens cross-border energy cooperation among member states. Through instruments such as the European Green Deal and the “Fit for 55” package, the EU sets ambitious targets for decarbonizing the energy sector and promotes the integration of renewables into electricity grids[27]. Special emphasis is placed on innovation, digitalization, and the development of energy storage technologies, as well as strengthening

the resilience of energy systems. At the same time, the European Union's strategy underscores the importance of a just transition, ensuring that the shift to clean energy is socially inclusive and sustainable for all regions and citizens.

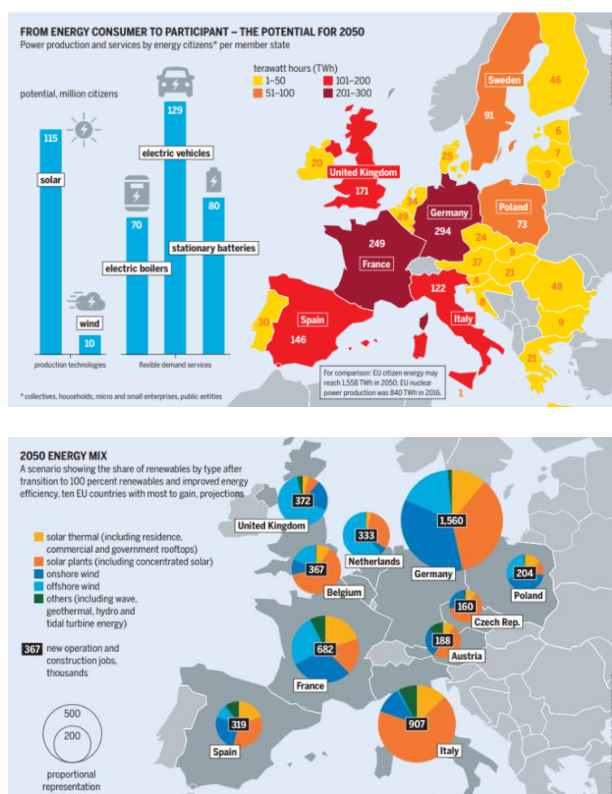


Figure 4. Projections of Renewable Energy Production in the European Union until 2050[26]

The EU aims to lead the global energy transition, not only through internal reforms but also through international cooperation, financing, and the sharing of best practices. In doing so, it sets an example in the development of a secure, competitive, and climate-neutral energy model based on renewable energy sources. The European Union recognizes renewable energy sources as the foundation of a sustainable energy future and a key instrument in addressing climate change. As part of its comprehensive climate and energy strategy, the EU is committed to a gradual transition from fossil fuels to clean, renewable sources such as solar, wind, hydro, biomass, and geothermal energy [28]. The EU's strategy includes the development of a regulatory framework that encourages investment in renewables, reduces administrative barriers, and strengthens cross-border energy cooperation among member states. Through

initiatives such as the European Green Deal and the “Fit for 55” package, the EU has set ambitious targets for decarbonizing the energy sector and integrating renewable sources into electricity grids. Special emphasis is placed on innovation, digitalization, and the advancement of energy storage technologies, as well as on enhancing the resilience of energy systems. At the same time, the EU's strategy highlights the importance of a just transition, ensuring that the shift to clean energy is socially inclusive and sustainable across all regions and communities. The European Union aims to lead the global energy transition not only through internal reforms but also through international cooperation, financing, and the exchange of best practices. In doing so, it positions itself as a model for the development of a secure, competitive, and climate-neutral energy system based on renewable energy sources.



Figure 5. The European Union's Renewable Energy Development Strategy: A Multidimensional Approach to Energy Transition

For decades, the European Union (EU) has been at the forefront of the global energy transition toward sustainable and clean energy sources. The strategy for the development of renewable energy forms a key component of the broader European Green Deal, which aims to achieve climate neutrality by 2050. This strategy encompasses multiple dimensions, including political commitment, legislative frameworks, technological innovation, financial instruments, and international cooperation (Figure 5). At the core of the EU's energy strategy lies an ambitious target: to increase the share of renewable energy in total energy consumption to at least 42.5% by 2030, with the potential to reach 45%, and to achieve full climate neutrality by 2050. These goals require not only the replacement of fossil fuels with solar, wind, hydro, biomass, and geothermal energy but also the comprehensive transformation of the EU's energy systems. One of the primary challenges is

the effective integration of decentralized renewable sources into the existing electricity grid. The strategy therefore emphasizes the modernization and digitalization of energy networks, alongside the development of smart grids and energy storage systems using batteries and hydrogen. These advancements enable stable electricity supply, even during periods without sun or wind. The EU continues to invest significantly in research and development of new technologies for harnessing renewable energy, including advanced photovoltaic cells, floating offshore wind turbines, bioenergy systems, and green hydrogen production technologies. Through programs such as Horizon Europe and the Innovation Fund, the Union provides substantial funding for pilot projects and the commercialization of innovations. The legislative framework includes several key instruments: the Renewable Energy Directive (RED II and RED III), which sets binding targets and defines guidelines to facilitate project development, and the Fit for 55 package, which outlines measures to reduce greenhouse gas emissions by 55% by 2030 [26]. Additionally, the ongoing reform of the electricity market aims to increase transparency, ensure supply security, and promote competitiveness. To achieve these goals, the EU mobilizes large-scale investments through the Recovery and Resilience Facility, InvestEU, the Just Transition Fund, and the European Regional Development Fund (ERDF). These instruments support energy projects, particularly in regions currently dependent on coal and fossil fuels, ensuring a fair and inclusive transition. Although the strategy is coordinated at the EU level, Member States are responsible for designing and implementing their own National Energy and Climate Plans (NECPs). These plans define specific steps, deadlines, and local priorities, while aligning with common objectives. The local level also plays a critical role by encouraging community investments in small-scale solar systems, energy cooperatives, and citizen-owned renewable initiatives. The EU's energy strategy extends beyond its borders, fostering stronger cooperation with third countries, particularly those rich in renewable resources. The EU works to establish cross-border energy corridors and infrastructure to import clean electricity from neighboring regions. This also enhances energy security and reduces dependence on fossil fuel imports. In summary, the European Union's renewable energy development strategy represents a comprehensive and multidimensional

approach to energy transition. By aligning ambitious climate goals with innovation, investment, and regulatory reforms, the EU is laying the groundwork for a sustainable, resilient, and competitive energy future. Its implementation contributes not only to environmental protection but also to job creation, technological advancement, and greater energy independence for all Member States. It is known that in the last ten years, the European Union has increased the share of renewable energy sources in total energy consumption [27–29]. The main contributors to this growth were wind power (38.5%) and hydroelectric power (28.2%), while solar energy contributed 20.5% of renewable energy production. Despite these positive trends, the EU is still falling short of its target of achieving a 42.5% share of renewable energy in total energy consumption by 2030. To reach this target, the implementation rate of renewable sources needs to be doubled, and a deeper transformation of the European energy system must take place. For a more detailed overview of trends and statistics, it is recommended to visit the European Environment Agency's website, which provides interactive graphs and additional information. An overview of key trends in the share of renewable energy in total energy consumption in the EU over the past three years shows an upward trajectory. The share of renewable energy in total energy consumption in the EU was 19% in 2021, increasing to 25% in 2022, indicating significant progress in integrating renewable energy sources. According to preliminary data, renewable sources accounted for 45.3% of gross electricity consumption in the EU, representing a 4.1 percentage point increase compared to the previous year. The main contributions came from wind power (38.5%) and hydroelectric power (28.2%), while solar energy contributed 20.5% of renewable energy production in 2023.

2.3. Natural Resources, Solar Energy Availability, and Trends in Solar Energy Utilization

Natural resources encompass all materials and phenomena found in nature that are beneficial to human life. These include water, land, wood, minerals, oil, wind, sunlight, and even living organisms—plants and animals. Without these resources, life on Earth would not be possible. For centuries, humans have relied on natural resources for food, constru-



Figure 6. Using solar energy using solar panels, solar collectors and solar cars [33]

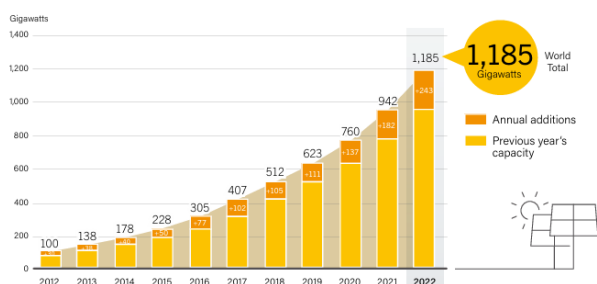
ction, heating, transportation, and energy production. However, as global development and technological advancement have progressed, the consumption of these resources has significantly increased[30]. A key concern is that many natural resources are finite. For instance, reserves of oil, gas, and coal are limited, and excessive use could lead to their eventual depletion. Moreover, the exploitation of these resources contributes to environmental pollution—contaminating air, water, and soil—and accelerates climate change. As a result, there is a growing emphasis on transitioning to renewable energy sources that are both sustainable and environmentally friendly. One of the most promising renewable energy sources is the Sun. The Sun is fundamental to life on Earth: it enables photosynthesis in plants, provides heat, and regulates the planet's climate. Solar energy can also be harnessed and converted into electrical or thermal energy for various human needs, ranging from lighting and heating to powering machines and vehicles. A major advantage of solar energy is its widespread availability. Every day, the Sun bathes the Earth in a vast amount of energy. For example, in just one hour, the Sun emits more energy than the entire human population consumes in a year—highlighting the immense potential of this natural resource. Furthermore, solar energy is clean; it produces no pollution, emits no harmful gases, and generates no waste. Utilizing solar energy can significantly reduce air and water pollution, mitigate climate change, and improve public health.

There are multiple ways to harness solar energy. The most well-known are solar panels, which convert sunlight into electricity. These panels are increasingly being installed on rooftops of homes, buildings, schools, hospitals, and factories. In many

cases, they can supply entire households, educational institutions, or even entire villages—especially in remote areas lacking access to conventional power grids. In addition to solar panels, solar collectors are used for heating water [31,32]. These systems absorb solar heat and transfer it to water stored in tanks, and they are becoming more common in homes, hotels, and sports facilities due to their cost and energy efficiency. In recent years, further innovations have emerged, including solar-powered vehicles, solar street lighting, and solar chargers for phones and other devices. These advancements illustrate the growing role of solar technology in everyday life and its potential to support a more sustainable future.

These innovations highlight the usefulness and adaptability of solar energy. Although sunlight is present across the globe, the amount of solar energy that can be harnessed depends on geographic location, weather conditions, and the time of year. For example, countries located closer to the equator experience more sunny days annually, making solar energy more accessible and efficient. In contrast, areas frequently covered by clouds, fog, or rain may see reduced performance from solar systems. Additionally, since solar energy cannot be collected during nighttime, batteries and energy storage systems are essential to store excess energy for later use [34,35]. While such systems can be expensive, they are highly beneficial as they ensure a continuous energy supply regardless of solar availability. The advantages of using solar energy are numerous—it is renewable, clean, silent, does not require fuel, and can be utilized almost anywhere. It contributes to environmental conservation and reduces electricity costs. Nevertheless, certain challenges remain: the high initial investment in equipment,

the need for effective energy storage, and dependence on weather conditions. Therefore, it is crucial for governments, scientists, and engineers to continue improving solar technologies to make them more accessible and efficient. Moreover, educating the public—especially young people—about the importance of renewable energy sources can accelerate the transition toward cleaner and smarter energy production methods. Solar energy stands out as one of the most valuable and promising natural resources we possess. Although there are certain barriers to its widespread adoption, the benefits it offers are substantial—both for humanity and the planet. At a time when we are facing pollution, climate change, and the depletion of conventional resources, solar energy emerges as a viable solution that is practically within our reach[36–38]. By investing in solar technologies, raising public awareness, and implementing effective legislation, we can build a world that utilizes natural resources in an intelligent and responsible manner. In doing so, we help both ourselves and future generations by leaving behind a cleaner, healthier, and more sustainable planet. Global annual photovoltaic (PV) solar capacity—both worldwide and in leading countries and regions—for the period from 2012 to 2022 is illustrated in Figures 7 and 8.

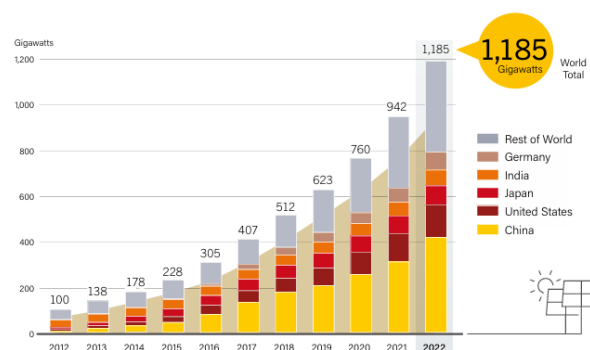


Source: See endnote 1 for this section.

Figure 7. Global Solar Photovoltaic (PV) Capacity Trends on an Annual Basis, 2012–2022 [12,13,40]

On the basis of Figure 7, we conclude that in the last ten years solar PV capacity has been continuously increasing, and in 2022 it reached 1,185 Gigawatts. The increasing trend is an exponential function. Based on Figure 8, we conclude that China is the leader in installing solar PV capacities, and the top five countries in the world in terms of installing solar PV capacities are: China, the United States, India, Brazil and Spain.

Based on the data shown by the authors in [12,13,40], we conclude that the participation of solar PV capacity in electricity production has increased in 2022, and certain countries rely on solar PV to produce electricity to meet their needs. The installation of solar PV systems in the world is due to the reduction in the price of the modules, which made the installation affordable and interesting, and the production itself is the largest in China, while the USA gives an incentive to produce the same modules in their countries.



Source: See endnote 9 for this section.

Figure 8. Trends in Global Solar Photovoltaic (PV) Capacity by Country and Region, on an Annual Basis, 2012–2022 [12,13,40]

The next five largest markets in 2022 were Germany, Japan, Poland, Australia, and the Netherlands. To rank among the world's top ten solar PV markets in 2022, a country needed to install at least 3.9 GW, up from 3.4 GW in 2021 (see Figure 9). The leading countries by cumulative installed solar PV capacity remained China, the United States, Japan, India, and Germany, while the top markets in terms of per capita capacity continued to be Australia, the Netherlands, and Germany (see Figure 9).

Many countries to encourage the use of solar PV capacity in residential systems have introduced subsidies, tax exemptions, simplified licensing and many other discounts to encourage the use of solar PV capacity. China's solar photovoltaic market is in first place, reaching 106 GW in 2022, an increase of about 93% compared to 2021 [12,13,40]. The centralized PV sector in China grew by approximately 18%, while the distributed PV sector expanded by 47%. This surge in rooftop installations was primarily driven by a three-year national rooftop solar program launched in early 2021, which resulted in twice as many installations in 2022 compared to 2021.

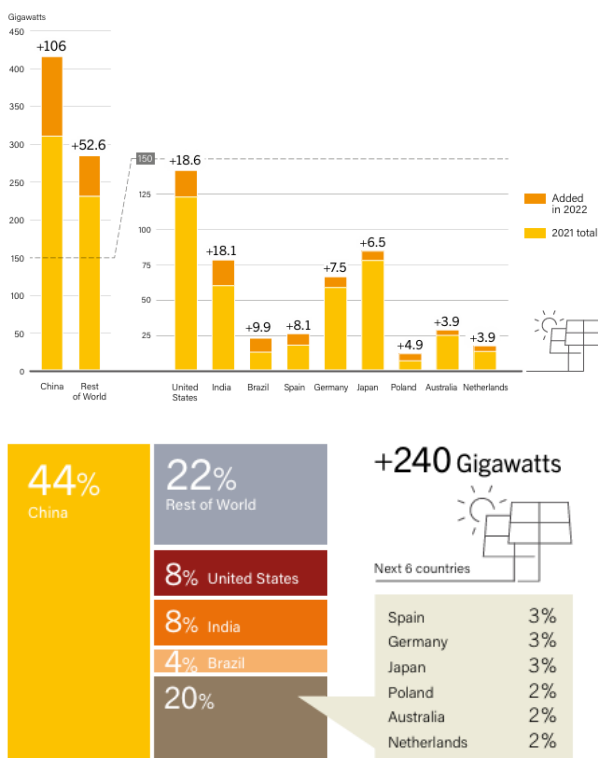
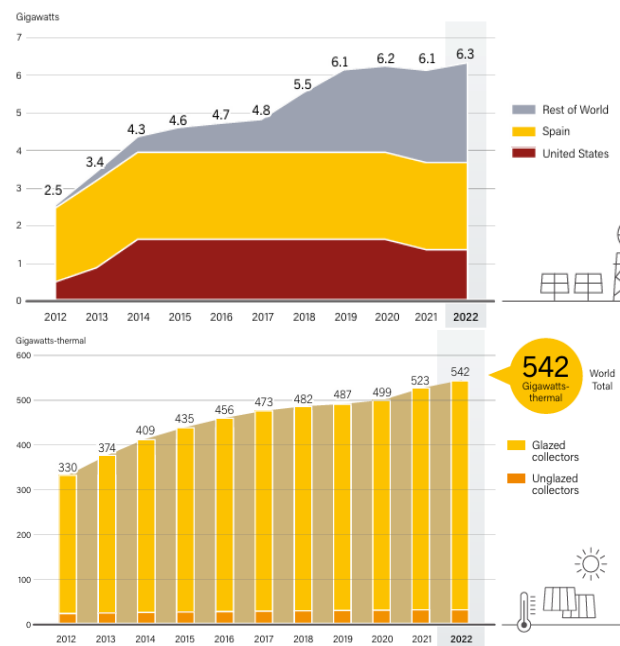


Figure 9. Solar Photovoltaic (PV) Capacity Trends with Additional Capacity in the Top Ten Countries Worldwide in 2022 [12,13,40]

China's total electricity generation (from all sources) rose by 3.6%, while generation from solar PV increased by 27.8%, reaching 418 TWh. The country's total electricity demand in 2022 amounted to 8,840 TWh, with solar PV accounting for 4.7% of the total. India once again ranked as the second-largest solar PV market in Asia, and third globally, adding approximately 18.1 GW in 2022—more than in the previous year—representing roughly 80% of the country's total new capacity additions (from all sources). These additions included about 15.7 GW from utility-scale solar and 2.4 GW from rooftop PV systems, bringing India's cumulative installed capacity to around 79 GW. However, this figure still fell short of India's 2022 target of 100 GW of solar capacity.

The shortfall—approximately 2 GW in utility-scale and 25 GW in rooftop PV—was attributed to several factors: net metering limitations, import duties that took effect in April 2022, unsigned renewable energy power purchase agreements that were offered but not finalized by distribution companies, and financing constraints, including higher interest rates and a shift in loan tenures for renewable energy from



Source: See endnote 1 for this section.

Source: IEA SHC. See endnote 10 for this section. Note: Data are for glazed and unglazed solar water collectors and do not include concentrating, air or hybrid collectors.

Figures 10. Global Trends in Solar Thermal Energy Capacity by Country and Region, and Global Capacity of Solar Collectors for Water Heating, 2012–2022 [12,13,40]

annual to monthly repayment schedules. Global installed capacity of concentrating solar power (CSP) increased by 200 MW in 2022, reaching a total of 6.3 GW (see Figure 10). New projects are known to have been announced or are currently under construction in emerging markets including Chile, China, Israel, Morocco, South Africa and the United Arab Emirates.

The solar thermal industry faced several challenges in 2022, including supply chain disruptions, logistical issues, and inflationary pressures, all of which contributed to rising costs. Solar thermal systems for hot water consumption and space heating account for about 60% of annual installations, and if in recent years this market has been shrinking in Europe and China. Cumulative global installed capacity reached an estimated 542 GWth in 2022, which represents an increase of 3.3% compared to 523 GWth in 2021 (see Figure 10). By the end of 2022, the total global operating capacity of solar collectors for water heating was sufficient to deliver approximately 442 TWh of heat per year, which is equivalent to the energy content of 260 million barrels of oil [12,13,40].

Over the past decade, renewable energy sources—particularly solar photovoltaic (PV) and solar thermal energy including concentrating solar power (CSP)—have experienced significant technological advancements, establishing themselves as central pillars in the global transition toward a sustainable energy future. PV technologies, driven by falling panel prices, improved efficiency, and large-scale deployment, have become a vital component of energy supply, both at the individual and industrial levels. At the same time, CSP, though less widespread, has progressed through the development of concentrated solar systems that allow for energy storage and electricity generation even during nighttime hours, significantly enhancing its flexibility and reliability[39,41]. The development of solar technologies is contributing to the reduction of greenhouse gas emissions, thereby supporting global efforts to combat climate change. PV and CSP systems enhance energy security, reduce dependence on fossil fuels, and generate new employment opportunities in the renewable energy sector. Although challenges remain—particularly regarding energy production variability and the need for advanced storage solutions—continued research and investment in solar technologies promise further improvements in efficiency and cost-effectiveness. Looking ahead, further growth of solar technologies is expected, driven by the urgent need for sustainable energy solutions and the evolution of supportive policy and economic frameworks. These advancements will ensure that solar energy continues to play a key role in the global energy transformation.

3. TECHNOLOGICAL ASPECTS OF SOLAR ENERGY

Solar energy represents one of the most promising renewable energy sources in contemporary society, and technological advancements in photovoltaic systems, solar thermal energy, and innovations in the solar energy sector are crucial for reducing greenhouse gas emissions and combating global warming [42,43]. This paper examines the key technological aspects of solar energy, with a particular focus on photovoltaic systems, solar thermal energy, and the latest innovations shaping the future of the solar industry.

3.1. Photovoltaic Systems and Their Efficiency

Photovoltaic (PV) systems use semiconductor materials, primarily silicon, to convert sunlight into electrical energy through the photoelectric effect. This phenomenon allows electrons to be released from the material when exposed to photons, generating an electric current. Photovoltaic panels are based on two main types of silicon: monocrystalline and polycrystalline, with monocrystalline panels achieving higher efficiency (18-22%) compared to polycrystalline panels (15-17%)[44,45].

Although significant progress has been made in photovoltaic technology, numerous challenges remain related to reducing production costs and increasing energy efficiency under low sunlight conditions. Additionally, the issue of energy storage is crucial, as photovoltaic systems generate energy only when sunlight is available. The development of advanced energy storage systems, such as batteries, is essential for increasing the efficiency of photovoltaic systems and enabling their widespread application.

3.2. Solar Thermal Energy

– Applications and Benefits

Solar thermal energy uses sunlight to heat water or air. This system involves collectors that absorb solar energy and convert it into thermal energy. There are two main types of collectors: flat-plate collectors, which use black surfaces to absorb sunlight, and evacuated tube collectors, which provide better insulation and reduce heat losses.

Solar thermal systems are widely used for heating water in households, industrial processes, or for space heating. These systems are highly efficient in areas with intense solar radiation, such as Mediterranean and tropical regions. The advantages of solar thermal energy include reduced energy costs, lower greenhouse gas emissions, and contributions to sustainability, while its disadvantages include high initial installation costs and the required system size for efficient operation.

3.3. Innovations in the Solar Energy Sector

The solar energy sector continues to develop dynamically, with technological innovations playing a key role in improving efficiency, reducing costs, and expanding the application of solar systems. Some of the most important innovations include[44,46,47] :

- *Increasing the Efficiency of Solar Panels:* The development of new materials, such as perovskites, offers the potential to create panels with greater efficiency in absorbing solar energy, leading to a higher return on investment.

- *Integration of Solar Building Materials:* The increasing integration of solar panels into building materials, such as solar roofs and solar windows, enables passive energy generation, reducing the need for external installations and enhancing the energy efficiency of buildings.

- *Smart Solar Systems:* With the development of the Internet of Things (IoT) technology, solar systems are becoming smarter, allowing better monitoring and optimization of energy production and consumption. These systems can adjust panel operation depending on environmental conditions, achieving greater efficiency.

- *Energy Storage Systems:* The development of advanced battery technologies, such as lithium-ion and hydrogen batteries, is crucial for enabling the storage of surplus energy produced during sunny days for use during low sunlight conditions or at night.

- *Floating Solar Systems:* Installing solar panels on water surfaces, such as lakes or seas, is an innovation that allows for increased energy production without the need for land use. These systems provide a new opportunity for urbanized areas or regions with limited land.

Technological advancements in the solar energy sector play a crucial role in shaping the future of sustainable energy sources. Photovoltaic systems and solar thermal energy represent important alternatives to fossil fuels, and ongoing innovations in technology allow for the broader application of solar energy on a global scale. The development of new technologies, including better materials for panels, smart systems, and advanced energy storage solutions, not only increases efficiency but also reduces costs, making solar energy more accessible and environmentally friendly for the future.

4.ECONOMIC AND ENVIRONMENTAL CHALLENGES OF SOLAR ENERGY

In the context of global energy transition and increasingly evident climate change, solar energy is taking on an increasingly important role in sustainable development strategies [48,49]. Although it offers sig-

nificant potential for decarbonizing the energy sector, its implementation involves a series of economic and environmental challenges. This paper examines the key economic and environmental aspects of solar energy through three main topics: investment costs and profitability, the impact on the economy and employment, and environmental benefits.

4.1. Investment Costs and Economic Viability

One of the primary challenges in implementing solar systems relates to high initial investment costs. While the prices of photovoltaic panels have significantly decreased in recent years due to technological advancements and mass production, the costs of installation, grid integration, and energy storage systems still represent a major expense [50].

The return on investment in solar systems varies depending on geographic location, government incentives, electricity prices, and the energy usage model. Economic viability is typically assessed over a time span of 10 to 20 years, depending on the type of system and market conditions. However, in the long term, solar energy allows for substantial savings, especially in regions with high solar irradiation and rising conventional energy prices.

In many countries, regulatory and administrative requirements further slow down solar energy integration. Therefore, the role of public policy, feed-in tariffs, and subsidies is crucial to reduce financial burdens and increase accessibility to this technology for a wider population [51].

4.2. Impact of Solar Energy on the Economy and Employment

The development of the solar energy sector opens numerous opportunities for economic growth and job creation. According to the International Renewable Energy Agency (IRENA), solar energy is one of the fastest-growing segments in the global energy sector, with millions of new jobs created in the last decade.

Employment spans a broad range of activities – from equipment manufacturing and installation to system maintenance and research and development. The potential for job creation is especially significant in rural and less developed areas, where solar projects can contribute to local development and energy independence [52].

Additionally, the growth of the solar industry stimulates innovation and demand in related sectors such as construction, electronics, and smart grid systems. This increases the overall competitiveness of the economy and reduces dependence on imported fossil fuels, positively impacting national energy security.

4.3. Environmental Benefits of Solar Energy

One of the key advantages of solar energy over conventional sources lies in its minimal negative impact on the environment. The production of electricity from solar power does not generate greenhouse gas emissions during operation, significantly contributing to the reduction of CO₂ emissions and combating climate change. Furthermore, solar energy does not pollute air, soil, or water, nor does it produce hazardous waste during the operational phase. Although certain chemicals are used in the manufacturing process of solar panels, advancements in recycling technologies and the development of more eco-friendly materials help reduce the overall environmental footprint [53].

Another major benefit is the reduced dependence on fossil fuels, whose extraction and use bring serious environmental and social consequences, including resource depletion, environmental degradation, and political instability linked to energy dependence.

While solar energy brings numerous advantages, its development is not without challenges. High initial investment costs, the need for effective energy storage, and reliance on regulatory frameworks remain key obstacles. On the other hand, long-term benefits in terms of economic viability, job creation, and environmental protection highlight the importance of continued support and investment in solar technologies. A successful transition to a sustainable energy system requires coordinated efforts between the public and private sectors, along with the active engagement of citizens and local communities.

5. MEASURING THE EFFICIENCY OF SOLAR ENERGY, CHALLENGES AND THE FUTURE OF SOLAR ENERGY

5.1. Measuring the Efficiency of Solar Energy

The efficiency of solar energy has become an increasingly relevant topic within the development of energy policy and sustainable technologies. To maximize the contribution of solar systems within

energy grids, it is essential to understand how their performance is measured, how they compare to other renewable energy sources, and what lessons can be drawn from successful applications [54,55]. This paper explores key indicators of solar energy performance, compares solar power with other renewable energy sources, and presents case studies that demonstrate its potential.

5.2. Key Performance Indicators of Solar Systems

The effectiveness of solar energy systems can be evaluated using several key indicators [56,57]:

- *Installed Capacity (kW/MW)*: This refers to the total power output of a system and serves as the foundation for calculating energy production.

- *Capacity Factor*: This indicates the ratio between actual electricity production and the maximum possible output if the system operated at full capacity 24 hours a day throughout the year. For solar systems, the capacity factor typically ranges between 15% and 25%, depending on geographic location and technology used.

- *LCOE (Levelized Cost of Energy)*: This economic indicator reflects the cost of producing one kilowatt-hour of electricity over the system's lifespan. The sharp decline in the LCOE of solar power in recent years has made it increasingly competitive with fossil fuels and other renewables.

- *Energy Payback Time (EPBT)*: EPBT measures the time required for a solar system to generate the amount of energy that was consumed during its production and installation. Modern photovoltaic systems generally have an EPBT between 1 and 4 years, while their total lifespan exceeds 25 years.

5.3. Comparison of Solar Energy with Other Renewable Sources

The efficiency of solar energy can be further analyzed by comparing it with other renewable energy sources such as wind, hydropower, and biomass. Wind turbines generally have a higher capacity factor (30–50%) due to more consistent operating conditions, while hydroelectric power plants can exceed 90% efficiency under optimal conditions. However, solar energy offers advantages in scalability, decentralized production, and lower maintenance costs. In terms of LCOE, solar energy is increasingly outper-

forming fossil fuels and is often cheaper than wind energy in many regions [58,59]. Additionally, solar systems can be integrated into building infrastructure (e.g., rooftop installations), reducing land use, unlike wind farms or biomass plants that require substantial resource inputs or space.

5.4. Case Studies – Successful Solar Projects

Several successful solar projects worldwide highlight the cost-effectiveness and scalability of this technology:

- *The Noor Solar Complex in Morocco* is one of the largest concentrated solar power systems globally. By combining photovoltaic and thermal technologies, Noor supplies electricity to hundreds of thousands of households and significantly reduces CO₂ emissions.

- *The Topaz Solar Farm in California* is one of the largest photovoltaic installations in the United States, with a capacity of 550 MW. Its performance illustrates the feasibility of large-scale solar deployment on non-agricultural land.

- *Germany's "Energiewende" program* also provides numerous case studies in which decentralized solar systems integrated into residential buildings contribute to energy security and reduce grid dependency.

These examples demonstrate that with proper infrastructure and support, solar energy can serve as a central component of the energy transition.

Measuring the efficiency of solar energy is essential for understanding its long-term sustainability and competitiveness. While solar energy generally has a lower capacity factor compared to wind or hydro power, its accessibility, declining costs, and implementation flexibility make it one of the most promising energy technologies. Global case studies confirm that well-planned solar projects can meet energy needs, reduce greenhouse gas emissions, and create new economic opportunities.

5.5. Challenges and the Future of Solar Energy

Solar energy represents one of the most promising renewable energy sources of the 21st century. Thanks to steadily decreasing technology costs, improved efficiency, and increasing interest in decarbonization, solar power has the potential to become a cornerstone of the global energy transition. Nevertheless, the development and implementation of so-

lar systems still face a number of challenges, while at the same time, technological innovations offer new solutions and open the door to broader application [60-62].

5.6. Barriers to the Development and Implementation of Solar Systems

Although the technical and economic conditions for solar energy development have significantly improved in recent years, several obstacles continue to slow its widespread adoption. One of the main issues is intermittent energy production—solar systems generate electricity only when sunlight is available, necessitating complementary solutions such as energy storage or backup sources. In addition, insufficient grid infrastructure and difficulties in integrating distributed sources into energy networks pose significant challenges, especially in developing countries. Administrative and regulatory barriers further complicate the implementation of solar systems. Uncoordinated legislation, lengthy permitting processes, and a lack of financial incentives often discourage investors and private users. Moreover, limited access to capital, particularly for small and medium-sized projects, hinders progress at the local level.

5.7. Future Trends – Advanced Technologies, Energy Storage, and Decentralization

Despite these challenges, current trends in solar technology development point to a bright future. Particularly notable progress has been made in the field of advanced photovoltaic cells, such as perovskite-based materials, which offer higher efficiency and lower manufacturing costs. Hybrid systems that combine photovoltaic and solar thermal technologies are also becoming increasingly relevant for both industrial and residential applications [63-65]. Energy storage is emerging as a crucial component of the energy transition. The development of battery systems—such as lithium-ion, sodium-ion, and solid-state batteries—enables better management of production and consumption, enhancing the reliability of solar systems. Simultaneously, the promotion of production decentralization through the concept of “prosumers”—consumers who also produce energy, often via rooftop solar systems—is gaining momentum. These models support greater community resilience, reduce transmission losses, and foster energy

independence. Technological developments, along with smart grid systems and digital energy management tools, further increase the efficiency and integration of solar energy into broader energy networks.

5.8. The Role of Solar Energy in Global Energy Strategy

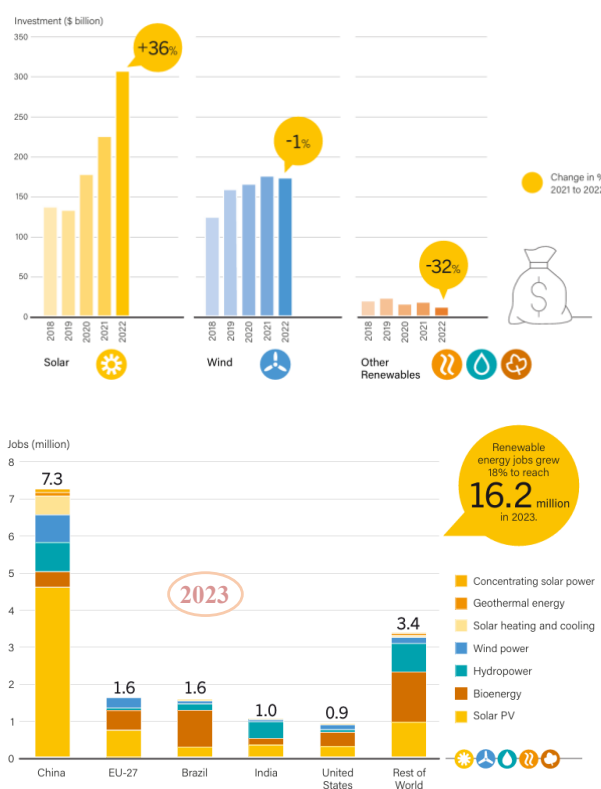
Solar energy is playing an increasingly important role in global decarbonization strategies. According to the International Energy Agency (IEA), solar energy could account for over 30% of total global electricity production by 2050, assuming continued investment and political support. Countries such as China, India, and the United States are already leading the way in implementing large-scale solar projects, while the European Union is also moving toward climate neutrality with strong support for photovoltaic technologies.

- Investment and job creation

Investments and employment in renewable energy have become key indicators of the global transition towards a low-carbon economy. The rapid expansion of renewable technologies, particularly solar and wind, has been accompanied by significant financial inflows and the creation of millions of new jobs worldwide [12,48,66].

Solar photovoltaic (PV) energy continues to dominate investments in renewable energy sources, accounting for 62% of total investments in 2022 (Figure 11), while wind energy represented 35%. Investments in solar PV grew by nearly 36% in 2022, reaching USD 307.5 billion, indicating strong and sustained sectoral growth. In contrast, investments in wind energy declined by 1.3% to USD 174.5 billion, reflecting regulatory barriers, inflationary pressures, and political uncertainty. The private sector has been the primary driver of renewable energy investments, accounting for 69% of total funding in 2020, particularly in commercially viable technologies such as solar PV. For solar PV technology, as much as 83% of financing originates from the private sector, making it attractive to investors due to its competitiveness and market sustainability.

Employment in the renewable energy sector reached a record high of 16.2 million direct and indirect jobs in 2023 (Figure 11), with solar energy leading in terms of newly created positions. Employment in the solar PV sector increased by an impressive 45%, rising from 4.9 million in 2022 to 7.1 million in



Source: See endnote 11 for this section. Source: See endnote 239 for this module

Figure 11. Trends in global investment in renewable energy and fuels during the period 2018–2022, and trends in global employment in renewable energy in 2023. [12,48,66]

2023, making it the largest employer among renewable energy technologies. China leads global solar energy employment with 7.3 million jobs, driven by strong industrial policies, developed infrastructure, and low labor costs. Asia remains the dominant region for solar PV employment, accounting for 77% in 2023, followed by Europe (10.7%) and the Americas (8.6%). Government policies and industrial strategies, such as the Inflation Reduction Act (IRA) in the United States and the European Union's Green Deal Industrial Plan, further support employment growth in the sector, including in solar energy.

Solar energy also plays a key role in reducing energy dependency and ensuring energy access in rural and remote areas, where conventional infrastructure is often lacking. As a decentralized and scalable source, solar systems can contribute to energy equity and inclusion, especially in the context of the Global South. Despite the numerous challenges in regulation, infrastructure, and storage, solar energy remains

a vital element of a sustainable future. Technological advancements, cost reductions, battery development, and support for decentralized solutions are opening new avenues for its broad implementation. Through integration into national and global energy strategies, solar energy can significantly contribute to climate change mitigation, economic development, and energy security.

6. CONCLUSION

Solar energy represents one of the key elements in the process of green transition, offering a sustainable solution to the growing energy needs of modern society. This paper has presented the main aspects of the development and application of solar energy, with a particular focus on its role in decarbonising the energy sector, reducing greenhouse gas emissions, and fostering economic growth based on renewable energy sources. Through an analysis of natural resources and global trends in solar energy use, a significant increase in the implementation of solar technologies can be observed, especially in countries that strategically develop renewables within the framework of their national climate policies. Incentives, regulatory frameworks, and international initiatives further accelerate the deployment of solar systems, thus contributing to the global goal of achieving climate neutrality. From a technological perspective, the development of photovoltaic systems and solar thermal energy enables increasingly efficient and accessible production of energy from solar radiation. Technological innovations contribute to improved efficiency, reliability, and flexibility of systems, with notable progress also evident in the integration of solar energy into existing power grids and in the advancement of energy storage solutions. The economic viability of investments in solar energy is confirmed by numerous indicators – from declining equipment costs and increasing market competitiveness to the growing number of jobs in the renewable energy sector. At the same time, the environmental benefits – such as the reduction of CO₂ emissions, environmental preservation, and decreased dependence on fossil fuel imports – make solar energy a sustainable choice not only from an energy standpoint but also from a broader societal perspective.

Measuring the efficiency of solar systems is essential for assessing their long-term sustainabil-

ity. By applying quantitative performance indicators, such as capacity, yield, and cost-effectiveness, stakeholders can make informed decisions regarding further investment and optimization of solar projects. Comparative analyses with other renewable energy sources further highlight the advantages of solar energy, particularly in regions with high solar irradiation. Despite its many advantages, the development and implementation of solar energy systems face several challenges. These include regulatory barriers, insufficient storage infrastructure, limited grid capacity, and the issue of managing waste from decommissioned photovoltaic systems. Addressing these challenges requires a comprehensive and systemic approach involving coordinated action from policymakers, industry, and the scientific community. Looking ahead, the future of solar energy lies in the development of advanced technologies – such as perovskite cells, bifacial panels, and building-integrated photovoltaics – as well as in the establishment of efficient energy storage systems that ensure a stable and continuous energy supply. Decentralisation of production and the growth of energy communities further strengthen energy independence at both individual and local levels. At the global level, solar energy plays a crucial role in achieving the objectives of the Paris Agreement and the 2030 Agenda for Sustainable Development. As the most accessible renewable source, with a wide range of applications and virtually limitless potential, solar energy forms the foundation of a new energy paradigm. Ultimately, solar energy is not only a technical solution – it is a symbol of a shift in how we produce, use, and perceive energy. Its successful integration into the energy system requires a synergy of technology, policy, economics, and social responsibility. Only through a multidisciplinary and inclusive approach can we achieve a truly sustainable future in which solar energy occupies a central role in the green transition.

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SOLARNA ENERGIJA KAO POKRETAČ ZELENE TRANZICIJE: PUT KA ODRŽIVOJ BUDUĆNOSTI

Sažetak: Solarna energija sve više dobija na značaju kao ključna komponenta održivog razvoja i tranzicije ka čistijim oblicima energije. Njena primjena doprinosi smanjenju zavisnosti od fosilnih goriva, umanjenju emisije štetnih gasova te donosi brojne ekonomske i ekološke koristi. U radu se razmatra uloga solarne energije u stvaranju zelenijeg energetskog sistema, s posebnim fokusom na tehničke, ekonomske i ekološke aspekte njene primjene. Rad započinje pregledom globalnih kapaciteta i aktuelnih trendova u korišćenju solarne energije, uz poseban naglasak na tehnološki napredak koji omogućava veću efikasnost solarnih sistema. Zatim se analiziraju finansijski aspekti, uključujući početne troškove, mogućnosti subvencionisanja i dugoročnu isplativost ulaganja u ovu tehnologiju. Ekološke prednosti solarne energije takođe su u fokusu rada, od smanjenja emisije ugljen-dioksida do očuvanja prirodnih resursa i poboljšanja kvaliteta vazduha. Jedan od ključnih elemenata rada jeste evaluacija efikasnosti solarnih sistema, budući da je precizno mjerenje neophodno za donošenje informisanih odluka o njihovoj primjeni i ekonomskoj opravdanosti. U tom kontekstu razmatraju se faktori kao što su proizvodni kapacitet, stepen efikasnosti, ekonomska održivost i poređenje s drugim obnovljivim izvorima energije. Rad se takođe bavi izazovima – prepreke vezane za infrastrukturu, finansiranje i regulatorni okvir i dalje ograničavaju širu primjenu solarne energije. Solarna energija posjeduje značajan potencijal za transformaciju energetskog sektora ka održivijem modelu. Međutim, da bi se taj potencijal u potpunosti ostvario, neophodno je nastaviti razvoj naprednih tehnologija, obezbijediti bolju integraciju solarnih sistema u postojeće mreže te unaprijediti institucionalnu i regulatornu podršku. Sistematsko ulaganje u inovacije i jačanje međunarodne saradnje mogu značajno doprinijeti globalnim naporima u borbi protiv klimatskih promjena i obezbjeđivanju energetske stabilnosti.

Ključne riječi: obnovljivi izvori energije, solarna energija, energetska efikasnost, zelena tranzicija, energetska nezavisnost.

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