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A Comparative Study of Traditional and Modern Methods for Solar Photovoltaic Integration in Buildings

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Abstract— *This research seeks to conduct a comprehensive review of previous studies on solar PV panels, types of solar PV, and solar energy systems. The primary goal is to identify and analyze basic fundamental characteristics to compare developments in photovoltaic (PV) technology from the past to the present. By synthesizing insights from existing studies, this research aims to reveal the key features that will guide the selection and implementation of new PV technology for future PV system installations. The findings highlight efficiency, cost, manufacturing processes, flexibility, environmental impact, and energy payback time as pivotal factors influencing the installation of PV systems in the future. In particular, emphasizing the significance of solar energy, these results underscore the imperative for ongoing research and innovation in solar photovoltaic technology to harness its full potential for sustainable and widespread energy solutions. In light of the study results, it is recommended to adopt environmentally friendly manufacturing processes, along with efforts to enhance the flexibility of photovoltaic systems for various applications. Furthermore, a focus on reducing environmental impact and shortening energy payback time is essential. Together, these recommendations contribute to the overarching goal of facilitating the sustainable deployment of PV systems in the future and ensuring their continuity as a large-scale, environmentally responsible energy solution.*

Keywords— *Solar energy, PV, technology, fundamental characteristics*

I. INTRODUCTION

Sustainable energy is derived from naturally replenishing sources that persistently remain abundant. Unlike traditional fossil fuels, which are known for their environmental impact and limited availability, renewable energy offers a viable and environmentally friendly alternative (Arutyunov and Lisichkin, 2017). These energy sources include solar, wind, hydro, geothermal, and biomass, each with distinct advantages and applications. The growing global consensus on the urgency of addressing climate change has accelerated the development of renewable energy infrastructure (Gielen et al., 2019). Governments, businesses, and researchers around the world are increasingly investing in technologies that harness the power of nature to generate electricity (Marcus et al., 2013). This underscores the pivotal role of renewable energy in transitioning towards a more resilient and environmentally conscious energy landscape (Marcus et al., 2013; Arutyunov and Lisichkin, 2017; Gielen et al., 2019).

Solar energy stands out among the diverse range of renewable sources due to its abundance and universal accessibility (Giwa et al., 2017). The utilization of solar energy is not a recent development, as human societies have tapped into the sun's power for centuries. In recent times, significant technological advancements, particularly in Solar Photovoltaic (PV) Panels, have propelled solar energy into mainstream acceptance (Dada and Popoola, 2023). These panels, constructed with semiconductor materials, facilitate the direct conversion of sunlight into electricity through the photovoltaic effect a groundbreaking innovation that is reshaping the landscape of energy production (Dada and Popoola, 2023). To harness the sun's radiance as a reliable power source, solar energy is integrated into sophisticated systems referred to as solar power systems (Singh, 2013). These intricately designed systems are engineered to capture, convert, and distribute solar energy, playing a pivotal role in unlocking the full potential of sunlight as a renewable resource.

In general, the solar power system comprises key components including solar panels, inverters, batteries, and a variety of control and monitoring devices (Aghaei et al., 2020). Solar panels, frequently situated on rooftops or in solar farms, act as the workhorses of solar power systems (Breyer et al., 2021). Through the photovoltaic process, these panels transform sunlight into direct current (DC) electricity. Inverters then convert this DC electricity into alternating current (AC), the standard form of electricity used in homes and businesses. The integration of batteries facilitates the storage of excess energy generated during peak sunlight hours, ensuring a reliable power supply even when the sun is not actively shining. Control and monitoring devices, such as charge controllers and energy meters, play a crucial role in the efficient operation and maintenance of the solar power system. Furthermore, the technological advances have further led to the development of smart grid solutions, enhancing the seamless integration of solar energy into existing power infrastructures and enabling better management and distribution of electricity.

Based on the above, the objective of this research is to conduct a comprehensive review of prior studies focused on Solar Photovoltaic Panels, Solar Photovoltaic Types, and Solar Energy Systems. The aim is to identify and analyze the key characteristics crucial for comparing advancements in PV technology from the past to the present. By synthesizing insights from existing studies, this investigation seeks to unveil essential features that will inform the selection and implementation of new Photovoltaic (PV) technology for future PV system installations.

II. METHODOLOGY

The current study adopts a comprehensive approach to comprehend and compare historical and contemporary solar photovoltaic (PV) technologies. The methodology encompasses distinct steps, as illustrated in Figure 1, facilitating a structured and systematic exploration of the subject.

2.1 History of Solar Photovoltaic Panels

The evolution of solar Photovoltaic (PV) is a fascinating journey spanning many decades, shaped by scientific breakthroughs, technological advances, and the growing global necessity for sustainable energy solutions. Generally, starting with emerging experiments with selenium in the 19th century, the narrative moves seamlessly to the contemporary era characterized by the deployment of highly efficient silicon solar cells. This historical exploration meticulously delves into the important milestones, policy impacts, and technological innovations that collectively elevated solar power to prominence in the global energy landscape. The complex interplay of these factors not only recapitulates the evolutionary arc of solar PV but also underscores their transformative impact on the way societies generate and consume energy. The evolution of solar PV panels from their early beginnings to the present day is discussed below (Murphy, 2017; Kaushika et al., 2018; Bosio et al., 2020; Oktik, 2022, Marques Lameirinhas et al., 2022; Surf Clean Energy Inc, 2023; Fraas and O'Neill, 2023) and illustrated in Figure 2.

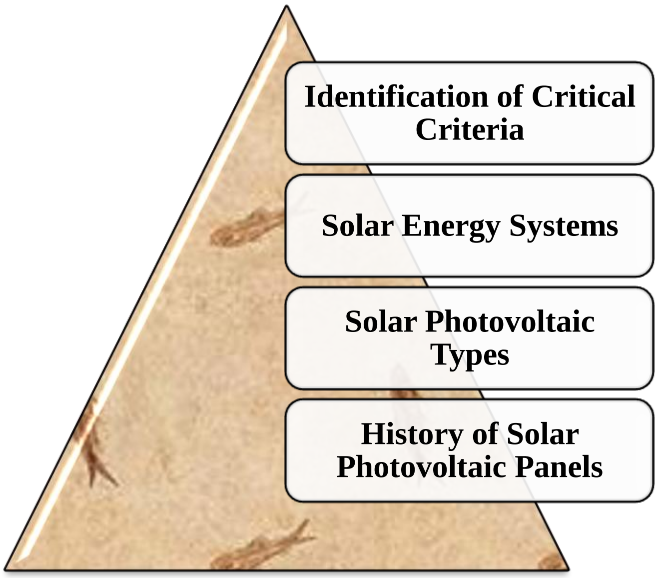


Figure 1. Methodology encompasses distinct steps

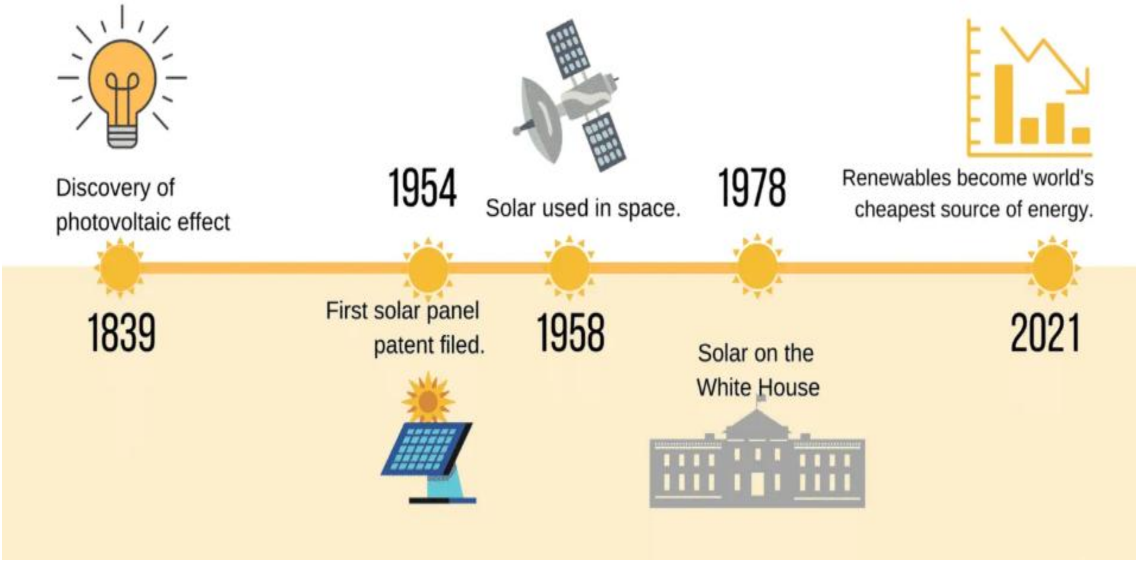


Figure 2. A brief history of solar energy (Zagame et al., 2023)

a). Early Developments (19th Century - 1950s)

The roots of solar PV technology trace back to 1839 when French physicist Alexandre Edmond Becquerel discovered the PV effect. This occurrence, in which specific substances produce an electric current upon exposure to light, established the groundwork for the utilization of solar energy. However, it wasn't until the 1880s that selenium, a semiconductor, was first used to create solar cells. Additionally, the 1950s represented a critical time with the development of the initial functional PV cell at Bell Labs. Physicists Gerald Pearson, Calvin Fuller, and Daryl Chapin developed a silicon-based solar cell that achieved 6% energy conversion efficiency. This breakthrough paved the way for the modern era of solar PV.

b). Space Race and Satellites (1960s)

As the Space Race unfolded in the 1960s, solar panels found a crucial application in space exploration. Vanguard 1, launched in 1958, became the first artificial satellite to use solar power, demonstrating the reliability of solar cells in the harsh conditions of outer space. Subsequent missions, including the 1962 Telstar communications satellite, solidified the role of solar panels in powering satellites and space probes. Furthermore, the demand for robust and sustainable power sources in space accelerated the integration of solar panels into various satellite missions, showcasing their adaptability and reliability beyond Earth's atmosphere.

c). Oil Crisis and Early Commercialization (1970s)

The oil crisis of the 1970s prompted a global shift in focus towards alternative energy sources, including solar power. Governments and research institutions invested heavily in solar research and development during this period. While solar technology was still in its infancy, the decreasing cost of manufacturing solar cells began making them more accessible for certain applications. Additionally, the oil crisis acted as a catalyst for early commercialization efforts, with businesses and consumers seeking alternatives to traditional energy sources. The growing awareness of environmental concerns further fueled the momentum behind solar energy as a viable and sustainable solution.

d). Incentives and Policies (1980s - 1990s)

The 1980s and 1990s saw the implementation of regulations and incentives designed to encourage the uptake of solar energy. Countries like Germany and Japan implemented feed-in tariffs and financial incentives, encouraging the installation of solar panels. These policies played a pivotal role in fostering the growth of the solar industry, making solar energy more economically viable for consumers and businesses alike. Moreover, the emergence of supportive policies provided a crucial framework for the expansion of solar power, creating a favorable environment for investment, research, and widespread adoption.

e). Technological Advancements (2000s)

The 2000s marked a period of significant technological advancements in solar PV. Researchers focused on enhancing the efficiency of solar cells, exploring new materials, and developing innovative manufacturing processes. Thin-film solar cells, using thinner semiconductor layers than traditional silicon cells, emerged as a promising alternative, offering flexibility and lower production costs. Furthermore, this era witnessed the mainstreaming of large-scale solar installations and the integration of grid-connected solar power plants into various energy systems. Innovations like concentrating solar power (CSP) systems gained attention as complementary technologies, diversifying the solar energy landscape.

f). Solar Boom and Global Expansion (2010s)

The 2010s witnessed an unprecedented boom in solar energy installations globally. The decreasing costs of solar panels, coupled with increased efficiency and growing environmental awareness, contributed to a surge in demand. China emerged as a dominant player in the solar industry, becoming the world's largest producer and consumer of solar panels. Moreover, advancements in energy storage technologies, particularly lithium-ion batteries, complemented solar PV by addressing the intermittent nature of solar power. This synergy led to the development of more reliable and flexible solar-plus-storage systems, enabling the integration of solar energy into mainstream electricity grids.

g). Grid Parity and Beyond (2020s)

In recent years, solar energy has achieved grid parity in many regions worldwide, signifying that the cost of electricity generated from solar panels is comparable to or lower than traditional sources. This milestone has accelerated the global adoption of solar power, with an increasing number of countries setting ambitious renewable energy targets. Furthermore, technological innovation has not slowed down in the 2020s. Advancements in solar panel design and manufacturing techniques, including tandem solar cells and transparent solar panels integrated into windows and building materials, showcase the potential for seamlessly integrating solar power into urban environments. These developments promise to reshape the future of solar PV, making them an integral part of sustainable energy solutions.

2.2 Solar Photovoltaic Types

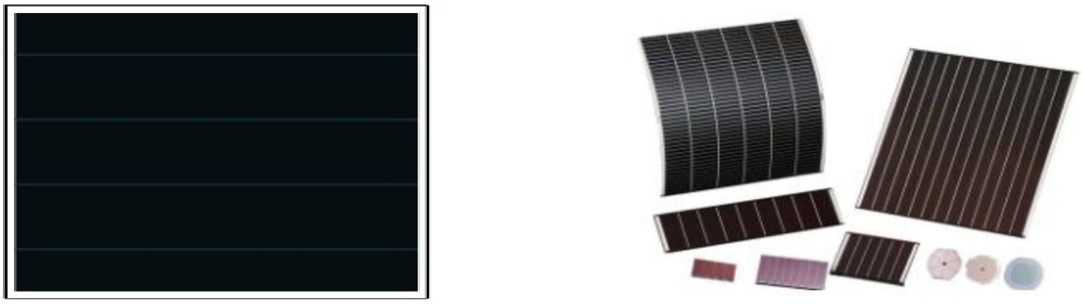
The development of solar PV panels has been characterized by constant innovation, resulting in different types of panels designed to improve efficiency, durability, and cost-effectiveness. The major solar PV panel types from the past to the present are reviewed below and presented in Figure 3.

a). Monocrystalline Silicon Solar Panels

According to Glunz et al., (2012), the history monocrystalline silicon solar panels spans from their emergence in the 1950s to their current status as a dominant force in the solar market. Monocrystalline silicon panels are made from a single crystal structure, which allows for a more uniform and efficient flow of electrons (Raabe ET AL., 2007). The silicon used in these panels is highly purified, resulting in a high-grade and high-efficiency solar cell (Raabe ET AL., 2007). Moreover, Monocrystalline solar panels are among the most efficient types of solar panels available (Dhilipan et al., 2022). They typically have efficiency rates ranging from 15% to 24%. Besides, they were more expensive to produce than polycrystalline panels (Ameur et al., 2021). However, advancements in manufacturing processes have narrowed the cost difference in recent years (Ameur et al., 2021).

Additionally, Monocrystalline panels tend to be more space-efficient compared to other types, such as polycrystalline according to Islam (2015). Also, they generally perform better in high-temperature conditions compared to some other types (Sawle and Thirunavukkarasu, 2021). This may be a significant element in areas with warm climates (Baghel and Chander, 2022). Furthermore, they are used in various applications, including residential rooftop installations, commercial and industrial buildings, and large-scale solar farms.


(a) Monocrystalline Silicon Solar Panels (b) Polycrystalline Silicon Solar Panels


(c) Thin-Film Solar Panels (d) Amorphous Silicon (a-Si) Solar Panels


(e) Cadmium Telluride (CdTe) Solar Panels (f) Copper Indium Gallium Selenide (CIGS) Solar Panels


(g) Bifacial Solar Panels

Figure 3. Solar PV panels

b). Polycrystalline Silicon Solar Panels

Polycrystalline silicon solar panels, also known as multicrystalline silicon solar panels, are another common type of photovoltaic (PV) solar panel. They are made from multiple silicon crystals, making the manufacturing process less expensive (Qazi, 2017; Sistine Solar, 2023). Polycrystalline solar panels typically have lower efficiency rates compared to monocrystalline panels (Nogueira et al., 2015; Mirzaei and Mohiabadi, 2017; Ameur et al., 2021), ranging from 13% to 20% (Ameur et al., 2021). Additionally, they are generally less space-efficient than monocrystalline panels, meaning they may require more space to generate the same amount of electricity (Jude, 2023). Besides, Polycrystalline solar panels are often more cost-effective to produce than monocrystalline panels (Goodrich et al., 2013; Rabczak and Proszak-Miąsik, 2020). Furthermore, they may be slightly less efficient than monocrystalline panels in high-temperature conditions (Hossain and Rehan, 2016; Ogbomo et al., 2017). Generally, they are widely used in various applications, including residential, commercial, and industrial installations. Also, they have a long lifespan and can last 25 years or more with proper maintenance.

c). Thin-Film Solar Panels

Thin-film solar panels are a type of photovoltaic (PV) solar panel that differs in construction and materials from traditional crystalline silicon panel (Green, 2003; ENERGY5, 2023). They utilize various semiconductor materials like amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) to convert sunlight into electricity (Lee and Ebong, 2017). Additionally, they generally have lower efficiency compared to crystalline silicon panels (Zendehdel et al., 2020; Energy5, 2023). Efficiency rates typically range from 10% to 12% (Energy5, 2023). However, their lower efficiency and concerns about certain materials, such as cadmium, have limited their widespread adoption in some markets. Moreover, they are often more cost-effective to produce than crystalline silicon panels (Lozanova, 2023; Manufacturer, 2023). Thin-film solar panels are more flexible than crystalline silicon panels (Li et al., 2021; Kim et al., 2021). This flexibility allows for unique applications, such as integrating solar cells into flexible and curved surfaces (Li et al., 2021; Kim et al., 2021). According to Zendehdel et al., (2020), thin-film panels are lightweight and can be easier to install than traditional solar panels. In addition, they can be integrated into building materials, making them suitable for building-integrated PV (BIPV) (Jelle et al., 2012; Sorgato et al., 2018) and other innovative installations. Thin-film panels may have better temperature performance compared to crystalline silicon panels (Maalouf et al., 2023). They often perform well in high-temperature conditions and may have a more stable efficiency across a wider temperature range (Manufacturer, 2023).

d). Amorphous Silicon (a-Si) Solar Panels

Amorphous Silicon (a-Si) solar panels represent a thin-film technology that diverges from the crystalline structure seen in traditional solar panels (Matsui et al., 2018). The characteristic feature of amorphous silicon lies in its disordered and non-crystalline atomic arrangement (Bayod-Rújula, 2019). This characteristic places it within the thin-film category, offering unique properties that cater to specific solar energy applications. One notable aspect of a-Si panels is their lower efficiency when compared to crystalline silicon counterparts (Dixon, 1981). However, these panels exhibit a higher tolerance to low-light conditions and indirect sunlight (Venkateswararao et al., 2020). This makes them suitable for installations in areas with less consistent sunlight or for applications where low-light performance is crucial (Venkateswararao et al., 2020). While amorphous silicon panels are less space-efficient than crystalline silicon panels, their flexibility is a standout feature (David and Addison, 2023). The non-crystalline structure allows these panels to be flexible, making them ideal for installations on irregular or curved surfaces (David and Addison, 2023). This flexibility opens up creative possibilities, enabling the integration of solar cells into unconventional environments (David and Addison, 2023). Furthermore, amorphous silicon technology is often more cost-effective to produce than crystalline silicon panels (Ballif et al., 2022; Jaiswal et al., 2022). The manufacturing process is simpler, and the material requirements are lower, contributing to reduced production costs (Ballif et al., 2022; Jaiswal et al., 2022). This cost-effectiveness enhances the appeal of a-Si panels, especially in scenarios where budget considerations play a significant role. Moreover, a-Si panels generally exhibit good temperature performance, making them suitable for deployment in a wide range of climates.

e). Cadmium Telluride (CdTe) Solar Panels

Cadmium Telluride (CdTe) solar panels are a type of thin-film solar technology that utilizes cadmium telluride as the semiconductor material. CdTe solar panels are made of a thin film of cadmium telluride, a compound of cadmium and tellurium (Scarpulla et al., 2023). This compound is deposited on a substrate, typically glass. The thin-film nature distinguishes CdTe panels from crystalline silicon panels (Scarpulla et al., 2023). Moreover, CdTe solar panels have achieved higher efficiencies over the years and are now among the most efficient thin-film solar technologies (Romeo and Artegiani, 2021; Scarpulla et al., 2023). Current CdTe panels have efficiencies ranging from 14% to 22%, making them competitive with some types of crystalline silicon panels (Curtin et al., 2020; Scarpulla et al., 2023). One of the notable advantages of CdTe solar panels is their cost-effectiveness (Rahman and Al Ahmed, 2021). The manufacturing process for CdTe panels is relatively simple, and the materials used are abundant and inexpensive. Furthermore, CdTe panels are generally less space-efficient than some crystalline silicon panels but more space-efficient than other thin-film technologies (Farji, 2021). Additionally, they are lightweight, which can be advantageous in certain applications and reduces the structural load on mounting systems (Scarpulla et al., 2023). Moreover, CdTe solar panels exhibit good temperature performance, maintaining efficiency even in high-temperature conditions (Romeo et al., 2018). Based on the previous studies, CdTe solar panels are commonly used in utility-scale solar projects due to their cost-effectiveness and improving efficiency. They are also suitable for large commercial and industrial installations. While not as flexible as some other thin-film technologies, they can be integrated into various settings, including ground-mounted arrays and building-integrated BIPV.

f). Copper Indium Gallium Selenide (CIGS) Solar Panels

Copper Indium Gallium Selenide (CIGS) solar panels are another type of thin-film solar technology that utilizes a compound of copper, indium, gallium, and selenium as the semiconductor material (Farooq et al., 2021). The combination of these elements forms a compound with favorable photovoltaic properties. Similar to other thin-film technologies, CIGS panels are deposited on a substrate, often flexible materials like stainless steel, plastic, or glass. CIGS solar panels offer relatively high efficiencies for thin-film technology (Powalla et al., 2018). One notable advantage of CIGS solar panels is their flexibility (Ramanujam et al., 2020). They can be manufactured on flexible substrates, allowing for bendable and lightweight solar modules (Ramanujam et al., 2020). This flexibility makes CIGS panels suitable for various applications, including building-integrated BIPV and portable solar devices. Additionally, CIGS panels are considered cost-competitive within the thin-film solar market (Wang et al., 2021). The manufacturing process involves deposition techniques, such as co-evaporation or sputtering, which can be more complex than some other thin-film technologies but still offer advantages in terms of material utilization and cost-effectiveness. While CIGS panels are generally more space-efficient than some thin-film technologies, they may still require more space than high-efficiency crystalline silicon panels (Rahman and Das, 2022). Also, the flexibility and versatility of CIGS, however, can offset space considerations in certain installations. Besides, CIGS solar panels typically exhibit good temperature performance, maintaining efficiency even in high-temperature conditions (Lin and Ravindra, 2020). This attribute makes them suitable for deployment in regions with warm climates.

g). Bifacial Solar Panels

Bifacial solar panels are a type of photovoltaic (PV) module designed to capture sunlight on both the front and rear sides (Appelbaum, 2016). Unlike traditional solar panels that generate electricity solely from the sunlight hitting the front surface, bifacial panels utilize reflected sunlight from surfaces such as the ground, nearby structures, or snow (Guerrero-Lemus et al., 2016). Furthermore, they have solar cells on both the front and rear sides, allowing them to capture sunlight that is reflected from surrounding surfaces (Hasan and Dincer, 2020). This additional exposure to sunlight can increase the overall energy yield of the panels (Hasan and Dincer, 2020). Moreover, the albedo effect refers to the reflection of sunlight from surfaces such as snow, sand, or other nearby structures. Bifacial panels take advantage of the albedo effect by capturing the reflected sunlight, increasing their efficiency (Guerrero-Lemus et al., 2016). The albedo effect is particularly beneficial in areas with high reflectivity. Besides, the ability to capture sunlight from both sides can result in a higher energy yield compared to traditional monofacial solar panels. Estimates suggest that the energy gain from bifacial panels can range from 5% to 30%, depending on factors such as albedo, tilt, and ground cover (Patel et al., 2019; Khan et al., 2019). Additionally, bifacial solar panels are typically installed on elevated structures, such as ground-mounted systems with a reflective surface underneath (Ernst et al., 2024). The reflected sunlight needs to reach the rear side of the panels to maximize their efficiency (Ernst et al., 2024). The choice of ground cover and panel tilt can influence the performance of bifacial installations. Generally, bifacial technology is available in various solar cell types, including monocrystalline, polycrystalline, and thin-film (Guerrero-Lemus et al., 2016). The choice of solar cell technology can impact factors such as efficiency and cost. In addition, bifacial solar panels have environmental benefits by generating more electricity with the same amount of installed capacity. This can contribute to a reduction in greenhouse gas emissions and reliance on non-renewable energy sources.

2.3 Solar energy systems

Solar energy is considered one of the most appealing renewable energy sources due to its abundance, versatility, and minimal environmental impact on land use. This form of energy is harnessed directly from the sun, which emits an immense amount of energy onto the Earth's surface daily. The generation of electricity from solar energy can be achieved using solar PV systems or concentrating solar-thermal power (CSP) systems, which drive conventional turbines as shown in Figure 4. These technologies offer various methods to harness solar power, contributing to the growing interest in solar energy as a sustainable and environmentally friendly energy source. Moreover, the advantages and disadvantages of solar energy are summarized by El Hammoumi et al. (2022). According to El Hammoumi et al. (2022), solar energy systems offer numerous advantages, making them an increasingly attractive option for sustainable power generation. Firstly, they harness a free and abundant energy source the sun. This translates to clean and green energy production, with no harmful greenhouse gas emissions during electricity generation. The environmental impact is minimal, aligning with eco-friendly practices. Solar energy systems operate silently, making them ideal for urban areas and residential applications, where noiseless energy production is crucial. Furthermore, they incur low operation and maintenance costs, making them a cost-effective solution compared to other renewable energy systems. Additionally, the decentralized nature of solar energy generation allows for installations closer to consumers, enhancing accessibility. Despite their numerous advantages, solar energy systems come with certain drawbacks. The initial cost of installation is relatively high, posing a barrier to widespread adoption. Additionally, these systems require a relatively large installation area, which might be challenging in some settings. The efficiency of solar panels, though improving, and remains lower compared to certain other renewable energy systems. Furthermore, solar energy systems are highly dependent on technological advancements, which could influence their long-term viability. Geographical conditions, such as sunlight availability, play a crucial role, making the effectiveness of these systems location-dependent. As technology evolves, addressing these disadvantages becomes pivotal for maximizing the potential of solar energy.

Moreover, the integration of photovoltaic (PV) systems into the global energy landscape is a critical step toward achieving sustainable and resilient power generation. PV systems, categorized by their connection types, play a pivotal role in addressing diverse energy needs and circumstances. This thesis explores and analyzes three prominent PV system connection types: Standalone PV systems (with and without batteries), Hybrid PV systems, and Grid-Connecting PV systems (including Bimodal and Directly Connected configurations). Each connection type presents unique advantages and challenges, contributing to the broader discourse on the efficient deployment of solar energy technologies. Figure 5 depicts the various primary solar PV systems, highlighting the diversity in solar photovoltaic technologies.

Figure 4. Type of solar energy systems (Stauffer, 2020; SolarPACES, 2023)

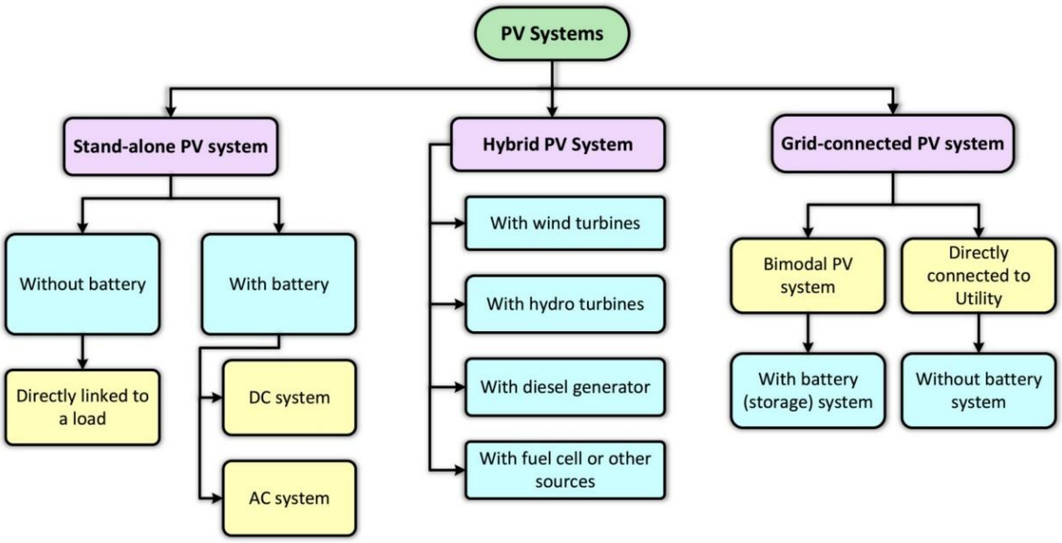


Figure 5. PV systems connection type (El Hammoumi et al., 2022)

a). Standalone PV Systems

Standalone PV systems serve as an indispensable solution in regions where a traditional grid connection is either unavailable or impractical. The fundamental premise of standalone systems is their ability to operate autonomously, converting sunlight into electricity directly. The versatility of this connection type is evident in its two distinct variations. The first variant incorporates a battery storage system, allowing the

PV system to store excess energy during periods of high sunlight and utilize it when sunlight availability is limited. This configuration provides a sustainable power source, mitigating the intermittency associated with solar energy generation. On the other hand, the standalone PV system without a battery component relies solely on real-time electricity generation and consumption. While this setup eliminates the need for energy storage, it requires careful synchronization of energy demand with sunlight availability.

b). Hybrid PV Systems

Hybrid PV systems represent a fusion of renewable energy sources, combining the benefits of solar energy with other technologies such as wind turbines or backup generators. This integration aims to address the intermittent nature of solar power, ensuring a more consistent and reliable energy supply. The hybrid approach leverages the complementary strengths of different renewable sources, optimizing energy generation based on environmental conditions. Hybrid PV systems are particularly valuable in scenarios where solar energy alone may not provide a continuous power supply. By diversifying the energy mix, these systems enhance resilience, reduce dependency on a single energy source, and contribute to a more stable and sustainable energy infrastructure.

c). Grid-Connecting PV Systems

Grid-connectivity represents a pivotal paradigm shift in the deployment of PV systems, enabling a dynamic relationship between individual installations and the broader electricity grid. Two primary configurations within this category are the Bimodal PV system and the Directly Connected PV system. The Bimodal PV system offers the advantages of grid connectivity alongside the flexibility of energy storage. By incorporating a battery component, this configuration allows users to store surplus energy during periods of abundant sunlight and draw power from the grid when needed. This duality enhances energy resilience and self-sufficiency, making it an appealing option for both residential and commercial applications. Conversely, the Directly Connected PV system dispenses with an intermediary battery, directly feeding excess energy into the utility grid. This setup facilitates a seamless two-way flow of electricity, empowering users to contribute to the grid during periods of surplus energy production and draw power from the grid when solar generation is insufficient. The Directly Connected PV system holds significance in its ability to participate actively in larger energy networks.

Furthermore, the integration of solar photovoltaic (PV) systems into the global energy landscape is a critical aspect of transitioning toward sustainable power generation. Also, exploring the expansive domains of solar energy deployment underscores the importance of comprehending the connection types of photovoltaic (PV) systems. Moreover, the main five distinct solar PV installations: rooftop, ground/land mounted, canal top, offshore, and floating as shown in Figure 6.

a). Rooftop PV Systems

Rooftop PV systems represent a ubiquitous and increasingly popular form of solar energy integration. The fundamental principle involves the installation of solar panels on the rooftops of residential, commercial, or industrial buildings. The advantages of this connection type are manifold. Rooftop installations maximize the use of existing structures, minimizing the demand for additional land. This proves particularly valuable in densely populated urban areas where land availability is limited. Rooftop PV systems contribute to decentralized power generation, enabling energy self-sufficiency at the point of consumption. However, challenges such as varying rooftop orientations and limited space for optimal panel alignment need to be considered for efficient energy production.

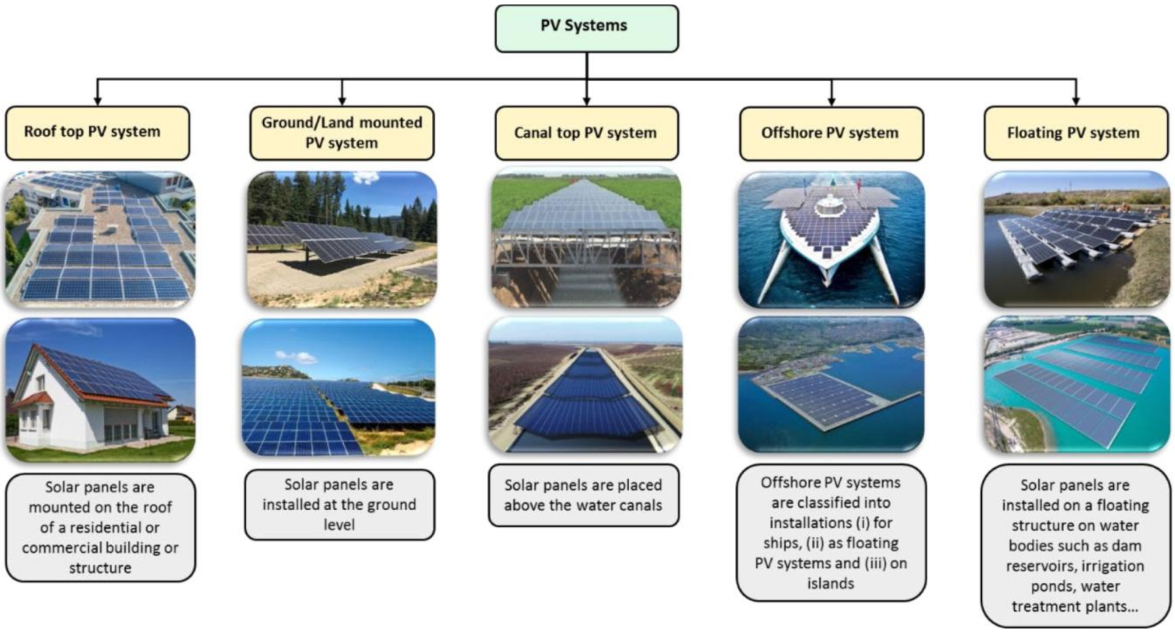


Figure 6. Types of solar PV installations (El Hammoumi et al., 2022)

b). Ground/Land Mounted PV Systems

In contrast to rooftop installations, ground-mounted PV systems are strategically positioned on open land, often in the form of utility-scale solar farms. These installations offer scalability, catering to the demand for large-scale energy generation. The benefits of ground-mounted systems include easy accessibility for maintenance, optimal alignment for sunlight exposure, and the potential for centralized energy production. However, the use of substantial land areas and potential land use conflicts pose challenges, necessitating careful planning and consideration of environmental impacts.

c). Canal Top PV Systems

Canal top PV systems present an innovative integration of solar power generation with water management infrastructure. By installing solar panels above water canals, this connection type serves a dual purpose. It maximizes land use efficiency, making productive use of otherwise underutilized spaces, while simultaneously reducing water evaporation from the canals. The advantages extend beyond energy generation, addressing water conservation concerns. However, canal top PV systems require careful engineering considerations to ensure the compatibility of solar infrastructure with water management requirements.

d). Offshore PV Systems

Offshore PV systems mark a departure from land-based installations, venturing into bodies of water, including lakes, reservoirs, or seas. This configuration addresses land constraints and explores the potential for higher efficiency facilitated by the cooling effect from water. Offshore installations present an intriguing opportunity to integrate renewable energy production with water resources. However, challenges such as offshore infrastructure development, environmental impact assessments, and the resilience of equipment in marine environments must be carefully navigated.

e). Floating PV Systems

Floating PV systems take the concept of water-based solar installations a step further by deploying solar panels on floating structures in water bodies. These installations offer a unique solution for regions with limited land availability but abundant water resources. Floating PV systems provide advantages such as land use optimization, reduced water evaporation, and the potential for renewable energy generation in water-rich areas. However, considerations regarding the stability and environmental impact of floating structures must be thoroughly addressed.

III. RESULTS

Comparing traditional solar panels with newer solar technologies involves evaluating several critical criteria. This comparison is essential for understanding the strengths, weaknesses, and advancements of different solar technologies. By considering factors such as efficiency, cost, manufacturing processes, flexibility, environmental impact, and energy payback time, stakeholders can make informed decisions tailored to the specific requirements and priorities of their projects. This comparative analysis contributes to the evolution of the solar energy landscape, encouraging technological innovation, reducing environmental footprints, and advancing the overall sustainability of solar power generation. Based on the previous scientific studies (Tsoutsos et al., 2005; Peng et al., 2013; Singh et al., 2013; Pandey et al., 2016; Ludin et al., 2018; Ahmadi et al., 2018; Abreu et al., 2019; Nayak et al., 2019; Oudes and Stremke, 2021; Bączkiewicz et al., 2021; Isabela et al., 2021; Kant and Singh, 2022; Kumari et al., 2022; Dhilipan et al., 2022; Pinho Correia Valério Bernardo et al., 2023), Table 1 outlines the essential criteria associated with the comparison of traditional solar panels and emerging solar technologies.

Table 1. Comparative analysis of traditional solar panels and new solar technologies

Criteria#1: Efficiency		
Type	*Value [%]*	*Commercial production*
Monocrystalline solar panel	15-22	1950s-Present
Polycrystalline panel	13-18	1980s-Present
Amorphous Silicon	10-12	1970s-Present
Cadmium Telluride	10-12	2000-Present
Copper Indium Gallium Selenide	10-12	2000-Present
Bifacial Solar Panel	10-22	2016-Present
Criteria#2: Cost-Effectiveness		
Type	*Value [USD/kWh]*	
Monocrystalline solar panel	1.00-1.50	
Polycrystalline panel	0.90-1.30	
Amorphous Silicon	0.80-1.20	
Cadmium Telluride	0.70-1.10	
Copper Indium Gallium Selenide	0.90-1.30	
Bifacial Solar Panel	1.10-1.60	
Criteria#3: Energy Payback Time		
Type	*Value [Year]*	
Monocrystalline solar panel	1-2	
Polycrystalline panel	1.5-2.5	
Amorphous Silicon	1-2	
Cadmium Telluride	< 1	

Copper Indium Gallium Selenide	> 1
Bifacial Solar Panel	< 1
Criteria#4: Environmental Impact	
Monocrystalline solar panel	• High energy consumption during the manufacturing process due to the need for high-purity silicon. • Silicon production involves significant energy use and emissions.
Polycrystalline panel	• High energy consumption during the manufacturing process due to the need for high-purity silicon. • Silicon production involves significant energy use and emissions.
Amorphous Silicon	• Lower energy consumption during manufacturing compared to crystalline silicon panels. • Less material usage and lower emissions.
Cadmium Telluride	• Lower energy consumption and fewer raw materials compared to crystalline silicon panels. • Cadmium is a toxic material, and its use in CdTe panels raises concerns about environmental impact and recycling
Copper Indium Gallium Selenide	• CIGS panels generally have a lower environmental impact compared to traditional silicon panels. • The use of non-toxic materials and lower energy consumption during manufacturing contribute to their eco-friendliness
Bifacial Solar Panel	• Bifacial panels share environmental considerations common to traditional solar panels, but with added advantages in terms of enhanced energy production. • The inclusion of glass on both sides may influence the recyclability of these panels.
Criteria#5: Flexibility and Design	
Monocrystalline solar panel	• Flexibility: They are typically rigid and less flexible compared to some thin-film technologies. • Design: They are well-suited for standard applications on rooftops or ground-mounted arrays due to their rigidity.
Polycrystalline panel	• Flexibility: Similar to monocrystalline panel, they are rigid and less flexible. • Design: They are commonly used in traditional solar installations on rooftops or ground-mounted arrays.
Amorphous Silicon	• Flexibility: They are more flexible than crystalline silicon panel, allowing integration into unconventional surfaces. • Design: They are suitable for building-integrated photovoltaic (BIPV)
Cadmium Telluride	• Flexibility: They are typically rigid but can be designed with some flexibility. • Design: They are commonly used in large utility-scale installations on fixed-tilt or tracking systems.
Copper Indium Gallium Selenide	• Flexibility: CIGS panels are known for their flexibility and can be integrated into various surfaces. • Design: Suitable for applications where a flexible and lightweight design is desirable, such as portable solar chargers or flexible roofing materials.
Bifacial Solar Panel	• Flexibility: Bifacial panels are generally rigid like traditional solar panels. • Design: They are designed to capture sunlight from the front and rear sides, enhancing energy production.
Criteria#6: Installation	
Monocrystalline solar panel	It can be installed using fixed-tilt or tracking mounting systems on rooftops or ground-mounted arrays.
Polycrystalline panel	It can be installed using fixed-tilt or tracking mounting systems on rooftops or ground-mounted arrays
Amorphous Silicon	It can be Integrated into building materials, making them suitable for building-integrated photovoltaic (BIPV)
Cadmium Telluride	It can be used in large utility-scale installations due to their cost-effectiveness and installed using fixed-tilt or tracking systems, depending on the project requirements
Copper Indium Gallium Selenide	It can be used in applications where flexibility and lightweight characteristics are essential. Also, it can be integrated into various surfaces and are suitable for both residential and commercial installations.
Bifacial Solar Panel	It can be installed using mounting systems that allow sunlight to reach both the front and rear sides. Also, ground-mounted installations with reflective surfaces or elevated structures can enhance energy yield.

IV. DISCUSSION AND CONCLUSIONS

Solar PV power, harnessing energy from the sun through Photovoltaic (PV) technologies, has emerged as a transformative force in the energy landscape. PV technologies, particularly solar panels, convert sunlight directly into electricity, offering a sustainable and renewable energy source. The efficiency and cost-effectiveness of PV systems have significantly improved over time, making solar PV power increasingly viable for widespread adoption. Ongoing research and development continue to advance PV technologies, enhancing their flexibility and environmental sustainability. As an essential contributor in the renewable energy field, solar PV power significantly aids in combating climate change and fostering a more sustainable energy future.

This research aims to comprehensively review prior studies on solar PV panels, different types of solar PV, and solar energy systems. The primary goal is to identify and analyze fundamental characteristics essential for comparing developments in photovoltaic (PV) technology from the past to the present. By synthesizing insights from existing studies, this research seeks to reveal key features that will guide the selection and implementation of new PV technology for future installations. The findings highlight efficiency, cost, manufacturing processes, flexibility, environmental impact, and energy payback time as pivotal factors influencing the installation of PV systems in the future. Particularly emphasizing the significance of solar energy, these results underscore the imperative for ongoing research and innovation in solar photovoltaic technology to harness its full potential for sustainable and widespread energy solutions. In light of the study results, it is recommended to adopt environmentally friendly manufacturing processes and enhance the flexibility of photovoltaic systems for various applications. Additionally, reducing environmental impact and shortening energy payback time are crucial focuses. It is essential to acknowledge the transformative role of solar PV power and evolving PV technologies in revolutionizing the energy landscape. Recognizing the dynamic nature of PV technologies, continuous research and development efforts are encouraged to stay at the forefront of advancements. Furthermore, it is imperative to emphasize the importance of establishing comprehensive criteria for selecting PV panels in the future, ensuring their optimal performance and efficiency in adapting to evolving energy demands. Together, these recommendations contribute to the overarching goal of facilitating the sustainable deployment of PV systems, securing their continued role as a large-scale, environmentally responsible energy solution.

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