



RECENT ADVANCES IN PHOTOVOLTAIC APPLICATIONS FOR ENERGY SUSTAINABILITY

***Ugwuanyi Sabastine Emeka**

Department Of Science Laboratory Technology, Physics Option, School Of Science And Technology, Federal Polytechnic Ohodo, Enugu State. [*sabrophysics2@gmail.com](mailto:sabrophysics2@gmail.com)

Abstract

Solar energy technology, particularly photovoltaics (PV), has experienced significant advancements over the past three decades. While photovoltaic technologies have achieved notable maturity in terms of materials, efficiency, cost, and production, various application domains continue to evolve. This review explores recent progress in PV applications across several less-reviewed areas, including transportation, domestic uses, street lighting, and water-related applications. Each domain's sub-applications and the potential future developments are highlighted. Advances include integrating smart controls to optimize energy use based on solar availability and building demand. Indoor PV applications involve using solar energy to power devices and systems within buildings, such as lighting, ventilation, and small appliances with recent progress which includes innovations in the use of transparent PV panels for windows and specialized PV cells for indoor light harvesting. These technologies aim to enhance energy efficiency and reduce reliance on grid power within homes. PV technology is increasingly utilized in street lighting systems, offering a sustainable alternative to traditional grid-powered lights which has recent developmental focus on integrating high-efficiency PV cells with LED lighting to reduce energy consumption. Innovations include autonomous, off-grid street lighting systems with integrated batteries to store solar energy for nighttime use even in practical physics experiment in school laboratory. In water applications, PV-powered desalination systems convert solar energy into electricity to drive desalination processes, providing fresh water in arid region. Advances include solar stills and solar-powered reverse osmosis systems.

Keywords: Photovoltaic, Applications, Energy Sustainability, Photovoltaic panel, power devices.

Introduction

The industrial revolution has marked a significant turning point in human civilization, with advancements often accompanied by an increased environmental footprint. Fossil fuels like coal and natural gas, along with other non-renewable resources, release harmful CO₂ emissions when used for electricity generation. In contrast, solar energy helps lower carbon dioxide emissions and enhances environmental quality. Additionally, solar energy is the most cost-effective and plentiful of all long-term natural resources available today. The advancement of solar thermal and photovoltaic technologies holds significant promise, with ongoing innovations likely to expand their use and market reach (Razykov et al., n.d). Solar energy is viewed as an ideal solution for global energy needs due to its broad availability. The photovoltaic (PV) industry has seen exceptional growth over the past decade, with an average annual growth rate exceeding 34%, driven by substantial cost reductions, improvements in solar technology, supportive renewable energy policies, and diverse financing options. Transportation applications in aircraft propulsion: The integration of PV technology in aircraft is an emerging field aimed at reducing fuel consumption and emissions. Solar-powered aircraft can benefit from PV panels integrated into their structure, providing supplementary power for on-board systems and, in some cases, supporting propulsion. Recent advancements include lightweight, flexible PV cells designed for integration into aircraft surfaces. Solar-powered UAVs (Unmanned Aerial Vehicles) are also being developed for extended flight durations and reduced

operational costs and also for energy sustainability. In addition, it is used in maritime propulsion: PV technology is increasingly used in maritime applications to power boats and ships, reducing reliance on diesel engines and lowering emissions. Recent Progress includes innovations in solar-powered vessels and hybrid systems combining PV panels with conventional engines. The focus is on optimizing panel placement for maximum exposure and integrating energy storage solutions to ensure reliable power supply and energy sustainability. In domestic applications PV systems are used to power heat pumps, which can be employed for heating and cooling in residential buildings with recent progress in the development of PV-powered heat pumps which has focused on improving the efficiency of both PV panels and heat pump systems Furthermore, solar technology is increasingly integrated into building construction, particularly in urban areas, reducing dependence on traditional energy sources. The rise of distributed energy systems is expected to boost the adoption of solar thermal collectors and photovoltaic/thermal systems in residential buildings. This paper aims to provide a valuable resource for researchers, architects, manufacturers, and designers working on solar building systems.. In recent decades, the environmental impact of industrial and technological progress has intensified, prompting a search for sustainable solutions (Pathak et al., 2022). Among these solutions, smart energy systems and renewable energy resources have emerged as viable options for mitigating harmful emissions and reducing environmental impact. Renewable energy sources, including wind, geothermal, and tidal energy, offer promising alternatives to traditional fossil fuels. These technologies are designed to be environmentally benign while supporting technological development. Each type of renewable energy comes with its unique set of advantages and challenges: Wind Energy: Utilizes wind turbines to convert wind energy into electricity. Wind energy is abundant and renewable but may face challenges such as noise, visual impact, and variable energy output depending on wind conditions. Geothermal Energy which harnesses heat from the Earth's interior to generate electricity or provide direct heating. It is a stable and reliable energy source with a low carbon footprint, although it is geographically restricted to areas with significant geothermal activity. Tidal energy exploits the rise and fall of tides to generate power (Wang et al., 2018). It is highly predictable and environmentally friendly, but the technology is still in the early stages of development and may face high initial costs and potential impacts on marine ecosystems.

2.0 Literature Review

Photovoltaic (PV) systems are cornerstone of Renewable Energy. Among renewable energy sources, solar energy stands out as a key player, with photovoltaic (PV) systems being the most widely adopted technology. PV systems are particularly notable for several reasons. PV systems are relatively cost-effective compared to other renewable technologies. Their installation and maintenance are straightforward, making them accessible for a wide range of applications. PV technology is distinguished by its versatility. Unlike other renewable sources, which are often limited to specific types of applications or geographical locations, PV systems can be adapted to various uses (Khargotra et al., 2023). For example: PV systems have been employed for decades to power satellites in space. Their reliability and ability to generate electricity in space conditions make them ideal for this application. Emerging research explores using PV technology to power or assist in the propulsion of aircraft, offering potential benefits for reducing fuel consumption and emissions. PV systems are particularly well-suited for remote or off-grid locations, such as deserts, where other renewable sources like wind or tidal energy may not be feasible (Gao & Chen, 2023).

The widespread adoption of PV technology can be attributed to several key advantages: PV systems can be integrated into a variety of settings and applications, from residential rooftops to large-scale solar farms, and even in unconventional areas like remote or extreme environments. The modular nature of PV systems allows them to be scaled up or down to meet different energy needs, making them suitable for both small and large installations. PV systems generate electricity without emissions during operation, contributing to a reduction in the overall carbon footprint and reliance on fossil fuels (Twinn et al., 2019).

The rapid advancement and adoption of photovoltaic (PV) technologies have significantly transformed the landscape of renewable energy, offering a versatile and efficient solution to address global energy demands while

minimizing environmental impact. This study aims to highlight the potential of PV technology across various innovative and smart applications, exploring its capabilities beyond traditional uses (Shao et al., 2021). One notable advantage of PV systems is their minimal space requirements compared to other energy technologies. This characteristic makes PV particularly suitable for applications where space is limited, such as street lighting. Additionally, PV systems can operate in indoor environments, a feature not applicable to many other energy sources. PV technology has evolved significantly since the late 1970s, driven by the oil crisis and the need for alternative energy sources (Wilson et al., 2020). Unlike traditional energy systems that rely on mechanical motion or high-temperature conversions, PV systems convert solar radiation directly into electricity through semiconductor materials (Awasthi et al., 2020). Early generations are primarily silicon-based, with significant advancements made in improving the efficiency and reducing the costs. The shift from monocrystalline to multicrystalline silicon cells was driven by economic factors, enabling a more cost-effective production while maintaining high performance. To address cost and material waste, second-generation cells used materials like cadmium telluride (CdTe) and copper-indium-gallium-selenium (CIGS). Although these cells have lower efficiency compared to bulk silicon, their reduced production costs and lower energy requirements make them an attractive alternative (Taser et al., 2023). Third Generation PV Cells is seen as emerging Technologies. This generation includes dye-sensitized solar cells, organic photovoltaics, and perovskite solar cells. These technologies aim to surpass the efficiency of traditional silicon cells, with perovskite cells achieving notable advancements. However, challenges remain regarding their long-term stability and lifespan compared to silicon-based technologies (Nazari et al., 2018).

The significant shift in the PV market occurred in 2008 when China rapidly expanded its PV manufacturing capabilities. The influx of low-cost manufacturing, materials savings, and reduced labor costs led to a dramatic decrease in the price of solar PV panels, with costs reducing by up to 85% between 2010 and 2020. This price reduction has led to a substantial increase in installed capacity, with the U.S. alone increasing its solar PV capacity from 218 MW in 2005 to approximately 51 GW by 2017.

2.1 Principle Behind Operation of Solar Cell

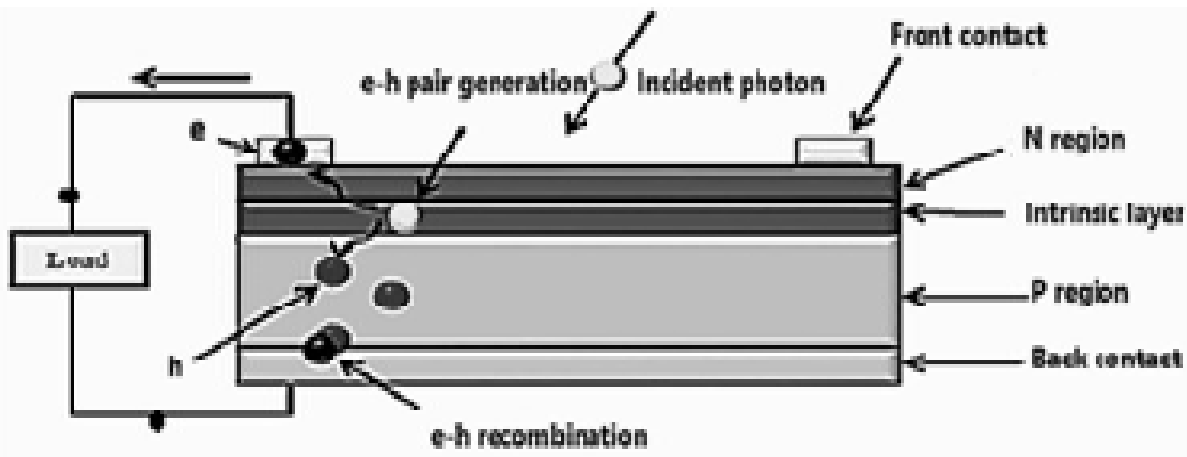


Figure 1: PV cell with semiconductor (Al-Ezzi & Ansari, 2022).

Every solar energy production system in which sunlight is converted to electrical energy quickly depends on a PV cell, the basic component. A p-n junction instrument is a solar cell. In a PV system, n-type and p-type refer to the negatively charged electrons provided by donor impurity atoms and the positively charged holes produced by acceptor impurity atoms respectively. Solar cells operate according to the photovoltaic effect, basically. Three fundamental mechanisms define the PV effect.

In a p-n junction electronic semiconductor, absorption of photons creates the charge carriers (electron-hole pairs). An electron is excited from the valence band 'Ev' to the conduction band 'Ec' leaving a void (hole) at the valence level; the absorption of a photon with energy greater than the gap energy 'Eg' of the doped semiconductor material means the energy is used to excite the electron. The extra photon energy ($h\nu - h\nu_0$) adds more kinetic energy to the electron or hole (Zhong et al., 2023). The least energy or work function of the semiconductor needed to create an electron-hole pair is given. Here, the energy gap is shown by the work function. The semiconductor turns any extra energy into heat. Subsequential separation of the light-generated charge carriers. In an external solar circuit, the holes can flow away from the junction through the p-region, and electrons can flow out across the n-region and pass through the circuit before they recombine with the holes.

Ultimately, the separated electrons may be used to power an electric circuit. Once the circuit has passed through, electrons will create with the holes. The n-type has to be made more slim than the p-type. As a result, the electrons can move through the circuit quickly and produce current before they recombine with the holes. Further, an anti-reflective coating is applied over the n-layer in order to increase the light's transmission to the semiconductor material and lower surface reflection (Al-Ezzi & Ansari, 2022).

General Applications of PV Technologies

This has so many applications in many areas that are explained below.

Applications of Photovoltaic Technology in Aircraft and Maritime Sectors

The flexibility and low cost of photovoltaic (PV) technology offer significant advantages for aircraft applications, where continuous exposure to sunlight can be effectively harnessed to supply power. Here's a closer look at how PV technology is applied in aviation, along with current challenges and future developments: Aircraft, particularly those operating at high altitudes, can benefit from the consistent and direct sunlight they receive (Dehghanimadvar et al., 2022). PV panels installed on aircraft surfaces can convert solar energy into electricity, which can then be used to power onboard systems, reduce fuel consumption, and extend the aircraft's range. One of the primary challenges for PV-powered aircraft is the absence of sunlight during night flights. To address this, efficient energy storage systems are required to store solar energy generated during the day for use during nighttime or when the aircraft is in the shade. Advances in battery technology, energy storage materials, and hybrid power systems are critical for overcoming this limitation. Research and development are focusing on improving the efficiency of PV panels and energy storage systems (Najlaoui et al., 2023).

Key areas of development include: Development of lightweight, high-efficiency PV panels that maximize energy capture and minimize weight. Innovations in battery technology and other storage solutions to provide longer periods of power supply and faster charging. Integrating PV panels into the aircraft's structure to minimize drag and optimize energy capture without affecting aerodynamic performance. In maritime applications, PV technology is increasingly being utilized due to its ability to provide power in remote locations and its compatibility with various marine environments (Nuhash et al., 2023). Here's how PV technology is applied in the maritime sector: PV panels can be installed on boats and ships to generate electricity for onboard systems. This application is particularly beneficial for vessels operating in remote or off-grid areas where traditional fuel sources may be limited or expensive. The main advantages of using PV technology in maritime applications include: By supplementing or replacing conventional fuel sources, PV systems can lower operational costs and reduce emissions. Solar power can enhance the operational range of vessels by providing additional energy for various onboard systems, including navigation and communication.

Challenges and Considerations: maritime vessels have limited space for installing PV panels. Designing efficient and compact PV systems that maximize energy capture within these constraints is a key challenge (Lotfi et al., 2023). Marine environments expose PV panels to harsh conditions, including saltwater, high winds, and UV radiation. Ensuring the durability and longevity of PV systems in these conditions is crucial. Similar to aircraft applications, energy storage is essential for maritime vessels to ensure a continuous power supply during periods

of low solar irradiance, such as during cloudy weather or at night. Development of integrated PV systems that can be seamlessly incorporated into the design of maritime vessels, including retractable or foldable panels to maximize space utilization (De Maio et al., 2022). Advances in materials and coatings to improve the resistance of PV panels to marine environments and extend their operational life. Exploration of hybrid power systems that combine PV technology with other renewable or conventional energy sources to ensure a reliable power supply under varying conditions.

Smart PV Applications

The integration of photovoltaic (PV) modules into various applications beyond traditional solar farms represents a significant advancement in the use of solar energy. These smart PV applications encompass a wide range of innovative uses where PV systems serve as primary or auxiliary power sources (Najlaoui et al., 2023). This approach aligns with the Green to Green (G2G) concept, which emphasizes the synergy between renewable energy generation and green storage technologies. Here's a detailed look at some of these smart PV applications: PV panels can be integrated into electric vehicles (EVs) or their charging stations. On vehicles, PV modules can supplement the battery by providing additional power to increase range or run auxiliary systems. In EV charging stations, PV arrays can offset grid electricity usage and reduce overall charging cost. Emerging research explores the use of PV systems for aircraft propulsion. Although still experimental, PV technology could potentially reduce fuel consumption and emissions in aviation by providing a supplementary power source for onboard systems. PV technology can also be applied to maritime vessels (Razykov et al., n.d.). Solar-powered boats and ships benefit from reduced reliance on fossil fuels, lower operating costs, and reduced environmental impact. PV modules can be used to power devices and lighting indoors, particularly in off-grid or remote locations. Innovative applications include integrating PV panels into building materials such as windows or facades. PV systems can be paired with heat pumps to enhance energy efficiency in residential heating and cooling (Najlaoui et al., 2023). By using solar energy to power the heat pump, homes can reduce their dependence on conventional energy sources. PV panels can be integrated into smart home systems, providing energy for smart devices, home automation systems, and energy management systems. This integration supports energy efficiency and sustainability in residential settings. PV-powered street lighting systems are increasingly common in both urban and rural areas. These systems operate independently of the grid, reducing energy costs and improving reliability in areas with unstable electricity supply. Solar street lights are also beneficial in remote locations where grid extension is not feasible. Advanced PV street lighting systems can be equipped with sensors and controls that adjust brightness based on real-time conditions, such as traffic flow or ambient light levels, further enhancing energy efficiency. PV technology can power desalination units, providing a sustainable method for producing fresh water from saline sources (Philipovic et al., 2023). This application is particularly valuable in arid regions with high solar irradiance and limited access to freshwater resources. PV systems can drive irrigation pumps for agricultural applications, providing water to crops without relying on grid power. This technology supports sustainable agriculture and reduces operational costs for farmers (Zhao et al., 2023). In addition to irrigation, PV-powered water pumping systems can be used for various water management tasks, such as filling reservoirs or supplying water to remote communities. PV energy can be used to produce hydrogen through electrolysis, creating a green fuel that can be stored and utilized in various applications, including transportation and power generation. Excess solar energy generated by PV systems can be used to pump water to elevated reservoirs, which can later be released to generate electricity during periods of high demand. In Compressed Air Energy Storage (CAES), PV-generated electricity can be used to compress air and store it in underground caverns or tanks. The compressed air can later be released to generate power when needed. In Battery Storage Systems, PV systems can be paired with battery storage to store excess solar energy for use during non-sunny periods. This integration enhances the reliability and flexibility of solar power (Ahmad et al., 2024).

Methodology

The methodology used was content analysis as this is review work with deep current literature search to know the current state of photovoltaic application for clean energy production for a better society in energy sector.

Findings

The versatility of PV technology allows it to be used in a wide range of applications. In transportation, research into using PV technology for aircraft propulsion is ongoing, aiming to reduce fuel consumption and emissions. PV systems are being explored for use in marine applications, offering potential benefits for reducing dependence on fossil fuels in maritime transport. In domestic applications, PV systems can be adapted for indoor applications, such as powering devices and lighting within buildings. Integration with heat pumps for residential heating and cooling systems enhances energy efficiency and reduces reliance on conventional energy sources. Furthermore, the compact size and ease of installation make PV systems ideal for street lighting, providing energy-efficient solutions for both urban and remote areas. PV-powered desalination systems offer a sustainable solution for producing fresh water from saline sources. PV technology can be used to power irrigation systems and water pumps, particularly in regions with limited access to conventional energy sources.

The performance of solar PV systems has improved significantly, with a notable percentage of systems operating at about 14% of their designed capacity. Efforts to enhance PV performance, including increasing efficiency and integrating PV systems into various applications, continue to advance. For instance, advancements in performance can lead to increases up to 15% in some applications.

Conclusion

In summary, while the industrial revolution and subsequent technological advancements have increased environmental challenges, renewable energy sources such as PV systems offer promising solutions. Their versatility, cost-effectiveness, and adaptability make them a cornerstone of modern renewable energy strategies. As PV technology continues to develop, its potential applications will expand, further integrating it into various sectors and regions, and contributing to a more sustainable energy future. The application of PV technology in diverse and innovative ways demonstrates its potential to transform energy systems and contribute to sustainable development. By integrating PV systems into transportation, domestic applications, street lighting, and water management, and coupling them with green energy storage solutions, we can leverage solar energy to address various energy challenges. These smart PV applications not only enhance energy efficiency but also promote the use of renewable resources, supporting the transition towards a more sustainable and resilient energy future. The application of PV technology in aircraft and maritime sectors highlights its versatility and potential to contribute to sustainable energy solutions in diverse environments. While challenges related to energy storage, space constraints, and environmental durability remain, ongoing research and technological advancements are paving the way for more efficient and practical implementations. The future of PV technology in these sectors will likely see further integration, enhanced performance, and expanded applications, driving innovation and sustainability in aviation and maritime industries. This paper underscores the diverse applications of PV technology, ranging from transportation and domestic use to agricultural and desalination applications. The continuous development of PV technology, driven by cost reductions and technological innovations, highlights its potential to provide sustainable energy solutions across various sectors. As PV technology evolves, its ability to address energy needs in novel and smart applications will further solidify its role in the global energy landscape.

Recommendations

1. The Cost of electricity from solar PV has been falling tremendously. However, the costs are still too high compare to the demand thereby reducing its accessibility to many consumer that need it. Therefore, the design and its construction should be made to affordable and as well give the needed service.
2. Solar PV has limitations concerning how much sunshine it could capture due to seasonal changes. This creates problems when trying to estimate the amount of energy to reserve for later uses. The amount of light that can be absorbed is nonexistent during the night, but there is still a need for energy. Moreover, there may be a mismatch in the peak supply of radiation with the peak demand for electricity. Hence, a means of reliable energy storage and retrieval is required. Therefore, more efficient one should be

designed and constructed to carry very large electricity capacity demand with lengthy duration in resilience.

3. Location may present a challenge. The capture of solar radiation is location dependent. Therefore, it implies that solar power generation has to be confined within certain regions where these systems can be installed and there should be design and construction of more adaptable one in a solar disadvantage area

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