

THE FUTURE OF SOLAR ENERGY IN DEVELOPING COUNTRIES

ABSTRACT:

Around the world, there is a lot of interest in using renewable energy as a future energy source. As one type of renewable energy source, solar energy—including concentrating solar power (CSP) and solar photovoltaic (PV) power—contributes only 3.6% of the world's electricity production. As the second most installed renewable energy resource after hydropower energy, it has solidified its position among other renewable energy technologies, accounting for over 31% of the installed renewable energy capacity in 2022. The solar power status of various nations and territories has been compared, taking into account each continent's installed PV capabilities and concentrated solar power. The literature review shows that there are still major gaps in the field of solar energy, even though the installed capacity of solar energy worldwide increased by almost 22% between 2021 and 2022. By building more solar farms, the solar PV industry can grow to become the second most important generating source in the next three decades, enabling nations to produce about 25% of the world's total electricity demands by 2050.

The solution and the force behind all of the energy we currently have and will utilize for some time to come is solar energy and its derivatives. Yet, it will take a while before it can replace existing programs, and then probably in ways we haven't yet recognized or accepted. All of the energy we consume today originates from the sun, regardless of whether it is classified as renewable or non-renewable. Current solar and thermal cells, wind, and other renewable energy sources all depend on the sun's direct rays. Increasing the direct use of solar energy through these renewables is necessary if we are to offset the non-renewable substantially. One potential obstacle or challenge **to the widespread adoption of PV systems, solar thermal systems, and energy storage options is their initial cost or finances. The initial outlay needed for equipment and installation may result from financial difficulties**, particularly in areas **with few economic resources and infrastructure challenges**

KEYWORDS: Fossil fuels, Environmental issues, Solar energy, Developing countries, Greenhouse gas(GHG), Energy crisis.

1. INTRODUCTION:

Energy is critical in economic development and human well-being, stimulating economic progress. A major worldwide challenge is access to adequate energy resources, especially in developing nations without a reliable energy supply^[1]. Rapid population expansion, especially on the African and Asian continents, and rapid economic development, especially in China and India, are driving up demand for

energy in developing nations. The main causes of the increased demand for energy are population expansion and rising living standards. According to estimates, the world's population will continue to grow by more than one billion people, reaching 8.5 billion by 2030, 9.7 billion by 2050, and roughly 11.2 billion by 2100^[2]. The current use of fossil fuel energy production and practices harms the environment at the local, regional, and global levels, lowering human well-being and putting the health of current and future generations of people at risk. Two-thirds of global greenhouse gas (GHG) emissions and 80% of carbon dioxide emissions are caused by the production and use of fossil fuel energy^[3]. The vast majority of anthropogenic greenhouse gas (GHG) emissions have historically come from developed nations, but in recent years, emerging nations have exceeded developed nations in terms of GHG emissions, and these proportions have continued to rise extremely quickly^[3]. Compared to the world's industrialized nations, developing nations have seen a steady increase in CO₂ emissions in recent years. Throughout recent years, carbon dioxide emissions linked to energy have significantly expanded throughout Asia, the Middle East, Africa, and the Pacific area. In order to keep up with the rapidly increasing demand for energy, emerging nations have significantly increased their usage of traditional fuels, such as coal, oil, and natural gas, which has led to an increase in CO₂ emissions. Nearly 40% of the world's primary energy is currently used to generate electricity, making the production of electricity from conventional energy sources the largest cause of greenhouse gas emissions globally, especially in developing nations^[4]. As a result, fossil fuel-powered power plants release a lot of hazardous chemicals into the atmosphere, including sulfur dioxide (SO₂), nitrogen oxides (NO_x), and carbon dioxide (CO₂)^[5]. Currently, the global average for CO₂ emissions from the power generation sector is close to 530 g CO₂/kWh. Additionally, the main source is the power industry, which accounts for around 70% of SO_x emissions in European nations and is the main source of SO₂ emissions in the US, South America, and East Asia. Acid rain is a regional and transboundary issue that is caused by SO₂ and NO_x pollution^[6]. The United Nations Environmental Program (UNEP) states that there is a significant cost associated with the environmental harm caused by GHG emissions. By 2050, it is predicted that these environmental damages will total 50 billion US dollars annually, only in Africa. Furthermore, most impoverished countries in the world depend heavily on forests to supply the energy they need for daily living, especially for cooking. In poor countries, traditional biomass, primarily firewood, accounts for 56% of all primary energy consumption.

The livelihoods of the impoverished are at risk due to the continued destruction of trees, which also ruins ecosystems and habitats that support biodiversity. More than 1.4 million square kilometers of forest have been lost due to deforestation since 1990, mostly in East Asia, Latin America and the Caribbean, the Pacific, and Sub-Saharan Africa (SSA). The overuse of biomass fuel harvesting is partially to blame for this deforestation^[7]. In many parts of the world, people have easy access to renewable energy sources. The reduction of environmental pollution, especially from greenhouse gas emissions, is the main advantage of using renewable energy sources. This is achieved by replacing conventional fuels with fossil-based electricity, which lowers atmospheric emissions^[8]. An amazing contribution to the sustainable provision of energy services is made by solar energy, an endless and pollution-free energy source. Solar energy does not release hazardous pollutants like CO₂, SO₂, and NO_x into the atmosphere like conventional fuels do. In order to combat the detrimental environmental effects of conventional fuels, many nations have already selected solar energy as a clean and alternative energy source. One of the primary ways to reliably, economically, practically, and sustainably meet both local and large-scale energy demands is through solar energy systems. Solar photovoltaics (PVs) use sunlight to generate electricity, without releasing pollutants into the atmosphere, it is a significant power source for

supplying the demand for electricity in emerging nations, particularly in rural and isolated areas. Photovoltaic generating systems are expected to play a significant role in the years to come due to their enhanced efficiency and ongoing cost reduction. Additionally, solar thermal power plants transform solar radiation into high-temperature heat in order to provide thermal or electrical energy. It can provide the energy requirements of the commercial, industrial, residential, and agricultural sectors. Reducing CO₂ emissions and lessening the burden of energy production for daily tasks in developing nations are the two main functions of solar energy systems^[9].

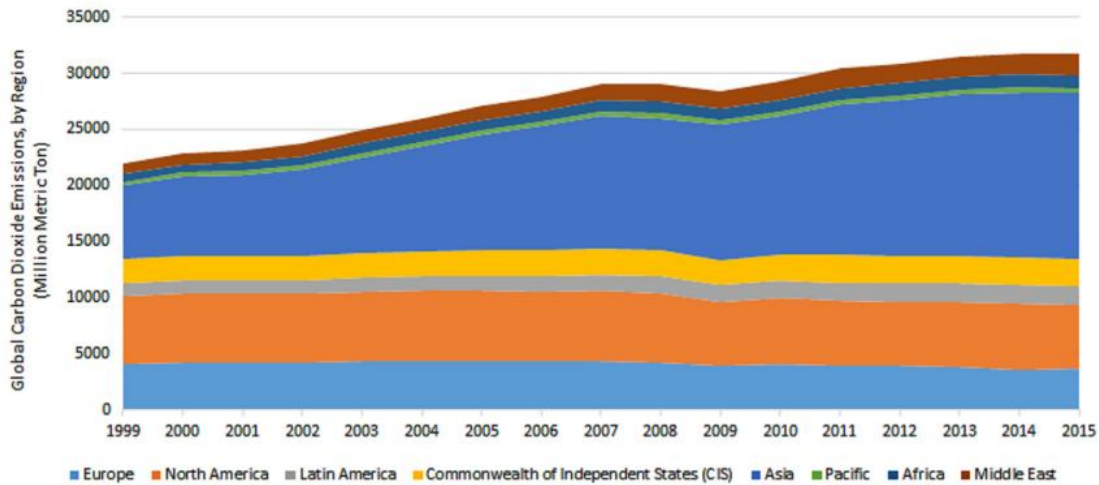


Fig. 1. Total carbon dioxide (CO₂) emissions from consumption of energy in the world during 1999–2015 (Million Metric Tons). Source: This data is provided by the Global Energy Statistical Yearbook.

2. LITERATURE REVIEW:

This Literature review attempts to provide a comprehensive understanding of the difficulties and possibilities that Developing Countries need to seize to achieve sustained energy-related policies. By analyzing the unique energy environment and contextual constraints in these nations. This research aims to pinpoint the main barriers to adopting sustainable energy solutions. Additionally, it looks for potential opportunities and innovative pathways that may lead to efficient energy transfers. The results and ideas from this research will be very helpful to policymakers, international organizations, and other stakeholders interested in putting sustainable energy policies into practice in developing countries.

To achieve these objectives, this paper is structured in the following way: (1) Definition and significance of Solar energy. (2) Application of Solar energy. (3) Electricity generation to homes. (4) Challenges and opportunities of solar energy in developing countries. (5) Benefits of solar energy. (6) Barriers and prospects. (7) Types of PV technologies, (8) Recommendations, and (9) Conclusion. There are many applications, ranging from closing the energy access gap to boosting industrialization and bolstering food security programs.

The purpose of this structured analysis is to add to the growing body of knowledge on Sustainable energy and development and to offer policymakers and Stakeholders actionable insights that can help

navigate the difficult obstacles and countless opportunities that stand in the way of a sustainable energy future in developing countries.

3. METHODOLOGY:

This paper seeks to examine the potential and future of Solar Energy in Developing Countries and it is a comprehensive review article. The researchers were able to employ a thorough analysis of the review of Web of Science, Scopus, Google Scholar, and PubMed, among other major scientific databases, to conduct a thorough search of peer-reviewed literature. Keywords included "Solar energy," "Fossil fuel," "Environmental issues," "Developing countries," "Greenhouse gas emission," "Pollution," "Energy crisis," and "Sustainable development" were among the search terms. The literature review included published papers between 2010, and 2024; was included in the search to guarantee that both previous and recent research materials were included. Studies that met the following requirements were considered: (a) Written in English, (b) published in peer-reviewed publications, (c) focus on Solar energy, (energy poverty (d) comprised of empirical data, theoretical models, or thorough evaluations. Titles and Abstracts were considered as the first screening. After passing the initial screening, the full-text articles were examined. To reduce bias, the screening and selection procedure was carried out by two separate reviewers. Definitions and significance of Solar energy, the potential impacts of solar energy, techniques and technologies of solar energy, worldwide perspectives, and policy implications were among the pertinent data that was taken from selected articles. Standardized instruments suitable for various study designs—such as STROBE for observational studies and PRISMA for systematic reviews—were used to evaluate the quality of the included studies. To combine the results of several research, a narrative synthesis technique was employed. Descriptive statistics were used whenever possible to summarize quantitative data. The researchers engaged specialist on Solar energy application to guarantee thorough coverage and understanding of the material. Since there was no primary data collection from humans for this review, ethical approval was not considered. The researchers took into consideration drawbacks including publication bias in favor of favorable findings and the omission of papers written in languages other than English.

4. DEFINITION AND SIGNIFICANCE OF SOLAR ENERGY:

Solar energy is the most plentiful renewable energy source and is available and cost-free in every nation. Solar power is the energy from the sun that is captured and transformed into heat and electrical energy, two major uses. In general, two primary types of solar energy technology can transform solar radiation into electrical energy. Solar energy origins can be found in ancient societies when buildings were built to reflect and intensify sunlight to provide warmth during the winter. Solar photovoltaic (PV) technology, which uses semiconductor materials to use the photoelectric effect to turn sunlight into electricity, was developed in the 19th century. Solar technology advanced significantly in the 20th century, mostly due to space exploration activities^[10]. A solar panel absorbs sunlight and transforms it into electricity, a charge controller, controls the energy flow from the solar panel to the battery, a battery, stores the electricity produced for later use, an inverter, transforms the stored DC power into AC power for household appliances, wires connecting the various parts, and, of course, the sun, which is the ultimate energy source, are the essential parts of a solar system. These elements work together to create a renewable and sustainable energy system that uses solar energy to generate clean electricity for various uses. A solar panel, charge controller, battery, inverter, wiring, and the sun (solar simulator) are the

essential parts of a solar system. With increased efficiency and lower costs, solar energy moved from a specialized application to a widely used energy source, and governments encouraged its use with financial assistance and regulatory changes^[11].

With solar panels frequently built of photovoltaic cells made of elements like silicon, modern solar technology is a monument to human intellect and engineering talent. The range of solar energy uses has increased thanks to developments in energy storage technologies, thin-film solar cells, and concentrating solar power systems. From the solar architecture of ancient civilizations to the cutting-edge solar panels on rooftops that power entire cities today, solar technology has advanced over millennia. The ability of humans to invent and utilize the wealth of natural resources is reflected in this journey. Recognizing the revolutionary potential of solar technology in tackling energy and developmental issues requires an understanding of this trend^[12].

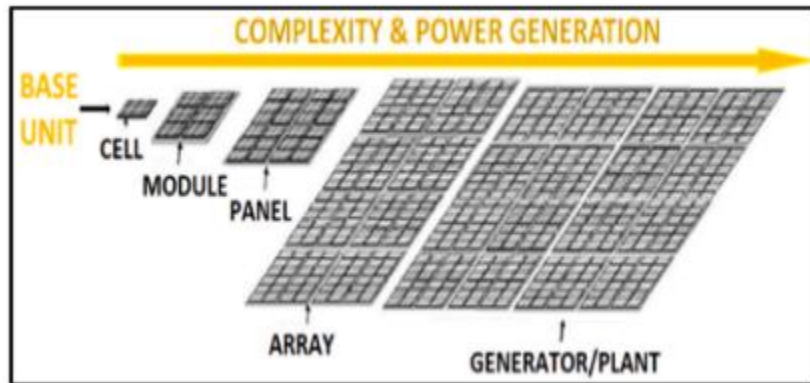


Fig.2. Different Photovoltaic architecture.

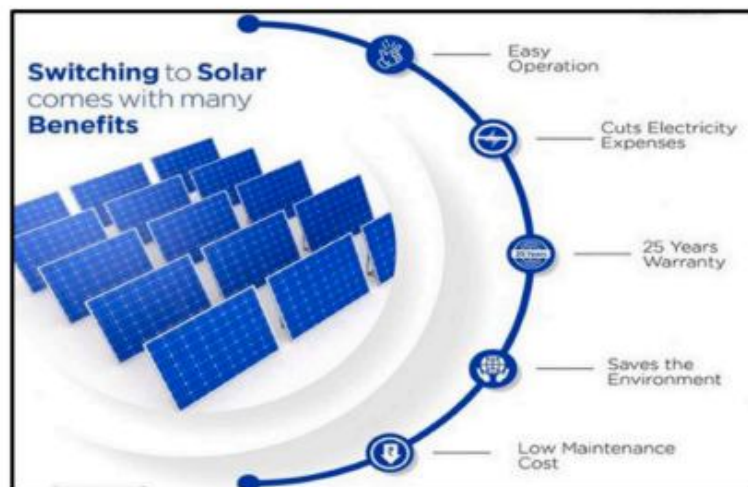


Fig.3. The Importance of Solar Energy.

The two primary kinds of solar technology are solar thermal systems and solar photovoltaic (PV) systems. PV systems, which range in size from tiny rooftop installations to massive solar farms, use the photoelectric effect to turn sunlight into power.

Beyond producing electricity, they may operate satellites and computers, supply energy in isolated areas, and provide off-grid options, among other uses. Solar thermal systems transform sunlight into thermal energy for heating or power generation by absorbing solar radiation as heat. They can help with space heating in buildings, supply hot water for the home, and lower energy usage in industrial operations. Combining PV and thermal systems can provide all-encompassing energy solutions that improve efficiency and tackle the issues the Developing Countriesface. It is essential to comprehend these categories to assess how well solar technology can solve these issues^[13].

4.1. APPLICATION OF SOLAR ENERGY:

The amount of energy that the sun provides to the earth's surface is sufficient to supply 7900 times the energy that the world's population now consumes. On average, 1700 kW-h (kWh) of electricity can be produced annually for every square meter of land that receives adequate sunlight. Nearly every location on the planet experiences 4380 hours of daylight annually, or half a year. The amount of accessible solar resources per surface area is measured by global horizontal irradiance or GHI.

Extreme environments, homes, transportation, industrial applications, automation, and agriculture are just a few of the industries that employ solar energy, which is a flexible energy source. It improves industry energy efficiency, lowers greenhouse gas emissions, and strengthens communities. Cleaner methods and sustainable farming are facilitated by solar-powered devices such as air conditioners, water heaters, and factory automation. The use of solar energy raises certain environmental issues, just as other energy sources (such as fossil fuels and renewable energy).

Since solar and wind energy are non-thermal renewables and don't require water for dry cooling systems, their operational water consumption intensities are extremely low. Certain photovoltaic systems use comparatively little water to clean their panels. While wet and hybrid cooling uses more water, CSP plants can use dry cooling methods to save water^[14].

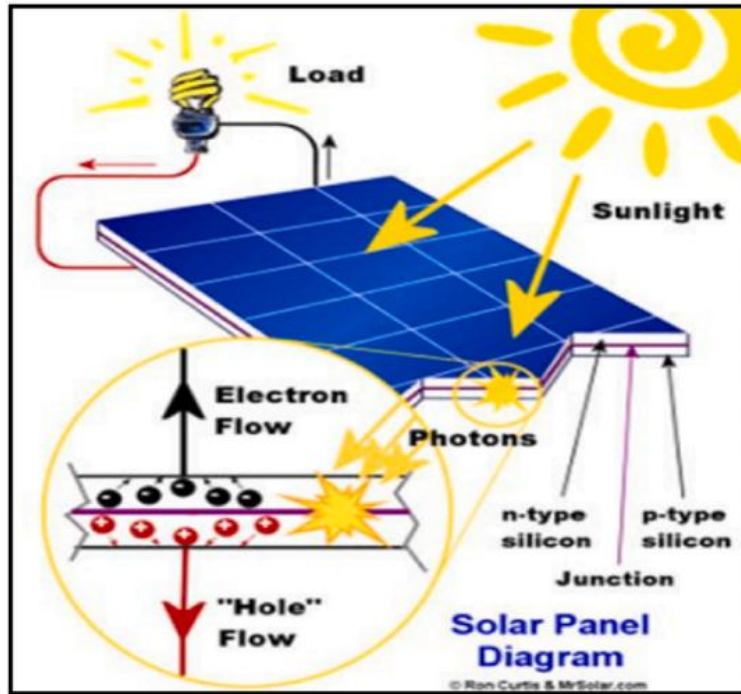


Fig.4. A picture of the working operation of Solar Energy.

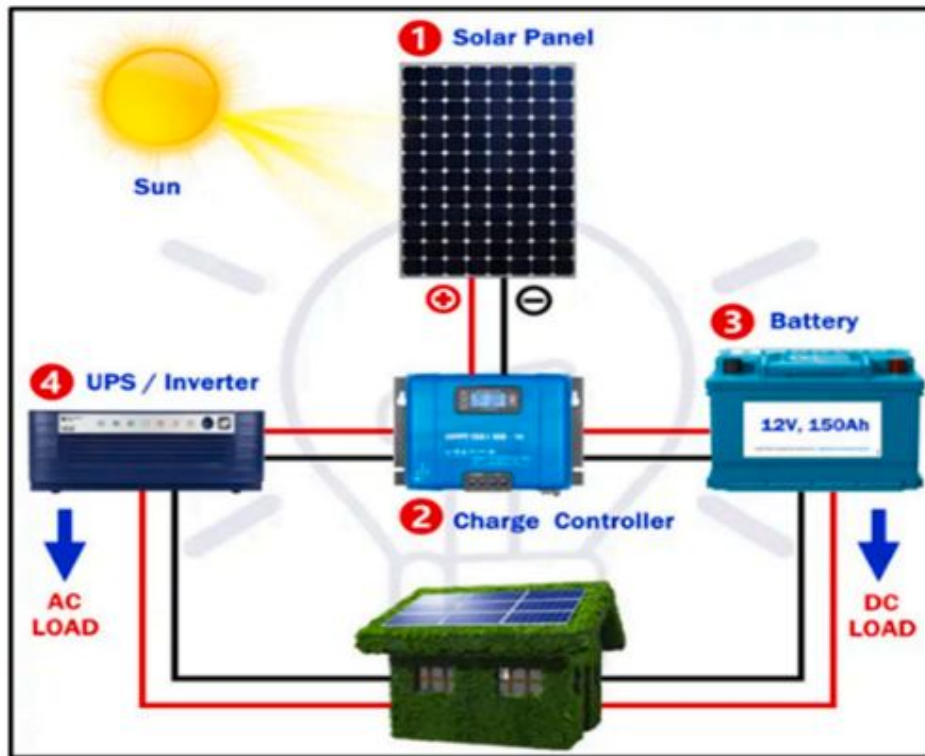


Fig.5. The main components of a Solar panel system.

4.2. ELECTRICITY GENERATION TO HOMES:

In Sub-Saharan Africa, three-quarters of the population does not have access to electricity. Over 590 million people lacked access to electricity, according to the IEA's World Energy Outlook 2020. By turning rooftops into energy producers, solar energy is completely changing how electricity is generated in homes. By enabling homeowners to become energy producers, this decentralized strategy changes the paradigm from passive energy consumption to active energy production. Homes using solar power may produce electricity during the day, meeting and even beyond their immediate energy needs. Homeowners can access their energy reserves at night or during overcast conditions by storing excess energy in batteries or reusing it in the grid. Additionally, solar energy has economic advantages including lower energy expenses and bills. Solar-powered homes also contribute to environmental stewardship by reducing reliance on fossil fuels and fostering a cleaner, greener environment for future generations. Solar-powered homes also demonstrate resilience in the face of energy disruptions, enhancing household preparedness and community resilience^[15].

4.3. TRANSPORTATION:

By converting electric cars and high-speed trains into environmentally friendly alternatives, solar energy is completely changing the transportation industry. Trains are powered by solar panels, which lower carbon emissions and support sustainability objectives. In addition to improving energy independence and resilience, electric vehicles (EVs) are changing the charging environment. In areas with particular difficulties, solar-powered transportation promotes holistic growth and advancement by influencing public opinion and behavior.

4.4. HIGH SPEED TRAIN:

Solar-powered trains are normally pushed by photovoltaic panels on or close to rail lines, which can supply enough electricity to initiate a traction current that will be transmitted to the grid. These technologies may provide several financial benefits to networks that currently rely heavily on grids. Because grids are filling up quickly and there is a growing scarcity of money, it is getting harder to generate electricity from renewable sources to power the railroads.

High-speed trains are using solar energy to generate electricity, lower carbon emissions, and improve energy efficiency.

Along train lines, solar panels are positioned strategically to collect sunlight and turn it into electricity. In line with international climate targets, solar-powered trains provide a greener, cleaner form of transportation. By capturing sunlight straight from their paths, they also improve energy efficiency and lessen the burden on traditional energy delivery systems. This intersection of rail infrastructure with solar energy is a prime example of solar energy's versatility and inventiveness in a variety of industries. A sustainable future for contemporary transportation, solar-powered trains complement international initiatives to reduce air pollution, fight climate change, and promote sustainable mobility.

4.5. ELECTRIC VEHICLES:

The automotive sector is changing as a result of the integration of solar energy into electric vehicles (EVs). The vehicle's overall driving range is increased by the strategically positioned solar panels that absorb sunlight and transform it into electrical power. This increases driving range, lessens the need for frequent charging stops, and makes owning an EV more convenient. Additionally, solar-powered EVs may lessen the need for frequent charging, increasing energy independence and promoting a more environmentally friendly driving experience. The incorporation of solar power into EVs is an example of technological advancement in the automobile industry that encourages a change in mindset toward environmentally friendly modes of mobility. The solar-powered revolution extends beyond automobiles and speaks to larger issues and possibilities in areas aiming for all-encompassing growth and advancement^[16].

4.6. EXTREME ENVIRONMENT:

In rural areas, solar energy is vital for overcoming obstacles and delivering necessary services. It illuminates access to clean water, powers vital infrastructure, and supports communication systems. Solar microgrids, which are composed of energy storage devices and solar panels, supply electricity to isolated towns, illuminating clinics, houses, and schools. While solar-powered water purification machines treat contaminated water sources to provide access to drinkable water, solar-powered communication systems guarantee uninterrupted connectivity^[17]. Additionally, solar energy powers medical equipment, refrigerates vaccines, lights clinics, and facilities, and supports healthcare services. Additionally, solar energy promotes literacy, prolongs study hours, and creates well-lit learning settings, all of which contribute to educational empowerment. Because solar energy has little environmental impact, biodiversity is protected and the balance of nature is not jeopardized by progress. Solar energy provides a ray of hope in harsh settings, showcasing human resourcefulness, resiliency, and a common dedication to a better future^[18, 19].

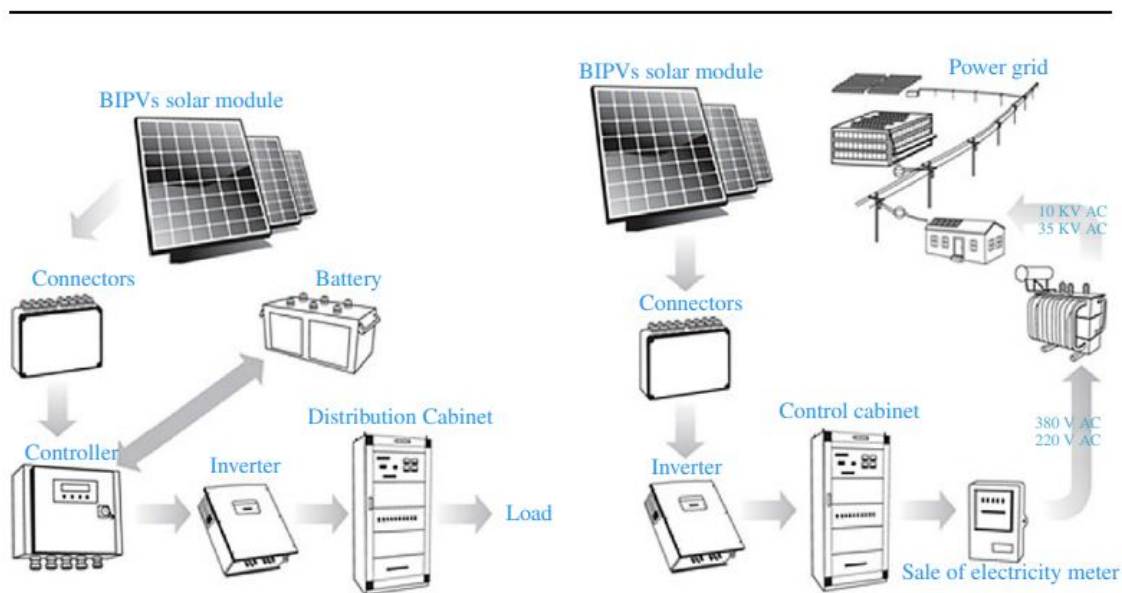


Fig.6. Design Schematics of grid-connected and off-grid Building Integrated Photovoltaic Products(BIPV)^[20].

5. CHALLENGES AND OPPORTUNITIES OF SOLAR ENERGY IN DEVELOPING COUNTRIES:

5.1. Challenges

The deployment of solar technology in the Developing Countries is fraught with difficulties. The difficulties include a lack of awareness, inadequate infrastructure, and budgetary limitations. Due to a complicated web of interrelated circumstances that limit its transformational potential, all of them prevent its widespread acceptance. First, a lack of awareness and gaps in expertise make it difficult for the Developing Countries to encourage the adoption of solar technology^[21]. Reliability, renewable energy, a smaller environmental impact, and the capacity to lessen energy poverty are some advantages of solar energy. This misinformation keeps people depending on traditional energy sources, which are frequently costly, unreliable, and bad for the environment. Governments, non-governmental groups, and neighborhood associations must work together to close this information gap. To reach groups outside of regular information streams, comprehensive awareness campaigns should be developed using a variety of communication channels. Communities' success stories with solar energy can serve as motivation and a reminder of the financial advantages as well as the wider effects on healthcare, education, and general quality of life. Additionally, solar technology presents the possibility of generating revenue through solar-powered businesses, promoting resilience and self-sufficiency^[22]. Second, the Developing Countries' adoption of solar technology is hampered by inadequate infrastructure. In areas with high solar power demand, essential elements like maintenance networks, effective grid integration mechanisms, and energy storage options are frequently absent. Strong investments are required to upgrade and fortify grid infrastructure to get over these challenges and guarantee that solar energy is efficiently distributed to communities. Purchasing cutting-edge energy storage systems can help guarantee a steady supply of electricity, particularly in areas with erratic sunlight. For solar-powered systems to last and function well, strong maintenance networks must be established, local personnel must be trained, and a sustainable culture must be promoted^[23]. Governments, international organizations, and the business sector must work together to overhaul the infrastructure challenges. Governments ought to give energy infrastructure investment priority, and international organizations can provide financial assistance, technical know-how, and information exchange to direct modernization. Innovations that address the unique requirements of the Developing Countries can be introduced by the private sector, which can also spur innovation and solutions to infrastructure obstacles. Thirdly, the adoption of solar technology in the Developing Countries is severely hampered by budgetary limitations and economic realities. Adoption of solar is hampered by high upfront prices, few resources, and a lack of easily available financing options^[20]. For people and communities to overcome these obstacles and adopt solar solutions, financial accessibility is essential. Governmental incentives like tax breaks, grants, and subsidies can lower the cost of clean energy and motivate people and businesses to switch to solar energy. By adjusting financial solutions to local circumstances and income levels and offering easily accessible investment opportunities, microfinance institutions can completely transform the adoption of solar^[24]. Additionally, creative financing mechanisms that lower initial costs and promote economic growth can be sparked by public-private collaborations. Governments, financial institutions, and private organizations must collaborate to establish a financial environment that makes solar adoption a reality for everyone by reducing income gaps. These will enable communities in the Developing Countries to overcome

economic obstacles and create a future in which solar energy empowers people, strengthens communities, and opens the door to sustainable development. Because used solar panels contain dangerous substances like lead, cadmium, and silicon, disposing of them is a major problem. Hazards to one's health and the environment can arise from improper disposal^[25]. To reduce these dangers and guarantee that solar panels are properly treated at the end of their useful lives, efficient recycling and waste management methods must be developed. Large-scale solar panel installations may cause habitat loss or deforestation, among other environmental problems, particularly if they take up a lot of land. Although installing solar panels on degraded land or existing infrastructure might reduce environmental effects, vulnerable ecosystems and land-use conflicts must be addressed through careful planning and regulation. Preventing performance problems, reliability concerns, and safety hazards requires making sure that solar panels offered in the market are safe and of high quality^[11]. Enforcement of quality regulations has difficulties, including counterfeit goods, poor manufacturing processes, and insufficient testing facilities, especially in the Developing Countries where control may be weak. To improve the quality control of solar panels, it is imperative to strengthen regulatory frameworks, develop standards and certification programs, and improve market surveillance. Solar panels need to be appropriate for the local climate, particularly in areas that experience regular dust storms, high humidity, or extremely high temperatures. For Example, solar panels in northern Nigeria have to endure extreme temperatures and Sahara Desert sand dust. Thorough testing, product design adjustments, and technology adaptation to regional conditions are necessary to guarantee the robustness, performance, and longevity of solar panels in a variety of environmental contexts. To overcome these obstacles and guarantee the efficiency and durability of solar panel installations in Developing Countries, cooperation between producers, researchers, and regional stakeholders is crucial. The acceptability of solar power in Developing Countries is significantly impacted by land acquisition issues, which impede the growth of large-scale solar projects and the spread of renewable energy. The lack of suitable land, competition from other land uses like agriculture and urbanization, and issues with ownership and land tenure are some of the major obstacles. Conflicting claims, disputes, and uncertainty surrounding land titles can make land acquisition processes more difficult, increasing investment risk and time. In addition to complicated regulations and bureaucratic obstacles, the community's objection stems from concerns about disruptions to livelihoods, environmental effects, and cultural heritage. To overcome these obstacles, a comprehensive plan involving multiple stakeholders is required. By simplifying regulatory frameworks, expediting permitting procedures, and providing unambiguous regulations, governments must first expedite permits and reduce administrative obstacles for developers. Increasing agency coordination can help make land acquisition processes easier. Second, it's critical to foster meaningful engagement and communication with local communities. In summary, overcoming land acquisition challenges requires addressing social and environmental concerns, resolving disputes between conflicting land uses, expediting regulatory processes, and encouraging inclusive decision-making processes. By addressing these challenges, stakeholders may make the most of solar energy to promote energy access, climate change mitigation, and sustainable development in the Global South. To overcome these challenges, cooperation between local communities, governments, international organizations, and businesses is essential. A solar-powered future that breaks down barriers and encourages sustainable development can be achieved through increasing awareness, creating specialized infrastructure, and putting creative financing ideas into practice.

5.2. Policies and drivers.

Policies that support climate resilience significantly help aid in the adoption of solar energy technology, especially in the most vulnerable regions of Developing Countries where the consequences of climate change are most acute. These programs aim to boost the usage of renewable energy sources like solar power by strengthening energy systems and infrastructure's resistance to climate change-related dangers. Policies that promote climate resilience include financial incentives, regulatory frameworks, research and development support, capacity-building initiatives, and adaptation planning to enable the widespread use of solar energy^[5]. Lowering the upfront costs of solar adoption requires financial incentives including tax credits, grants, subsidies, and low-interest loans. These subsidies have made solar energy more affordable for households, companies, and governments. These benefits have made solar energy more affordable for households, businesses, and governments, which encourages investment in solar systems and grows the industry. The clarity, predictability, and confidence that come with the regulatory frameworks established under climatic resilience policies are advantageous to solar energy providers and investors. Renewable energy goals, feed-in tariffs, net metering plans, and interconnection laws are some of the regulatory instruments that facilitate grid integration and promote solar integration into the energy mix^[26]. The smooth integration of solar electricity into existing energy networks is made feasible by these tools. Research, development, and innovation in solar energy technology are also aided by policies that support climate resilience^[27]. By providing funding for research and development, governments can hasten technological advancements, increase efficiency, reduce costs, and enhance the dependability and performance of solar energy systems. This speeds up the adoption and deployment of solar electricity by making it more competitive and marketable. Initiatives for technical assistance and capacity building must be part of policies that support climate resilience. These initiatives increase local expertise in solar energy deployment, operation, and maintenance by lowering adoption barriers and ensuring the long-term growth of solar energy infrastructure. Regulations that include risk management strategies and adaptation planning also help to address the potential impacts of climate change on solar energy infrastructure. By identifying vulnerabilities, assessing risks, and implementing measures to increase resilience to extreme weather events, policymakers may ensure the reliability and durability of solar systems in the face of climatic fluctuation and change. Climate resilience policies provide a framework that promotes the use of solar energy by addressing technical, financial, regulatory, capacity-building, and risk management challenges. By incorporating climate resilience considerations into energy policy and planning processes, governments can hasten the transition to a low-carbon, sustainable energy future powered by solar and other renewable energy sources.

6. BENEFITS OF SOLAR ENERGY IN DEVELOPING COUNTRIES:

6.1. Alleviating Energy poverty

In many regions of the world, energy poverty poses a serious threat to environmental sustainability, economic growth, and human health. Even though living conditions have increased in many developing countries, over 2.7 billion people globally, particularly in Wood and other solid fuels are still used for heating and cooking in developing Asia and Sub-Saharan Africa. In emerging nations, energy poverty is a serious problem that impacts billions of people. All too frequently, people and communities do not have access to reasonably priced and dependable electricity. Lack of power in rural and isolated places not only makes daily living more difficult, but it also impedes the growth of important industries like healthcare, education, and the economy^[27]. One of the strongest arguments in favor of solar energy is the need for greater energy availability. Poverty is indicated and caused by a strong reliance on

inefficient conventional biomass fuels like fuelwood, charcoal, wood waste, agricultural leftovers, and dried animal dung, as well as a lack of access to dependable and reasonably priced sources of energy generation^[1].

6.2. Environmental Benefits: Combating Climate Change

Beyond just producing power, solar energy has many other positive environmental effects. Like the rest of the world, developing nations are battling the effects of climate change, which include altered rainfall patterns, more frequent and severe weather events, and agricultural disruptions. These countries support international efforts to lower greenhouse gas emissions and slow down climate change by implementing solar energy^[25]. Due to its minimal carbon impact, solar energy is a vital tool in the fight against global warming. Photovoltaic systems are an environmentally beneficial and sustainable energy source because they capture solar energy without releasing greenhouse gases. Solar energy improves air quality and public health by replacing fossil fuels in the production of power, which lowers dangerous air pollutants^[27]. This shift to cleaner energy is in line with global climate agreements and paves the way for developing nations to set an example of responsible energy management in addition to lowering their own emissions^[2].

6.3. Economic Benefits: Job creation and Cost Reduction

The Application of solar energy has two financial advantages. First, there are a lot of job creation prospects in this industry. Jobs could be created by the installation, upkeep, and production of solar panels and associated technologies, especially in areas with significant solar potential. These positions support local economies and livelihoods and range in skill level from technicians to engineers. Second, solar energy has the ability to lower energy expenses for both individuals and companies. Solar-powered electricity is becoming more and more competitive with traditional energy sources as the cost of solar technology keeps falling. This decrease in energy costs frees up funds that can be used for infrastructure development, healthcare, education, and other pressing needs. Businesses that have lower energy expenses are more profitable and competitive, which boosts the economy and raises living standards^[25].

6.4. Energy Security: Reducing Dependence on Fossil Fuels

Due to their heavy reliance on imported fossil fuels, developing nations' economy are frequently vulnerable to geopolitical concerns and fluctuating global oil prices. This reliance on imports of fossil fuels may have negative economic effects and compromise energy security in general. By offering a sustainable, local, and indigenous power source, solar energy provides an answer. Solar energy can help developing countries diversify their energy sources and lessen their reliance on outside energy supply interruptions and price swings. Adoption of solar technology increases energy security by stabilizing electricity supply and encouraging independence and economic resilience. Additionally, solar energy can be used in distributed systems that enable local communities to produce their own electricity, including micro grids and rooftop solar panels. Energy security and resilience are further improved by this decentralization of energy production, which lessens the need for long-distance transmission lines and centralized power plants^[25].

Solar energy is a critical step in addressing energy security, economic development, environmental sustainability, and energy access issues. It offers a special opportunity to address the problems of energy

poverty, climate change, and economic inequality. By taking advantage of these opportunities, developing countries may change their energy landscapes, promote sustainable development, and guarantee a cleaner, better future for their people.

7. Barriers and Future Prospects

Even though PV technologies, solar thermal systems, and energy storage solutions have many advantages and have advanced, a number of obstacles still prevent their broad use. These issues must be resolved to hasten the adoption and incorporation of these technologies into the mainstream energy industry. This segment explains the main obstacles, possible solutions, and hopes for the future.

7.1. Cost and Economic viability of Solar energy

Challenges: One potential obstacle to the widespread adoption of PV systems, solar thermal systems, and energy storage options is their initial cost. Financial difficulties may arise from the initial outlay needed for equipment and installation, particularly in areas with few financial resources.

7.2. Strategies to overcome the challenge:

Cost reduction: Research and development activities are ongoing with the goal of bringing down the price of energy storage technologies, PV systems, and solar thermal systems. This covers improvements in system design, material selection, and manufacturing techniques design

Government assistance and incentives: To encourage the use of solar energy, governments might offer grants, tax credits, and other financial incentives solutions for energy storage and related technologies.

These incentives increase the technology's commercial viability and help defray their upfront expenses.

Future prospects: Costs would continue to drop as solar thermal systems, PV technology, and energy storage solutions develop further and larger manufacturing which enables economies of scale.

Furthermore, encouraging laws and incentives can promote broader adoption, increasing the economic appeal of these technologies.

8. Types of PV Technologies

Examining the panorama of PV innovation requires looking at a variety of developed PV technologies. They primarily include cost-effective poly-Si, efficiency-focused mono-Si, monoPERC, and clever half-cut solar cells intended to improve performance.

8.1. Monocrystalline Silicon(Mono-Si) Solar cells

Mono-Si is a cutting-edge PV technology that achieves remarkable energy conversion efficiency by using single-crystal ingots. Mono-Si is a program to differentiate between computer-generated and natural photos and investigates the conversion efficiency of monocrystalline silicon solar cells using statistical distribution law. Additionally included is electrochemical etching for the fabrication of porous silicon, processing techniques, mathematical methods, statistical methods, and experimental procedures to validate statistical methodologies^[28].

8.2. Polycrystalline Silicon(Poly-Si) Solar cells

Poly-Si embraces cost-effectiveness without compromising its potential by using numerous silicon crystals to create a viable option for solar energy generation. The mechanical behavior of polycrystalline silicon solar cells (PSCs) in PV modules. To forecast the homogenized response, they employed a mean-field homogenized scheme and a Voronoi-tessellation scheme using the finite element (FE) method. This study examined the degradation of stiffness brought on by pre-existing micro cracks and contrasted heterogeneous and homogeneous modeling. The homogenized FE solution accurately, computationally, and efficiently depicts a progressive failure in solar cells^[29].

8.3. Monocrystalline Passivated emitter and Rear cell (Mono-PERC).

Through its reflective back surface, Mono-PERC enhances light collection, ushering in a new era of greater efficiency thanks to innovative design. The passive emitter and rear cell (PERC) idea would rule the PV market going forward. Pilot lines, like the GUNAM PV line, link mass-produced products with concepts tested in laboratories. The Mono-PERC can be used in an industrially relevant setting by concentrating on conventional PERC solar cells with a p-type base and Al₂O₃ rear passivation. They computed freshwater eutrophication, Eco toxicity, abiotic depletion potential, human toxicity, global warming, and energy payback time using life cycle assessment (LCA) techniques. Environmental consequences are marginally improved by PERC technology when compared to Al-BSF, but they are decreased by electronic and upgraded metallurgical quality silicon^[30].

8.4. Half Cut Solar Cells

Half-cut solar cells revolutionize the traditional method by drastically lowering shading losses, and redefining the efficiency dynamics of solar cells. By splitting cells in half and improving their connections, researchers have discovered a possible technique to increase output efficiency and reduce energy loss. Half Cut Solar Cells looked into how solar radiation—which includes visible, infrared, and ultraviolet rays—affects solar panel efficiency and performance. High summer temperatures have the potential to reduce voltage and power. Additionally, shade may jeopardize the security and longevity of solar panels. In order to lessen losses brought on by high temperatures and the impact of shade on panel productivity and safety, this article suggests utilizing solar panels with half-cut cells^[31].

8.5. Emerging trends and the Sustainable Development Goals(SDG)

The Sustainable Development Goals (SDGs) center on how humans and nature interact. The objectives are generally intended to support the growth of the ecosystem, economic, and social life. To achieve the goal of a better community and the world, all stakeholders must demonstrate a strong commitment to and track company progress toward the seventeen(17) Sustainable development goals. The three aforementioned sectors of development are mutually and dependently reinforced by all seventeen of the United Nations' stated goals. Executives and managers can assess how well their companies are performing in creating a sustainable future by analyzing operations and progress in light of the SDGs

8.6. The importance of Renewable energy to achieve SDGs.

For the impoverished population, renewable energy offers the chance to expand access to contemporary energy facilities, which is crucial for achieving the SDGs that seek to lessen poverty, hunger, disease and inequality, child labor, and create a sustainable environment. The nation must assess and track the precise amount of renewable energy's contribution to achieving the SDGs, which will spur social and economic advancement

9. RECOMMENDATION:

These are a few recommendations that will enhance the future of Solar energy in developing countries;

Here are five strategic and practical recommendations for solar energy in developing countries:

1. Implement Scalable Off-Grid Solar Solutions

- **Recommendation:** Develop and scale up decentralized solar energy systems, such as solar home systems (SHS) and mini-grids, especially in remote or rural areas lacking grid infrastructure.
- **Practical Steps:**
 - Partner with local governments and NGOs to identify off-grid communities.
 - Provide affordable financing options such as pay-as-you-go models or micro-loans to allow households to invest in solar energy.
 - Offer solar-powered appliances (lights, radios, phone chargers) alongside basic solar systems to improve living standards.

2. Enhance Public-Private Partnerships (PPPs) for Solar Infrastructure

- **Recommendation:** Establish and promote public-private partnerships to leverage the strengths of both sectors in developing large-scale solar projects and improving grid infrastructure.
- **Practical Steps:**
 - Create a supportive policy environment (tax incentives, subsidies) to attract private investments.
 - Collaborate with international development organizations and financial institutions to co-finance solar projects.
 - Focus on long-term, sustainable investments that include the development of the workforce for installation and maintenance.

3. Promote Solar-Integrated Agricultural Solutions

- **Recommendation:** Integrate solar energy into agricultural practices to boost food security, improve productivity, and reduce reliance on traditional, polluting energy sources.
- **Practical Steps:**

- Support the adoption of solar-powered irrigation systems, water pumping, and solar-powered cold storage for preserving food in rural areas.
- Provide training to farmers on how to use solar technology to increase efficiency in farming and reduce costs.
- Create partnerships with agricultural organizations to provide low-cost, solar-powered solutions for food production.

4. Strengthen Local Capacity and Skills for Solar Energy

- **Recommendation:** Focus on building local capacity for the installation, maintenance, and repair of solar energy systems to ensure long-term sustainability and job creation.
- **Practical Steps:**
 - Set up vocational training centers and certification programs in solar energy technology.
 - Encourage private-sector companies to invest in local training programs and internships.
 - Foster partnerships with universities and research institutes to promote innovation in solar technologies and solutions.

5. Facilitate Access to Financing for Solar Projects

- **Recommendation:** Provide accessible and flexible financing mechanisms tailored to the needs of different stakeholders, from low-income households to large-scale businesses and utilities.
- **Practical Steps:**
 - Introduce microfinance options and low-interest loans to help households and small businesses adopt solar solutions.
 - Work with development banks and international funds to create solar-specific financing programs for large-scale projects.
 - Encourage innovative financing models such as "pay-as-you-go" systems for residential solar to reduce the upfront costs of solar technology.

These recommendations are both strategic and practical, addressing key barriers and opportunities for scaling solar energy in developing countries, while fostering local ownership and long-term sustainability.

CONCLUSION:

Solar energy is one of developing countries' most promising renewable energy sources. It is highly reliable and not overly susceptible to variations in seasonal weather patterns. Both solar thermal and solar photovoltaic (PV) methods can be used to harness sun energy for various purposes. Solar-powered power is not only comparatively easier to produce but it is also far more ecologically beneficial than producing electricity from non-renewable resources like coal and fossil fuels. Changing to solar energy may be a wise decision given that global energy consumption has been rising over time.

It is clear from the analysis that nearly every nation that uses solar energy to generate electricity has solar-specific laws. Solar energy use in the United States, Canada, Germany, Spain, Australia, China, and France are a few of the success stories.

The implementation of solar energy policies in these nations has greatly increased the production of solar power. Generally speaking, the policies of the majority of nations include renewable portfolio mandates, tax exemptions, subsidies, feed-in tariffs, and formation incentives.

The effects of negative externalities on human health, the environment, economic development, or institutional goals like emissions growth management have been more and more the focus of policy evaluations worldwide.

The governments of developing countries have developed a number of policies on renewable energy development, including laws, regulations, economic incentives, technical research and development, industrialized support, and renewable energy model projects, to encourage and guarantee the quick, efficient, and seamless development of renewable energy.

Even with these developments, several obstacles still exist. To fully achieve the potential of solar technology, issues pertaining to cost competitiveness, manufacturing scalability, efficiency, stability, grid integration, environmental effect, legislative support, and public acceptance must be resolved.

It will take sustained investment in R&D, encouraging legislation, and cooperation from other industries to overcome these obstacles.

For solar technology, the future is bright. There is potential for even higher efficiency and uses with emerging trends like artificial photosynthesis, floating solar farms, next-generation photovoltaics, and enhanced energy storage. Solar technology stands out as a crucial remedy as the globe struggles with the effects of climate change and the demand for sustainable energy.

DISCLAIMER: (Artificial Intelligence)

Author (s) hereby declare that NO generative AI technology such as Large Language models (ChatGPT, COPILOT, etc) have been used during the writing or editing of manuscripts.

References :

- [1] OMER A M. Energy, environment and sustainable development [J]. *Renewable and Sustainable Energy Reviews*, 2008, 12(9): 2265-300.
- [2] KALOGIROU S A. Environmental benefits of domestic solar energy systems [J]. *Energy Conversion and Management*, 2004, 45(18): 3075-92.
- [3] HOSENUZZAMAN M, RAHIM N A, SELVARAJ J, et al. Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation [J]. *Renewable and Sustainable Energy Reviews*, 2015, 41: 284-97.
- [4] BLACK G, TAYLOR BLACK M A, SOLAN D, et al. Carbon free energy development and the role of small modular reactors: A review and decision framework for deployment in developing countries [J]. *Renewable and Sustainable Energy Reviews*, 2015, 43: 83-94.
- [5] YIN H, POWERS N. Do state renewable portfolio standards promote in-state renewable generation? [J]. *Energy Policy*, 2010, 38(2): 1140-9.
- [6] STADELMANN M, CASTRO P. Climate policy innovation in the South – Domestic and international determinants of renewable energy policies in developing and emerging countries [J]. *Global Environmental Change*, 2014, 29: 413-23.
- [7] MBOUMBOUE E, NJOMO D. Potential contribution of renewables to the improvement of living conditions of poor rural households in developing countries: Cameroon 's case study [J]. *Renewable and Sustainable Energy Reviews*, 2016, 61: 266-79.
- [8] MOHAMMED Y S, MUSTAFA M W, BASHIR N. Status of renewable energy consumption and developmental challenges in Sub-Sahara Africa [J]. *Renewable and Sustainable Energy Reviews*, 2013, 27: 453-63.
- [9] SHARMA A, CHEN C R, VU LAN N. Solar-energy drying systems: A review [J]. *Renewable and Sustainable Energy Reviews*, 2009, 13(6): 1185-210.
- [10] KUMAR A, FERDOUS R, LUQUE-AYALA A, et al. Solar energy for all? Understanding the successes and shortfalls through a critical comparative assessment of Bangladesh, Brazil, India, Mozambique, Sri Lanka and South Africa [J]. *Energy Research & Social Science*, 2019, 48: 166-76.
- [11] D'ALESSANDRO S, LUZZATI T, MORRONI M. Energy transition towards economic and environmental sustainability: feasible paths and policy implications [J]. *Journal of Cleaner Production*, 2010, 18(6): 532-9.
- [12] TYAGI V V, KAUSHIK S C, TYAGI S K. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology [J]. *Renewable and Sustainable Energy Reviews*, 2012, 16(3): 1383-98.
- [13] LI K, LIU C, JIANG S, et al. Review on hybrid geothermal and solar power systems [J]. *Journal of Cleaner Production*, 2020, 250: 119481.

- [14] WISER R, MILLSTEIN D, MAI T, et al. The environmental and public health benefits of achieving high penetrations of solar energy in the United States [J]. *Energy*, 2016, 113: 472-86.
- [15] KRISTIANSEN A B, MA T, WANG R Z. Perspectives on industrialized transportable solar powered zero energy buildings [J]. *Renewable and Sustainable Energy Reviews*, 2019, 108: 112-24.
- [16] SAGARIA S, DUARTE G, NEVES D, et al. Photovoltaic integrated electric vehicles: Assessment of synergies between solar energy, vehicle types and usage patterns [J]. *Journal of Cleaner Production*, 2022, 348: 131402.
- [17] KANAGAWA M, NAKATA T. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries [J]. *Energy Policy*, 2008, 36(6): 2016-29.
- [18] YU J, TANG Y M, CHAU K Y, et al. Role of solar-based renewable energy in mitigating CO₂ emissions: Evidence from quantile-on-quantile estimation [J]. *Renewable Energy*, 2022, 182: 216-26.
- [19] MUDAHERANWA E, NTAGWIRUMUGARA E, MASENGO G, et al. Microgrid design for disadvantaged people living in remote areas as tool in speeding up electricity access in Rwanda [J]. *Energy Strategy Reviews*, 2023, 46: 101054.
- [20] MOSTAFAEIPOUR A, JADIDI M, MOHAMMADI K, et al. An analysis of wind energy potential and economic evaluation in Zahedan, Iran [J]. *Renewable and Sustainable Energy Reviews*, 2014, 30: 641-50.
- [21] LIN B, KAEWKHUNOK S. The role of socio-Culture in the solar power adoption: The inability to reach government policies of marginalized groups [J]. *Renewable and Sustainable Energy Reviews*, 2021, 144: 111035.
- [22] WEKO S, GOLDTHAU A. Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South [J]. *Energy Policy*, 2022, 169: 113192.
- [23] HAQUE A N, LEMANSKI C, DE GROOT J. Why do low-income urban dwellers reject energy technologies? Exploring the socio-cultural acceptance of solar adoption in Mumbai and Cape Town [J]. *Energy Research & Social Science*, 2021, 74: 101954.
- [24] ADENLE A A. Assessment of solar energy technologies in Africa-opportunities and challenges in meeting the 2030 agenda and sustainable development goals [J]. *Energy Policy*, 2020, 137: 111180.
- [25] ENDIZ M S, COŞGUN A E. Assessing the potential of solar power generation in Turkey: A PESTLE analysis and comparative study of promising regions using PVsyst software [J]. *Solar Energy*, 2023, 266: 112153.
- [26] GÓMEZ A, ZUBIZARRETA J, DOPAZO C, et al. Spanish energy roadmap to 2020: Socioeconomic implications of renewable targets [J]. *Energy*, 2011, 36(4): 1973-85.
- [27] SAMPAIO P G V, GONZÁLEZ M O A. Photovoltaic solar energy: Conceptual framework [J]. *Renewable and Sustainable Energy Reviews*, 2017, 74: 590-601.
- [28] SUN J, ZUO Y, SUN R, et al. Research on the conversion efficiency and preparation technology of monocrystalline silicon cells based on statistical distribution [J]. *Sustainable Energy Technologies and Assessments*, 2021, 47: 101482.
- [29] BOULMRHARJ S, BAKHOUYA M, KHAIDAR M. Performance evaluation of grid-connected silicon-based PV systems integrated into institutional buildings: An experimental and simulation comparative study [J]. *Sustainable Energy Technologies and Assessments*, 2022, 53: 102632.
- [30] M. LUNARDI M, ALVAREZ-GAITAN J P, CHANG N L, et al. Life cycle assessment on PERC solar modules [J]. *Solar Energy Materials and Solar Cells*, 2018, 187: 154-9.
- [31] KHAN F, ALSHAHRANI T, FAREED I, et al. A comprehensive degradation assessment of silicon photovoltaic modules installed on a concrete base under hot and low-humidity environments: Building applications [J]. *Sustainable Energy Technologies and Assessments*, 2022, 52: 102314.

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