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Review of penetration and impact of utility solar installation in developing countries: policy and challenges

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Abstract

This review examines the penetration and impact of utility-scale solar installations in developing countries, focusing on the policy landscape and challenges associated with their adoption. Solar energy has emerged as a vital component of the global shift towards renewable energy, offering substantial potential for alleviating energy poverty and fostering sustainable development in regions with abundant solar resources. Despite these opportunities, the penetration of utility-scale solar in developing countries faces several barriers. These include financial constraints, inconsistent policy frameworks, technological challenges, and social acceptance issues. This review explores the current status of solar energy adoption, highlighting regional trends and key countries such as Kenya, India, and South Africa, which have made significant strides in solar deployment. It assesses the economic, social, and environmental impacts of utility solar projects, emphasizing their role in job creation, electrification, and climate change mitigation. However, challenges such as high initial costs, limited access to financing, weak grid infrastructure, and regulatory bottlenecks continue to impede broader adoption. Policy and regulatory support are critical to overcoming these challenges. This review outlines the national and international frameworks that influence solar energy penetration, as well as the incentives, subsidies, and financing mechanisms available. Recommendations include streamlining regulatory processes, improving access to finance through innovative models, and enhancing grid infrastructure. Finally, the review discusses future trends, including advancements in solar technology, energy storage, and smart grid integration, which could accelerate the growth of solar installations in developing countries. The findings underscore the need for comprehensive strategies that address policy, financial, and social challenges to fully realize the potential of solar energy in these regions.

Keywords: Solar Installation; Developing countries Policy; Challenges

1. Introduction

Global energy trends are undergoing a fundamental shift as countries around the world face growing pressure to transition away from fossil fuels and adopt cleaner, renewable energy sources (Tian *et al.*, 2022). The traditional reliance on coal, oil, and natural gas has led to significant environmental challenges, including air pollution and global climate change. This has intensified the focus on renewable energy as a key component of future energy systems (Bassey, 2022). Renewable energy sources like wind, hydropower, and especially solar power are becoming increasingly important in the global energy mix. Solar energy, in particular, has emerged as one of the fastest-growing sectors due to its scalability, declining costs, and technological advancements (Tabassum *et al.*, 2-021). Among renewable sources, utility-scale solar installations large solar farms that generate electricity for distribution via grid

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networks have seen a notable rise. As the cost of photovoltaic (PV) technology decreases, solar has become competitive with traditional energy sources in many parts of the world (Timilsina, 2021). Countries such as the United States, China, and India have led the way in large-scale solar deployment, significantly increasing global solar capacity. Solar energy's importance is underscored by its ability to provide a clean, abundant, and decentralized energy source, making it a critical component in the pursuit of global climate targets and sustainable development goals (Zahmatkesh *et al*., 2022).

Solar energy plays an especially crucial role in developing countries, where energy poverty remains a significant challenge (Agyekum, 2020). Many developing nations struggle with unreliable power grids, limited access to electricity, and an overreliance on expensive or polluting energy sources. According to the International Energy Agency (IEA), over 770 million people worldwide still lack access to electricity, with the majority residing in sub-Saharan Africa and parts of Asia. This energy deficit stifles economic growth, restricts access to education, healthcare, and clean water, and perpetuates poverty cycles. Utility-scale solar energy presents an opportunity for developing countries to leapfrog traditional fossil fuel-based energy systems and transition directly to clean, renewable energy (Ram *et al*., 2022). The abundant solar resources in many developing regions make solar a particularly viable option. Solar power can help address energy poverty by expanding access to electricity, particularly in rural or off-grid areas, while reducing dependence on costly fuel imports. Moreover, the adoption of solar energy contributes to sustainable development by promoting low-carbon economic growth, reducing greenhouse gas emissions, and enhancing energy security. The potential for solar energy to drive socio-economic development is vast (Anam *et al*., 2022). In addition to providing a reliable and affordable energy supply, solar installations can create jobs, improve public health by reducing air pollution, and promote technological innovation. Solar energy also aligns with global efforts to meet the United Nations Sustainable Development Goals (SDGs), particularly Goal 7, which aims to ensure access to affordable, reliable, and modern energy for all.

This review aims to provide an in-depth examination of the penetration and impact of utility-scale solar installations in developing countries. While solar energy offers tremendous potential, its widespread adoption in these regions faces numerous challenges. The review will explore the current state of solar energy adoption, focusing on key regions and countries where large-scale solar projects have been implemented. Additionally, this analyze the policy frameworks that govern solar energy development in developing countries. Policy plays a crucial role in determining the success of renewable energy projects. It can either facilitate the rapid deployment of solar installations through supportive regulations and incentives or hinder progress due to bureaucratic hurdles, financial constraints, and inconsistent regulatory environments. This review will assess how national policies, international agreements, and market mechanisms influence the penetration of solar energy. Finally, the review will address the significant challenges that developing countries face in adopting utility-scale solar. These challenges include financial barriers, such as the high upfront costs of solar projects, limited access to affordable financing, and weak grid infrastructure (Orie and Christian, 2015). Additionally, it will explore technological hurdles, including the intermittency of solar power and the need for advanced energy storage solutions. Social acceptance and land-use conflicts will also be examined, as they play a critical role in the successful implementation of large-scale solar projects. By examining the penetration, policy environment, and challenges of utility-scale solar installations in developing countries, this review seeks to highlight the opportunities and obstacles in realizing the full potential of solar energy for sustainable development.

2. Current Penetration of Utility-Scale Solar Installations

Utility-scale solar installations have experienced rapid growth worldwide, with significant regional variation in adoption (Nilson and Stedman, 2022). Globally, solar photovoltaic (PV) capacity has increased exponentially, with major solar markets like China, the United States, and India driving the bulk of this expansion. These countries have implemented large-scale solar projects to meet growing energy demands while transitioning away from fossil fuels. In developing regions, utility-scale solar is gaining traction, particularly in Asia, Africa, and Latin America. South and Southeast Asia, led by India, have seen some of the most dramatic increases in solar capacity. India, in particular, is a global leader in utility-scale solar, with major projects like the Bhadla Solar Park, which has a capacity of over 2.2 GW. In Africa, utility-scale solar is emerging as a key solution to energy poverty, with countries like South Africa and Morocco leading the way in installed capacity (Brunet *et al*., 2022). South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has been instrumental in driving large-scale solar investments. Morocco has also made significant strides with its Noor Ouarzazate complex, one of the largest solar installations in the world. Despite these successes, many regions in sub-Saharan Africa and parts of Southeast Asia still lag behind in solar penetration due to financial, infrastructural, and regulatory barriers. However, the global trend indicates increasing momentum toward renewable energy, and utility-scale solar projects in these regions are expected to rise as technology becomes more affordable and policies more supportive (Bassey, 2023; Mathew and Ejiofor, 2023).

Several key factors are driving the adoption of utility-scale solar installations across developing regions. Many countries have introduced financial incentives to stimulate investment in solar energy (Qadir *et al*., 2021). These include tax credits, feed-in tariffs, and subsidies for renewable energy projects. Moreover, the cost of generating electricity from utility-scale solar plants has become highly competitive with traditional fossil fuel-based energy sources. In some regions, solar is now the cheapest form of electricity generation. The economic benefits of solar are further amplified by its scalability and ability to provide energy to rural or off-grid areas, making it a cost-effective solution for addressing energy poverty. Many developing countries are located in regions with high solar irradiance, which makes solar energy particularly attractive. Countries near the equator, such as Kenya, India, and Nigeria, benefit from year-round sunshine, providing ideal conditions for solar PV systems (Sulaiman, 2021). This geographic advantage reduces the levelized cost of electricity (LCOE) from solar projects, making them more financially viable in these regions compared to others with lower irradiance. The cost of PV technology has declined sharply over the past decade, driven by advances in manufacturing, efficiency improvements, and economies of scale. In 2020, the global weighted-average LCOE of utility-scale solar PV projects dropped by 85% since 2010. This dramatic reduction in costs has enabled developing countries to afford large-scale solar projects, even with limited financial resources. The decreasing cost of energy storage systems has also helped address the intermittency challenge of solar power, further supporting its adoption (Worku, 2022).

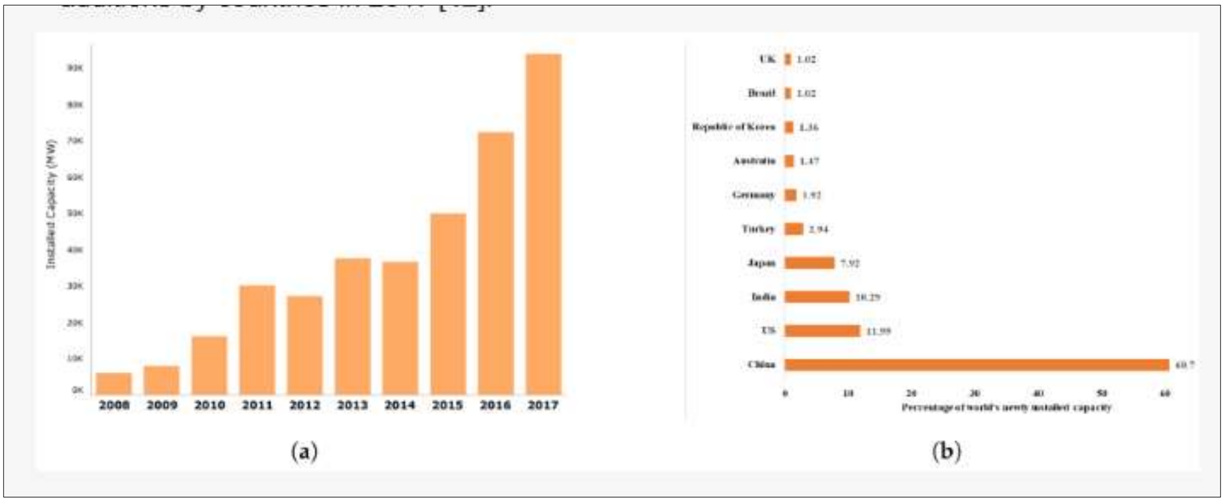

Figure 1 (a) Yearly global PV capacity additions (IRENA, 2015); (b) % of global PV capacity additions by countries in 2017 (Olowu et al., 2018)

Kenya has emerged as a leader in solar energy development in East Africa. The Garissa Solar Power Plant, with a capacity of 54 MW, is one of the largest utility-scale solar projects in the region. The project has helped diversify Kenya's energy mix, which has historically relied on hydropower. Additionally, it has contributed to reducing Kenya's carbon emissions while addressing the nation's energy deficit. With ongoing solar developments, Kenya is poised to increase its renewable energy share significantly. India's success in utility-scale solar is a global benchmark (Ngome and Yeom, 2023). The country has committed to ambitious solar targets under its National Solar Mission, aiming for 100 GW of solar capacity by 2022, of which a significant portion is expected to come from large-scale installations. The Bhadla Solar Park, located in Rajasthan, is one of the largest solar parks in the world, with over 2.2 GW of capacity. India's rapid expansion of solar energy is attributed to strong government support, favorable policies, and significant cost reductions in PV technology. South Africa's REIPPPP has positioned the country as a solar leader on the African continent. The program has attracted substantial private sector investment and resulted in several large-scale solar installations. One notable example is the Kathu Solar Park, a concentrated solar power (CSP) facility with a capacity of 100 MW. South Africa's solar projects have contributed to alleviating the country's electricity shortages and reducing its reliance on coal.

The current penetration of utility-scale solar installations in developing countries highlights both significant progress and ongoing challenges (Bassey and Ibegbulam, 2023). While countries like India, Kenya, and South Africa have made remarkable strides, many other regions still face financial and infrastructural barriers. However, as solar technology continues to advance and costs decline, utility-scale solar is likely to become an even more integral part of the energy landscape in developing regions. With supportive policies and investment, the adoption of solar energy could play a crucial role in addressing energy poverty and driving sustainable development in the years to come (Kylili *et al*., 2021; Mathew and Adu-Gyamfi, 2024).

2.1. Impact of Utility Solar Installations on Developing Countries

Utility-scale solar installations have emerged as a transformative force in many developing countries, offering numerous economic, social, and environmental benefits (Swilling *et al*., 2022). These installations, by generating large amounts of renewable energy, address critical challenges such as energy poverty, fossil fuel dependency, and climate change. However, there are also challenges, including land use and ecosystem concerns, that need careful management.

The economic impact of utility-scale solar installations in developing countries is significant, particularly in terms of job creation and economic growth. Solar energy projects provide employment opportunities across various sectors, from manufacturing and construction to operations and maintenance (Majid, 2020). For instance, large-scale solar projects require a substantial workforce for their development, including engineers, technicians, and laborers. Once operational, these installations continue to create jobs in maintenance and monitoring, contributing to long-term employment in regions where job opportunities may be scarce. Moreover, the solar energy industry drives demand for related sectors such as manufacturing of PV components, logistics, and services (Mastrocinque *et al*., 2022). In addition to job creation, utility-scale solar installations reduce developing countries' reliance on fossil fuels and energy imports. Many developing nations, particularly in Africa and Asia, rely on costly imported fossil fuels to meet their energy needs. This dependency not only strains national budgets but also exposes economies to volatile global oil and gas markets. By harnessing domestic solar resources, countries can diversify their energy mix, reduce fuel import costs, and enhance energy security. This shift towards renewable energy can free up financial resources for other critical sectors such as healthcare, education, and infrastructure development, fostering broader economic growth (Ng e al., 2021; Bassey, 2022).

The social impact of utility-scale solar installations in developing countries is closely tied to improved energy access, particularly in rural areas (Sward *et al*., 2021). In many developing nations, large segments of the population still lack access to reliable electricity. Solar energy, with its decentralized nature, can provide power to remote and underserved areas where grid extension is costly and logistically challenging. Utility-scale solar installations, combined with mini-grid systems or off-grid solutions, can dramatically improve electrification rates, helping to bridge the energy access gap. Access to reliable electricity has far-reaching social benefits. It enables the provision of essential services such as healthcare, education, and clean water, all of which are closely linked to improved quality of life (Mathew, 2024). For example, schools with electricity can adopt technology-enhanced learning, and health clinics with power can offer better medical services, including vaccine refrigeration and emergency care. Additionally, clean energy access through solar power reduces reliance on traditional energy sources such as kerosene or biomass, which are hazardous to health and the environment (Khan *et al*., 2024). By providing a safer and more sustainable energy option, utility-scale solar projects contribute to enhancing the overall quality of life in developing regions.

The environmental impact of utility-scale solar installations is a major advantage, especially in terms of mitigating climate change. Developing countries are particularly vulnerable to the effects of climate change, including extreme weather events, rising temperatures, and shifting rainfall patterns (Clarke *et al*., 2022). Utility-scale solar installations help combat these challenges by significantly reducing greenhouse gas (GHG) emissions. Solar power generation produces zero emissions during operation, which means that each megawatt-hour (MWh) of solar energy displaces the equivalent amount of electricity generated from fossil fuels like coal or natural gas. This leads to a substantial reduction in carbon dioxide (CO2) emissions and contributes to the global effort to meet climate targets. Furthermore, utility-scale solar installations reduce air pollution associated with fossil fuel combustion. In many developing countries, air quality is a pressing issue due to high levels of particulate matter and toxic emissions from coal plants, vehicle exhaust, and industrial activities (Anjum *et al*., 2021). Solar energy, by providing a cleaner alternative, can help improve public health by reducing air pollution and related respiratory diseases. However, there are environmental challenges associated with utility-scale solar projects, particularly related to land use and ecosystem disturbances. Large solar farms require substantial amounts of land, which can lead to conflicts with agricultural use or the displacement of local communities. Additionally, the construction of solar projects may disrupt local ecosystems, particularly in biodiverse or sensitive areas (Malunguja and Paschal, 2024). Solar installations can affect wildlife habitats and lead to soil degradation if not carefully managed. To mitigate these challenges, some projects adopt innovative solutions such as dual-use solar farms, where solar panels are installed on degraded or unused land, or in combination with agricultural activities (agrivoltaics), allowing for both energy production and farming (Guarino and Swanson, 2022; Bassey *et al*., 2024).

Utility-scale solar installations offer developing countries numerous benefits, including economic growth, job creation, enhanced social welfare through electrification, and significant environmental advantages, particularly in reducing GHG emissions and combating climate change (Heeter and Reames, 2022; Mathew and Fu, 2024). While challenges related to land use and ecosystem disturbances must be addressed, the overall impact of solar energy on developing nations is overwhelmingly positive. As solar technology becomes more affordable and accessible, it is poised to play a central role in promoting sustainable development, improving energy security, and reducing poverty across the developing world.

2.2. Policy Landscape for Utility Solar in Developing Countries

The policy landscape for utility-scale solar installations in developing countries plays a critical role in accelerating the adoption of renewable energy (Chowdhury, 2020). National policies, international agreements, and support mechanisms are key drivers of solar energy development. However, challenges remain, including financing gaps, regulatory hurdles, and the need for coordinated efforts between governments, international bodies, and private sector stakeholders.

National policies are crucial for setting the direction and pace of solar energy development in developing countries. Many governments have set ambitious solar and renewable energy targets to meet both domestic energy needs and global climate goals (Praveen *et al*., 2020). For instance, India's National Solar Mission aims for 100 GW of solar power by 2022, reflecting the country's commitment to becoming a global solar leader. Similarly, Kenya's Vision 2030 includes substantial investments in renewable energy, particularly solar, to diversify the country's energy mix and enhance energy security. These national targets are often embedded within broader policy frameworks that support renewable energy adoption. Policy tools such as renewable energy mandates, energy transition plans, and climate action strategies are commonly used to integrate solar energy into national energy grids (Williges *et al*., 2022). Some countries have also created dedicated institutions or ministries to oversee renewable energy development, such as the Renewable Energy Agency in Ghana or India's Ministry of New and Renewable Energy. These entities ensure that solar projects align with national development priorities, such as energy access, economic growth, and environmental sustainability. However, not all developing countries have comprehensive solar policies in place. In regions where institutional capacity or financial resources are limited, the lack of coherent policy frameworks can hinder the growth of solar energy. Policy uncertainty, regulatory barriers, and a lack of transparency in tendering processes can deter private investment and slow down solar adoption (Bassey, 2023).

International organizations and global agreements significantly influence the policy landscape for utility-scale solar in developing countries. The Paris Agreement, for instance, has prompted many nations to adopt renewable energy strategies as part of their nationally determined contributions (NDCs) to reduce greenhouse gas emissions (Ouedraogo, 2020; Laudari *et al*., 2021). These commitments are crucial in driving solar energy expansion, as they often come with technical assistance and funding support from international organizations. In addition to climate agreements, international donors and financial institutions play a pivotal role in supporting solar energy projects in developing countries. The World Bank, for example, has initiated the Scaling Solar program, which aims to create a standardized approach to solar project development in Africa (Soumonni and Ojah, 2022). Similarly, the African Development Bank (AfDB) and the International Renewable Energy Agency (IRENA) provide funding, policy guidance, and technical support to countries seeking to expand their renewable energy capacity. These international efforts help to bridge financing gaps and reduce the risks associated with large-scale solar investments. The Green Climate Fund (GCF) is another critical player, providing financing to developing countries for climate mitigation and adaptation projects. Through GCF-supported initiatives, developing nations can access concessional financing and grants to support the deployment of utility-scale solar projects, thereby accelerating their transition to renewable energy (Bassey, 2023).

Developing countries have implemented various incentives and support mechanisms to encourage utility-scale solar installations (Mathew and Orie, 2015). Feed-in tariffs (FiTs), tax breaks, and subsidies are common tools used to attract investment in solar energy. Feed-in tariffs guarantee a fixed price for electricity generated from renewable sources, ensuring that solar developers receive predictable revenue for their energy output. Countries like South Africa and Uganda have implemented FiTs to stimulate solar energy development, making utility-scale projects more financially viable. Tax breaks and subsidies also play a key role in reducing the cost of solar energy projects. By offering tax exemptions or reductions on solar equipment imports, governments can lower the initial capital investment required for solar projects (Ding *et al*., 2020). Subsidies for solar energy production or investment can further enhance the financial attractiveness of these projects. Kenya, for example, has provided tax exemptions on solar equipment to reduce the financial burden on investors and encourage the adoption of renewable energy technologies. Public-private partnerships (PPPs) have also been effective in fostering investment in solar infrastructure (Awuku *et al*., 2021). These partnerships allow governments to collaborate with private sector entities to share the risks and costs associated with large-scale solar projects. South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) is a notable example of a successful PPP. Through competitive bidding processes, the program has attracted billions of dollars in private investment for solar and other renewable energy projects, contributing significantly to the country's energy transition. In addition to national and international incentives, investment in grid infrastructure is crucial to accommodate the integration of utility-scale solar power (Bassey *et al*., 2024). Many developing countries face challenges with outdated or inadequate transmission networks, which limit the potential of large-scale solar projects. As a result, governments and international partners are focusing on upgrading grid infrastructure to ensure that solar power can be efficiently transmitted and distributed.

The policy landscape for utility-scale solar installations in developing countries is shaped by a combination of national policies, international agreements, and incentive mechanisms (Lockwood, 2022). While many countries have set ambitious solar targets and implemented supportive policy frameworks, challenges remain in terms of financing, regulatory hurdles, and grid infrastructure. International organizations and financial institutions play a crucial role in providing the necessary support to overcome these barriers, while incentives such as feed-in tariffs, tax breaks, and public-private partnerships are instrumental in attracting investment. As developing countries continue to prioritize renewable energy, utility-scale solar installations are expected to play an increasingly vital role in their sustainable development trajectories (Bassey *et al*., 2024).

2.3. Challenges in Solar Installation Penetration

Solar energy holds tremendous potential for addressing energy poverty and promoting sustainable development, particularly in developing countries (Zhao *et al*., 2022). However, the penetration of utility-scale solar installations faces several challenges that hinder widespread adoption. These challenges encompass financial and economic barriers, policy and regulatory hurdles, technological limitations, and social and cultural obstacles. Understanding and addressing these issues are crucial to accelerating the deployment of solar energy on a global scale (Li *et al*., 2022).

One of the primary challenges to the penetration of solar installations is the high upfront capital costs (Mathew, 2024). Developing countries often lack the financial resources needed to invest in large-scale solar projects. The cost of solar photovoltaic (PV) panels, inverters, land acquisition, and installation infrastructure can be prohibitive, especially in regions with limited access to financing. While the cost of solar technology has declined significantly over the past decade, financing options remain limited in many developing countries. Local banks and financial institutions may have limited experience or willingness to fund solar projects, further constraining the availability of capital. Currency instability and exchange rate risks also pose significant barriers, particularly for foreign investors (Trusova *et al*., 2022). In many developing countries, fluctuating currency values can result in unpredictable project costs, making long-term investments in solar energy more risky. For instance, a sharp depreciation in local currency could increase the cost of imported solar equipment or make it difficult for developers to service debt in foreign currency. This financial volatility often deters foreign investors, who play a critical role in funding large-scale solar projects. Additionally, developing countries may face high borrowing costs due to perceived political and economic risks, further complicating efforts to secure financing for solar installations (Bassey *et al*., 2024).

Inconsistent policy frameworks and a lack of regulatory clarity can impede the growth of utility-scale solar projects. Many developing countries do not have well-defined or stable renewable energy policies, leading to uncertainty for investors and project developers (Mathew, 2024). Sudden changes in policies, such as the reduction or removal of subsidies or feed-in tariffs, can have a detrimental impact on the financial viability of solar projects. Moreover, a lack of long-term policy commitment can make it difficult for investors to plan for the future, as they may be unsure of the regulatory environment in which they will be operating (Deschryver and De Mariz, 2020; Boston, 2021). Delays in permitting and approvals for solar projects also pose significant challenges. In many cases, the process for obtaining the necessary permits and approvals is slow, bureaucratic, and lacks transparency. This can cause lengthy delays in the development of solar installations, increasing project costs and deterring potential investors (Mahbub *et al*., 2022). In countries with decentralized governance, conflicting regulations between national and local authorities can further complicate the approval process, causing confusion and inefficiencies. These regulatory barriers can create significant roadblocks for solar energy projects, preventing timely development and grid integration.

Technological and infrastructure challenges also limit the penetration of utility-scale solar installations, particularly in rural and remote areas (Bassey *et al*., 2024). One of the most significant issues is the lack of adequate grid infrastructure to support large-scale solar energy integration. In many developing countries, existing electrical grids are outdated or insufficiently developed to handle the variability of solar energy generation (Iweh *et al*., 2021). Poor grid connectivity can lead to inefficiencies in transmitting solar power to where it is needed, resulting in energy losses and limiting the potential for solar energy deployment. Additionally, the remote locations of many potential solar project sites pose technological and maintenance challenges. These areas often lack access to reliable infrastructure, making it difficult to transport materials and equipment. Furthermore, maintaining solar installations in remote regions can be costly and complicated due to limited access to skilled technicians and spare parts. Technical expertise may be required to manage complex solar systems, especially when dealing with issues such as energy storage, inverter malfunctions, or system degradation over time (Sutikno *et al*., 2022). The absence of adequate technical support can increase maintenance costs and reduce the operational efficiency of solar installations in these areas.

Social and cultural factors can also impede the expansion of solar energy projects. In some cases, communities may resist the construction of large-scale solar installations due to concerns about land use, environmental impact, or perceived disruption to their way of life (Silva and Sareen, 2021). For example, the large land area required for solar farms can lead to conflicts over land ownership or usage rights, particularly in regions where land is a scarce or valuable resource. These disputes may slow down the development of solar projects or even halt them entirely if consensus cannot be reached among stakeholders. A lack of public awareness and education about the benefits of solar energy can further contribute to resistance (Mathew, 2023). In some regions, communities may not fully understand the environmental and economic advantages of solar power, leading to skepticism or opposition to new projects. Public outreach and engagement are essential for gaining local support, as successful solar projects often require collaboration with communities and local stakeholders. Without adequate community involvement and awareness-building efforts, solar installations may face delays or opposition due to a lack of social acceptance (Bassey, 2024).

The penetration of utility-scale solar installations in developing countries is hindered by a combination of financial, regulatory, technological, and social challenges. High upfront costs, limited financing options, currency instability, and inconsistent policy frameworks present significant barriers to solar energy adoption (Oryani *et al*., 2021). Technological and infrastructure issues, such as inadequate grid connectivity and maintenance challenges in remote areas, further complicate efforts to expand solar energy. Additionally, social and cultural barriers, including community resistance and land disputes, must be addressed to ensure the successful implementation of solar projects. Overcoming these challenges will require coordinated efforts between governments, international organizations, private investors, and local communities to unlock the full potential of solar energy in developing regions (Barua, 2020; Mathew and Fu, 2024).

2.4. Solutions on Widespread Adoption of Solar Energy

To overcome the challenges hindering the penetration of utility-scale solar installations in developing countries, a multi-faceted approach involving policy reforms, financial innovation, technological improvements, and social engagement is essential (Wilkinson *et al*., 2021; Mathew and Fu, 2023). These solutions can drive the widespread adoption of solar energy, contribute to sustainable development, and help mitigate climate change.

One of the key steps toward accelerating solar installation is to streamline regulatory processes. In many developing countries, delays in obtaining permits and approvals significantly slow down solar projects. Governments should simplify and expedite these procedures by reducing bureaucratic red tape and creating transparent, efficient pathways for project developers (Mergel, 2021). Establishing one-stop regulatory bodies that coordinate across different sectors could facilitate faster project approvals and eliminate overlapping or contradictory regulations. Streamlining the process ensures that solar installations are deployed quickly, reducing costs and fostering investor confidence. Stable and supportive policy frameworks are also critical for long-term solar energy growth. Governments must develop clear, long-term renewable energy targets and policies that provide certainty to investors and developers. These policies should include financial incentives like feed-in tariffs, tax breaks, and subsidies to encourage solar investment (Babich *et al*., 2020). Furthermore, policies must be adaptable to technological advancements and evolving market conditions. Stability and clarity in policy frameworks reduce investor risk, fostering greater participation from both local and international players in solar energy projects.

To overcome financial barriers, innovative financing models should be adopted to make solar installations more accessible. Green bonds, which allow investors to support environmentally sustainable projects, can be leveraged to fund large-scale solar initiatives. Micro-financing schemes can also enable smaller communities and individuals to access solar energy, especially in rural areas where grid connectivity is weak (Robert *et al*., 2021). These models provide flexibility for diverse stakeholders and address the high upfront costs associated with solar energy deployment. Additionally, international climate finance can be a significant driver of solar adoption. Developing countries can tap into funds from global initiatives like the Green Climate Fund or the Climate Investment Funds. These financial resources can help lower the costs of solar infrastructure and reduce the financial burden on governments and local institutions. By leveraging international climate finance, developing nations can bridge the gap between high initial costs and the long-term benefits of solar energy (Prasad *et al*., 2022).

Technological advancements and infrastructure improvements are essential for supporting the growth of utility-scale solar installations (Singh and Pandey, 2021). One key area of focus is investment in grid modernization. Many developing countries lack the grid infrastructure necessary to integrate large amounts of solar energy. Modernizing grids and incorporating smart technologies will enable more efficient energy transmission and storage. In addition, energy storage solutions, such as battery systems, should be prioritized to address the intermittent nature of solar power and ensure a stable energy supply. Capacity building for the local solar industry is another crucial element. Developing local expertise in solar installation, maintenance, and manufacturing can reduce dependency on foreign technology and expertise, which are often costly (Behuria, 2020). This can be achieved through vocational training programs, government-led incentives for solar entrepreneurship, and collaboration with international organizations. By building local capacity, developing countries can create a self-sustaining solar industry that drives job creation and economic growth.

Effective social and community engagement is vital for the successful deployment of solar energy projects. Raising public awareness about the benefits of solar energy through campaigns can help counter community resistance and build support for solar installations (Crawford *et al*., 2022). These awareness campaigns should emphasize the environmental and economic advantages of solar power, such as reducing greenhouse gas emissions, creating jobs, and improving energy access in rural areas. Additionally, involving local communities in the planning and decision-making processes of solar projects fosters a sense of ownership and increases the likelihood of social acceptance. Social equity considerations must also be central to the distribution of solar energy. Ensuring that marginalized and underserved populations have equitable access to solar power is crucial for achieving social justice in energy distribution. Governments should prioritize solar installations in rural and low-income communities, where energy poverty is often most acute. By focusing on equitable access, solar energy can play a transformative role in improving quality of life for disadvantaged populations and contributing to more inclusive economic growth (Cantarero, 2020; Biswas *et al*., 2022).

To address the challenges limiting the penetration of utility-scale solar installations in developing countries, comprehensive solutions are required across policy, finance, technology, and social engagement. Streamlining regulatory processes, establishing stable policy frameworks, and adopting innovative financing models can attract investments and reduce financial barriers (Falchetta *et al*., 2022). Technological improvements, particularly in grid modernization and capacity building, will ensure the long-term sustainability of solar energy. Lastly, engaging communities and ensuring equitable access to solar energy will foster social acceptance and maximize the societal benefits of renewable energy. By implementing these strategies, developing countries can unlock the full potential of solar power and accelerate the transition to a sustainable energy future (Aleluia *et al*., 2022).

2.5. Future Trends and Outlook

The future of utility-scale solar installations in developing countries appears promising, driven by technological advancements, expanding markets, and the increasing role of digitalization (Cali *et al*., 2021). As the global energy landscape continues to evolve, these trends will significantly influence how solar energy is deployed, integrated, and utilized to meet energy demands and combat climate change.

Emerging solar technologies are reshaping the landscape of solar energy generation. One notable innovation is bifacial solar modules, which capture sunlight from both sides, resulting in increased energy output compared to traditional monofacial panels (Tina *et al*., 2021). These modules can significantly enhance efficiency, making them an attractive option for large-scale installations, particularly in areas with high albedo (reflectivity). Another promising development is floating solar farms, which utilize bodies of water to support solar panels (Solomin *et al*., 2021). This approach minimizes land use conflicts, conserves valuable land resources, and enhances efficiency due to the cooling effect of water. The adoption of these advanced technologies can lead to higher energy yields and lower costs, driving further solar deployment in developing regions (Shahsavari and Akbari, 2018). Integration with energy storage systems is another critical advancement in the solar energy sector. As solar power generation is inherently intermittent, energy storage solutions such as batteries can store excess energy generated during peak sunlight hours for use during periods of low generation. This capability enhances grid reliability and supports the integration of solar energy into national grids. The decreasing costs of battery technology are making energy storage solutions more accessible, thus facilitating the widespread adoption of solar installations in developing countries (Shaqsi *et al*., 2020). As these technologies continue to evolve, their synergy will enhance the resilience and reliability of solar energy systems.

The potential for solar energy markets in developing countries is vast, with projected growth expected to accelerate over the coming years (Tabassum *et al*., 2021). As nations strive to meet their energy needs while addressing climate change, solar energy presents a viable solution. Various reports indicate that developing regions could see a surge in solar installations driven by decreasing costs, increasing energy demands, and supportive government policies. Markets in Africa, Asia, and Latin America are particularly poised for growth, with opportunities for large-scale utility projects and decentralized solar solutions for rural electrification (Lee *et al*., 2020). Furthermore, the potential for regional and cross-border energy trading is emerging as a significant trend in expanding solar markets. Collaborative efforts among neighboring countries can facilitate the sharing of renewable energy resources, optimize grid operations, and enhance energy security (Alotaibi *et al*., 2020). Initiatives such as the African Continental Free Trade Area (AfCFTA) and various regional energy agreements can foster cooperation and investment in solar infrastructure. By enabling energy trade across borders, developing countries can benefit from diverse energy portfolios, balancing supply and demand while maximizing the utilization of renewable energy resources.

The integration of digital technologies is transforming the solar energy sector, particularly through smart grid innovations (Tan *et al*., 2021). Smart grids enhance the efficiency and reliability of electricity distribution by utilizing advanced communication and monitoring systems. These technologies enable real-time data collection, predictive maintenance, and efficient energy management, optimizing the performance of solar installations. By incorporating smart grid solutions, utility companies can better manage fluctuations in solar generation and demand, ultimately leading to improved grid stability (Ourahou *et al*., 2020). Additionally, the role of artificial intelligence (AI) and the Internet of Things (IoT) in optimizing solar energy deployment cannot be overlooked. AI algorithms can analyze vast amounts of data to predict energy generation patterns, identify potential maintenance issues, and optimize the operation of solar systems (Afridi *et al*., 2022). IoT devices can facilitate real-time monitoring of solar installations, providing valuable insights into performance and efficiency. Together, these technologies can drive significant improvements in solar energy management, enhance operational efficiency, and reduce costs.

The future of utility-scale solar installations in developing countries is characterized by technological advancements, market expansion, and the integration of digital solutions (Alam, 2022). Emerging solar technologies such as bifacial modules and floating solar farms will enhance energy output and address land use concerns, while energy storage systems will bolster the reliability of solar power generation. Expanding solar markets present substantial opportunities for investment and growth, supported by collaborative regional efforts in energy trading (Jackson *et al*., 2021). Moreover, digitalization and smart grid technologies will optimize the deployment and management of solar installations, leading to more efficient and resilient energy systems. As these trends unfold, the role of solar energy in achieving sustainable development goals and addressing climate change will become increasingly vital (Izam *et al*., 2022).

3. Conclusion

In summary, utility-scale solar installations have emerged as a pivotal component of the energy landscape in developing countries. The current status of these installations reflects a significant shift towards renewable energy adoption, with substantial economic, social, and environmental impacts. As demonstrated, utility-scale solar not only addresses energy poverty but also fosters economic growth through job creation and reduces dependence on fossil fuels. However, numerous policy challenges persist, including inconsistent regulatory frameworks and financial barriers that hinder further penetration of solar energy.

The importance of continued solar expansion cannot be overstated, particularly in the context of sustainable development for developing countries. Solar energy presents an opportunity to bridge the energy gap, enhance energy security, and contribute to climate change mitigation efforts. By embracing solar technology, developing nations can foster sustainable economic development, improve quality of life, and achieve energy independence. The role of solar energy is vital for creating resilient energy systems that can adapt to changing climate conditions while supporting long-term socio-economic progress.

A call to action is necessary to address the existing challenges that impede the growth of utility-scale solar installations. International cooperation among governments, financial institutions, and non-governmental organizations is crucial in facilitating knowledge transfer, mobilizing investment, and promoting best practices in solar energy deployment. Policy reforms must prioritize streamlined regulatory processes, stable incentives, and supportive frameworks that encourage solar investment. Additionally, advancing technological innovations, particularly in energy storage and grid modernization, will play a critical role in enhancing the efficiency and reliability of solar energy systems. By collectively addressing these challenges, stakeholders can unlock the full potential of utility-scale solar installations, driving sustainable development and resilience in the face of global energy demands and climate change.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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