

Solar Energy in Developing Countries: Challenges and Opportunities for Smart Cities

¹Ms. Nidhi Saraswat, ²Megha Pandeya, ³Ravi Kant Pareek, and ⁴Kuldeep Singh Kulhar,

¹Assistant Professor, Department of Computer Science Engineering, Sanskriti University, Mathura, Uttar Pradesh, India.

²Assistant Professor, Maharishi School of Engineering & Technology, Maharishi University of Information Technology, Uttar Pradesh, India.

³Associate Professor, Civil Engineering, Vivekananda Global University, Jaipur, India.

⁴Professor, Civil Engineering, Vivekananda Global University, Jaipur, India.

Abstract. This perspective article explores the dynamic landscape of solar energy adoption in developing countries, particularly within the framework of smart cities. Developing nations face a compelling need to bridge the energy gap, reduce emissions, foster economic growth, and enhance energy security. Solar energy offers potential solutions to these challenges. Despite the promise of solar energy, obstacles exist. Financial constraints, outdated infrastructure, grid instability, technical expertise gaps, and regulatory hurdles hinder widespread adoption. However, technological advances in solar panels, energy storage, smart grids, and data analytics present avenues for overcoming these challenges. Collaborative initiatives, consistent policies, and public-private partnerships offer support for sustainable development. Smart cities play a crucial role in this transition. Sustainable urban planning, smart infrastructure, and digitalization contribute to the efficient use of solar power. Case studies from India, Rwanda, and Brazil exemplify successful integration of solar energy within smart city projects. Balancing challenges with opportunities is the key to success. By addressing obstacles and seizing available prospects, developing countries can lead the charge toward a sustainable energy future.

1 Introduction

The 21st century has ushered in an era of unprecedented global challenges, with climate change standing at the forefront. As the world grapples with the devastating consequences of rising temperatures, extreme weather events, and a looming environmental crisis, the need for sustainable, renewable energy sources has never been more pressing. Solar energy,

Corresponding Author: ¹nidhi.soeit@sanskriti.edu.in

²megha.pandeya@gmail.com

³ravikant_pareek@vgu.ac.in

⁴k.singh@vgu.ac.in

with its potential to provide clean and abundant power, has emerged as a beacon of hope in this dire situation.

Developing countries are not immune to the impacts of climate change, and they often face the most severe consequences. These nations are also in the midst of rapid urbanization, a trend that presents both challenges and opportunities. The convergence of these two realities has given rise to a critical topic of concern: Solar Energy in Developing Countries and its integration within the framework of Smart Cities.

1.1 The Context: Energy in Developing Countries

Developing countries are characterized by a series of interconnected challenges when it comes to energy. First and foremost is the issue of energy access. A substantial portion of their populations still lacks access to reliable electricity, which hampers economic development, quality of life, and educational opportunities. As a result, it is imperative for these nations to find sustainable ways to bridge the energy gap, which is where solar power enters the picture.

Additionally, the pursuit of solar energy aligns closely with the goals of mitigating climate change. Developing nations, often disproportionately affected by climate-related disasters, have a vested interest in transitioning to low-carbon energy sources. Solar energy offers a means to significantly reduce greenhouse gas emissions and combat global warming.

From an economic standpoint, the solar energy sector can be a catalyst for job creation and reduced energy costs. As the cost of solar technology continues to decline, it has the potential to bolster local economies by fostering a culture of innovation and entrepreneurship. Furthermore, the reduced energy expenses for businesses and households can free up resources for other vital needs, spurring economic growth.

Energy security is another pressing concern for many developing countries. These nations often rely heavily on fossil fuel imports, which are vulnerable to price fluctuations and supply disruptions. By harnessing their solar potential, they can reduce their dependence on imported energy sources and enhance energy security.

1.2 Challenges on the Road to Solar Energy Adoption

However, transitioning to solar energy is not without its challenges. Financing remains a major obstacle, with developing nations frequently constrained by limited financial resources for infrastructure development. Building the necessary solar infrastructure, including solar farms, distribution networks, and energy storage solutions, requires substantial upfront investments.

Infrastructure and grid integration issues pose additional hurdles. Many developing countries have outdated energy infrastructure, which must be upgraded and modernized to accommodate the fluctuations in energy supply that are inherent to solar energy. Ensuring grid stability while integrating renewable sources is a complex and costly endeavour.

Moreover, there is often a lack of technical expertise in these regions, which can hinder the effective deployment and maintenance of solar energy systems. A skilled workforce is crucial for ensuring the long-term success of solar projects.

On the policy front, inconsistent regulations, bureaucratic barriers, and a lack of clear incentives can further deter investment in solar energy. These regulatory hurdles can stifle growth and innovation in the sector.

In light of these challenges, the promotion of solar energy in developing countries is not a straightforward task. However, technological advancements, policy initiatives, and the concept of smart cities offer a glimmer of hope, providing opportunities to overcome these obstacles and usher in a new era of sustainable and resilient urban development. This perspective article delves deeper into these critical dimensions, aiming to provide a comprehensive understanding of the challenges and opportunities associated with solar energy adoption in the context of smart cities within developing nations.

2 Solar Energy in Developing Countries

Solar energy has become an indispensable player in the global effort to address energy challenges and foster sustainable development, particularly in developing countries. Understanding the multifaceted dimensions of solar energy adoption in these regions is essential, as it holds the key to a brighter, cleaner future.

2.1 Energy Access: Alleviating Energy Poverty

Energy poverty is a pressing issue in developing countries, affecting billions of people. Far too often, individuals and entire communities lack access to reliable and affordable electricity. In rural and remote areas, the absence of electricity hampers not only daily life but also the development of crucial sectors such as healthcare, education, and economic activities. The need for increased energy access is one of the most compelling reasons to embrace solar energy. Off-grid and decentralized solar solutions, including solar home systems and mini-grids, are empowering communities that were once left in the dark. These solutions provide an affordable and sustainable source of power, improving the quality of life, enhancing educational opportunities, and catalysing economic growth for those living in energy-starved regions.

Furthermore, access to energy is a driving force for gender equality. In many developing countries, women are disproportionately affected by energy poverty, as they are often responsible for household tasks like cooking, which can involve dangerous and polluting fuels. Solar energy can reduce this burden by providing cleaner and safer cooking alternatives, thus empowering women and improving their overall well-being.

2.2 Environmental Benefits: Combating Climate Change

The environmental benefits of solar energy extend far beyond providing electricity. Developing countries, like the rest of the world, are grappling with the consequences of climate change, including more frequent and severe weather events, changing rainfall patterns, and disruptions to agriculture. By adopting solar energy, these nations contribute to the global effort to reduce greenhouse gas emissions and mitigate climate change.

Solar energy's low carbon footprint makes it an invaluable asset in the fight against global warming. Photovoltaic systems harness the power of the sun without emitting greenhouse gases, making it a sustainable and eco-friendly energy source. By displacing fossil fuels for electricity generation, solar energy reduces harmful air pollutants, improving air quality and public health. This transition towards cleaner energy aligns with international climate agreements and sets the stage for developing countries to not only reduce their own emissions but also serve as examples of responsible energy management.

2.3 Economic Benefits: Job Creation and Cost Reduction

The economic benefits of solar energy adoption are twofold. First, the sector presents significant opportunities for job creation. The installation, maintenance, and manufacturing of solar panels and related technologies have the potential to generate employment opportunities, particularly in regions with high solar potential. These jobs span various skill levels, from technicians to engineers, bolstering local economies and livelihoods.

Secondly, solar energy offers the potential for reduced energy costs for both citizens and businesses. As the cost of solar technology continues to decline, electricity generated from solar sources becomes increasingly competitive with conventional energy sources. This reduction in energy expenses frees up resources that can be allocated to other essential needs, including education, healthcare, and infrastructure development. Lower energy costs for businesses also enhance competitiveness and profitability, thereby contributing to economic growth and improved living standards.

2.4 Energy Security: Reducing Dependence on Fossil Fuels

Developing countries often rely heavily on imported fossil fuels, exposing their economies to volatile international oil prices and geopolitical risks. This dependence on fossil fuel imports can have detrimental economic consequences and hinder overall energy security. Solar energy offers a solution by providing a local, indigenous, and sustainable source of power. By diversifying their energy mix with solar, developing nations can reduce their vulnerability to external energy supply disruptions and price fluctuations. Enhanced energy security through solar adoption not only stabilizes energy availability but also promotes economic resilience and independence.

Furthermore, solar energy can be harnessed in distributed systems, such as rooftop solar panels and microgrids, which empower local communities to generate their own electricity. This decentralization of energy production reduces the reliance on centralized power plants and long-distance transmission lines, further enhancing energy security and resilience.

In summary, solar energy's role in developing countries transcends a simple shift in energy sources; it represents a pivotal step towards addressing energy access, environmental sustainability, economic development, and energy security. The challenges of energy poverty, climate change, and economic disparities are met with opportunities that solar energy uniquely provides. By leveraging these opportunities, developing countries can transform their energy landscapes, foster sustainable development, and ensure a brighter, cleaner future for their citizens.

3 Challenges in Solar Energy Adoption

While the benefits of solar energy in developing countries are substantial, a range of challenges must be overcome to realize its full potential. These challenges encompass financial constraints, outdated infrastructure, insufficient technical expertise, and complex policy and regulatory environments.

3.1 Financing: Limited Financial Resources for Infrastructure Development

One of the most significant hurdles in the widespread adoption of solar energy in developing countries is the limited availability of financial resources. Building the

necessary solar infrastructure requires substantial upfront investments in solar panels, inverters, energy storage systems, and distribution networks. While the long-term economic benefits are evident, acquiring the initial capital to fund such projects remains a formidable challenge. Government budgets are often strained, and the private sector may be hesitant to invest due to perceived risks and uncertainties.

Bridging this financial gap necessitates innovative financing mechanisms. These can include public-private partnerships, international development aid, concessional loans, and the establishment of dedicated funds for renewable energy projects. Implementing effective financial solutions can facilitate the deployment of solar energy infrastructure, making it more accessible to a broader population and a broader range of investors.

3.2 Infrastructure and Grid Integration: Outdated Infrastructure and Grid Instability

The existing energy infrastructure in many developing countries is outdated and ill-equipped to manage the variable and decentralized nature of solar energy. Solar generation is intermittent, and grid instability can occur if the infrastructure cannot adapt to the fluctuations in power supply. This presents a two-fold challenge: the need to modernize the electrical grid and the incorporation of smart grid technologies to accommodate renewable energy sources seamlessly.

Upgrading infrastructure involves substantial investment and time. However, it is essential for the effective integration of solar energy into the energy mix. The transition to a smart grid, with real-time monitoring and control capabilities, can enhance grid stability, enable efficient energy distribution, and minimize energy losses during transmission.

Microgrid solutions are also viable options for remote and off-grid areas, as they can operate independently or in conjunction with the main grid. These microgrids provide localized energy generation and distribution, making them resilient to external grid disturbances and contributing to energy security.

3.3 Lack of Technical Expertise: Insufficient Training and Knowledge

Solar energy systems require specialized technical expertise for installation, maintenance, and efficient operation. Unfortunately, many developing countries face a shortage of qualified personnel in this field. Insufficient training and knowledge can result in poorly designed and maintained solar installations, leading to suboptimal performance, increased costs, and reduced system lifespan.

Addressing this issue involves investing in training and education programs for local technicians, engineers, and maintenance personnel. By providing comprehensive training and certification opportunities, countries can foster a skilled workforce capable of ensuring the effective operation of solar energy systems. This investment in human capital not only promotes the sustainability of solar projects but also creates job opportunities, supporting economic growth.

3.4 Policy and Regulatory Hurdles: Inconsistent Policies and Regulations

Inconsistent and unclear policies and regulations can create a hostile environment for solar energy adoption. Frequent policy changes, bureaucratic red tape, and a lack of standardized regulations can deter investors and disrupt project development. The absence of well-defined incentives, subsidies, and feed-in tariffs can further discourage solar energy initiatives.

A comprehensive and transparent regulatory framework is essential to provide clarity and stability for the solar energy sector. Governments should develop and implement supportive policies, offering incentives and subsidies to encourage investment in solar projects. Regulatory agencies must work alongside industry stakeholders to create a favourable environment that facilitates project development, protects investor interests, and ensures a smooth transition to solar energy.

In conclusion, while the potential of solar energy in developing countries is immense, these nations must navigate a series of complex challenges to fully leverage its advantages. Overcoming financial barriers, modernizing infrastructure, nurturing technical expertise, and creating supportive policy environments are critical steps in the journey toward sustainable and resilient solar energy adoption. Addressing these challenges will not only accelerate the transition to clean and reliable energy sources but also stimulate economic development and improve the quality of life for countless individuals in developing regions.

4 Technological Advancements

Technological progress plays a pivotal role in overcoming the challenges associated with solar energy adoption in developing countries. Advances in various aspects of solar technology, including solar panel efficiency, energy storage solutions, smart grid and microgrid systems, and the integration of the Internet of Things (IoT) and data analytics, hold the potential to transform the landscape of solar energy deployment.

4.1 Solar Panel Efficiency: Improvements in Solar Panel Technology

One of the key areas of innovation in solar energy technology is the enhancement of solar panel efficiency. Traditional photovoltaic panels have seen significant improvements over the years, with more efficient designs that capture a greater amount of sunlight and convert it into electricity. These improvements increase the energy yield per square meter of solar panels, making solar energy systems more productive and cost-effective.

Emerging technologies, such as multi-junction solar cells, thin-film solar panels, and bifacial solar panels, are pushing the efficiency boundaries even further. Multi-junction solar cells, for example, are highly efficient and capable of generating electricity even under low light conditions, making them ideal for regions with variable sunlight. Thin-film solar panels are lightweight and flexible, offering new possibilities for installation on diverse surfaces. These advancements not only make solar energy more accessible but also ensure better energy production, even in less-than-ideal conditions.

4.2 Energy Storage Solutions: Advancements in Battery Technology

Energy storage is a crucial element of a reliable and sustainable solar energy system. Battery technology has witnessed remarkable advancements, with improvements in energy density, cycle life, and cost-effectiveness. Energy storage systems, such as lithium-ion batteries, are increasingly becoming integrated into solar installations, allowing excess energy generated during the day to be stored and used during the night or during periods of reduced sunlight.

Furthermore, research into next-generation energy storage technologies, including solid-state batteries and flow batteries, holds promise for even greater energy storage capacity, longer lifespans, and reduced costs. Energy storage innovations are particularly beneficial for developing countries where energy access is unreliable, as they enable a more consistent and resilient power supply.

4.3 Smart Grids and Microgrids: Enhancing Grid Management

The integration of smart grid technologies is vital for effectively managing the influx of intermittent renewable energy sources like solar power. Smart grids and microgrids incorporate advanced communication and control systems that enable real-time monitoring, optimization, and demand-side management. These technologies ensure the efficient distribution of electricity, reduce losses, and enhance grid stability.

In the context of developing countries, smart grids and microgrids are invaluable for remote and off-grid areas, as they allow for localized generation and distribution of electricity. By minimizing reliance on central grids and reducing transmission losses, they enhance energy security, particularly in regions with unreliable or non-existent grid access.

4.4 IoT and Data Analytics: Monitoring and Optimizing Solar Energy Systems

The Internet of Things (IoT) and data analytics play a significant role in the management and optimization of solar energy systems. IoT-connected sensors and devices enable real-time monitoring of solar panels, inverters, and energy storage systems. Data analytics tools process this information to provide insights into system performance, identify potential issues, and optimize energy production.

Predictive maintenance, powered by data analytics, helps prevent system failures and reduces maintenance costs. Furthermore, energy management platforms can optimize the consumption of electricity within homes and businesses, reducing overall energy costs and maximizing the utilization of solar-generated power.

In developing countries, where resources may be limited, IoT and data analytics help ensure the efficient operation of solar energy systems, prolong their lifespan, and enhance their economic viability.

Technological advancements in these areas not only make solar energy more efficient and reliable but also contribute to its widespread adoption in developing countries. These innovations play a crucial role in bridging the energy gap, reducing greenhouse gas emissions, and fostering sustainable economic growth while bolstering energy security and resilience. As these technologies continue to evolve, they offer a promising future for solar energy's role in the development of smart cities and a cleaner, more sustainable world.

5 Policy Implications

Policymaking in the context of solar energy adoption in developing countries is a multifaceted challenge. Effective policies and regulatory frameworks are essential for creating an environment conducive to solar adoption. The policy implications include incentives and subsidies, a clear regulatory framework, and fostering public-private partnerships, all of which are instrumental in driving the transition to renewable energy sources.

5.1 Incentives and Subsidies: Government Support to Spur Solar Adoption

Government incentives and subsidies have been instrumental in promoting the adoption of solar energy in developing countries. These financial mechanisms are designed to reduce the cost and risk of investing in solar infrastructure and to stimulate both residential and commercial solar projects.

- a. **Feed-In Tariffs (FiTs):** Feed-in tariffs guarantee a fixed price for solar-generated electricity over a specified period, offering long-term stability for investors and encouraging the development of a renewable energy market.
- b. **Investment Tax Credits (ITCs):** Tax credits provide businesses and individuals with reductions in income taxes, making solar installations more financially attractive. They significantly reduce the upfront cost of solar systems.
- c. **Grants and Rebates:** Government grants and rebates provide direct financial incentives to install solar panels, often covering a portion of the initial investment.
- d. **Net Metering:** Net metering allows solar system owners to receive credits for excess electricity they feed back into the grid. This enables consumers to offset their electricity bills and promotes solar adoption.

Incentives should be designed in a way that makes solar energy projects economically viable, fosters job creation, and supports energy access for marginalized communities. By reducing the financial barriers to entry, governments can promote wider adoption of solar energy and accelerate the transition to renewable power sources.

5.2 Regulatory Framework: Clear and Consistent Policies

A stable and transparent regulatory framework is essential to ensure the long-term sustainability of solar energy projects. Frequent policy changes and regulatory inconsistencies can deter investors and disrupt project development. Therefore, governments must create a clear, predictable, and supportive environment for solar energy initiatives.

- a. **Zoning and Land Use Regulations:** Zoning regulations and land use policies should encourage the installation of solar panels, whether on residential rooftops, commercial properties, or open land. This promotes solar adoption by minimizing regulatory obstacles.
- b. **Grid Connection Procedures:** Clear and streamlined procedures for connecting solar systems to the grid are crucial for the efficient integration of solar energy. Delays or complexities in grid connection can hinder project development.
- c. **Quality Standards:** Governments should establish and enforce quality standards for solar equipment, ensuring that consumers receive reliable and safe solar systems. This protects consumers and enhances trust in the technology.
- d. **Power Purchase Agreements (PPAs):** Policies that allow power purchase agreements between solar project developers and utilities ensure stable and fair compensation for solar-generated electricity.

A well-designed regulatory framework should foster collaboration with stakeholders, including the solar industry, utilities, and local communities. It should aim to balance the interests of various parties while promoting renewable energy growth.

5.3 Public-Private Partnerships: Collaboration for Sustainable Development

Public-private partnerships (PPPs) are a powerful mechanism for promoting solar energy in developing countries. These collaborations leverage the strengths of both the public and private sectors to drive investment, develop infrastructure, and ensure the long-term sustainability of solar projects.

- a. **Project Finance:** Public-private partnerships can attract private sector funding for large-scale solar projects. Public entities provide support through grants, subsidies, or policy incentives, while private companies offer financing, expertise, and technology.

- b. **Research and Development:** Collaborations in research and development promote innovation in solar technology, reducing costs and improving efficiency. This is particularly relevant for creating solar solutions tailored to the specific needs of developing countries.
- c. **Education and Training:** Partnerships can facilitate the training of a skilled workforce capable of installing, operating, and maintaining solar systems. This fosters job creation and ensures the longevity of solar projects.
- d. **Community Engagement:** PPPs can also promote community engagement and awareness campaigns to garner local support and foster a sense of ownership for solar projects. This is essential for the successful implementation of distributed energy solutions.

Effective public-private partnerships require clear roles, responsibilities, and collaboration mechanisms. These partnerships should prioritize the mutual goal of sustainable development and create value for all stakeholders involved.

In conclusion, well-crafted policies are indispensable for the successful deployment of solar energy in developing countries. Incentives and subsidies make solar adoption more economically viable, a clear regulatory framework ensures predictability and stability, and public-private partnerships leverage the resources and expertise of both sectors. These policy implications not only accelerate the transition to clean and sustainable energy but also contribute to economic growth, job creation, and the development of resilient and environmentally responsible smart cities.

6 Smart Cities and Solar Integration

The concept of smart cities represents a transformative approach to urban development that leverages technology and innovative solutions to create sustainable, efficient, and resilient urban environments. In the context of solar energy adoption, smart cities play a pivotal role in accelerating the transition to renewable energy sources. This section explores the key components of smart cities and how they facilitate the integration of solar energy.

6.1 Sustainable Urban Planning: Integration of Solar Energy into City Planning

Sustainable urban planning is the cornerstone of smart city development. It involves the integration of solar energy into the design and layout of the city. This includes incorporating solar installations into building designs, planning for green spaces, and optimizing the placement of solar panels on rooftops, parking lots, and public infrastructure.

Zoning regulations and building codes can be structured to encourage solar deployment. For example, cities can incentivize or mandate solar-ready construction and allocate designated areas for solar farms or community solar projects. Sustainable urban planning also addresses issues like shading, to ensure that solar panels receive maximum sunlight.

Moreover, city planners should consider the broader implications of solar energy adoption, including the need for energy storage, grid integration, and distributed energy resources. By incorporating solar energy into the initial urban planning stages, smart cities can develop a holistic approach to energy generation, distribution, and consumption.

6.2 Smart Infrastructure: Implementing Energy-Efficient Systems

Smart infrastructure encompasses the implementation of energy-efficient systems throughout the city. This includes smart buildings with integrated solar panels, energy-efficient lighting, and advanced heating, ventilation, and air conditioning (HVAC) systems. These technologies not only reduce energy consumption but also contribute to the overall sustainability of the city.

Additionally, the integration of electric vehicle (EV) charging infrastructure is essential for promoting sustainable transportation. Solar-powered EV charging stations can reduce the carbon footprint of urban transportation and encourage the adoption of electric vehicles.

In the case of public transportation, smart cities can explore the use of electric buses powered by solar energy. The development of efficient transportation networks and transit-oriented development (TOD) also helps reduce urban sprawl, decrease the need for personal vehicles, and lessen greenhouse gas emissions.

6.3 Digitalization and Connectivity: Leveraging Technology for Efficient Energy Management

Digitalization and connectivity are key elements of smart city development. These technologies enable real-time monitoring and control of energy systems, enhancing overall energy management and efficiency. The integration of IoT devices and data analytics platforms allows for intelligent energy use and grid management.

Smart meters and sensors can provide valuable data on energy consumption patterns, allowing city officials to identify areas for improvement and optimization. This data is particularly important for understanding peak energy demand and planning solar energy generation accordingly.

Demand response programs, which encourage consumers to adjust their energy usage during peak periods, can be implemented more effectively in smart cities. By leveraging digitalization and connectivity, smart cities can automatically adjust lighting, heating, and cooling systems to optimize energy consumption and minimize costs.

The use of advanced energy management systems also supports the efficient integration of renewable energy sources, including solar power. These systems balance the energy generated from solar panels with demand in real time, ensuring a reliable and stable energy supply.

In conclusion, the integration of solar energy into smart cities represents a holistic approach to sustainable urban development. Sustainable urban planning, smart infrastructure, and digitalization contribute to the efficient and effective use of solar energy, promoting environmental sustainability, energy security, and economic growth. By embracing these principles, smart cities are not only reducing their carbon footprint but also setting the stage for a more sustainable and resilient urban future.

7 Case Studies

The real-world implementation of solar energy adoption and smart city initiatives in different developing countries provides valuable insights into the challenges, opportunities, and policy approaches that have been effective in fostering sustainable urban development. Below, we explore case studies from India, Rwanda, and Brazil, highlighting key projects and their impacts.

7.1 India - The Solar Cities Program [10,11]

The Solar Cities program in India is a comprehensive initiative designed to promote solar energy and sustainability in urban areas. Launched by the Ministry of New and Renewable Energy, the program aims to transform select cities into "Solar Cities" by integrating solar technology into various aspects of urban life.

Key Features and Impacts:

- **Solar Rooftop Installations:** The program encourages the installation of solar panels on rooftops to generate clean energy for households, businesses, and public facilities.
- **Solar Street Lighting:** Solar-powered streetlights reduce energy consumption and enhance safety in urban areas.
- **Renewable Energy Awareness:** Public awareness campaigns and training programs inform citizens about the benefits of renewable energy and sustainable practices.
- **Waste-to-Energy Projects:** Some Solar Cities have implemented waste-to-energy projects, converting organic waste into biogas and electricity.
- **Urban Planning and Development:** The program integrates solar energy solutions into urban planning, helping cities adopt sustainable practices for transportation, construction, and waste management.

The Solar Cities program exemplifies India's commitment to fostering sustainable urban development through solar adoption and clean energy practices. By leveraging public awareness and government support, the program has made substantial progress in transforming cities into hubs of renewable energy.

7.2 Rwanda - The Kigali Innovation City Project [12,13]

Rwanda's Kigali Innovation City project is an ambitious initiative that seeks to create a knowledge-based economy and support sustainable development. It incorporates renewable energy, smart city concepts, and digital infrastructure.

Key Features and Impacts:

- **Green Infrastructure:** The project prioritizes sustainable construction and green building practices to reduce energy consumption.
- **Solar Energy Integration:** Solar panels are installed on buildings to generate renewable electricity for city operations.
- **Smart Mobility:** The development includes plans for a public transportation system and infrastructure for electric vehicles.
- **Digital Connectivity:** Kigali Innovation City focuses on digitalization and connectivity, supporting technology-driven innovation.

The project aims to position Rwanda as a technology hub in Africa while showcasing the potential for solar energy and smart city concepts to drive economic growth and sustainable development.

7.3 Brazil - Sustainable Initiatives in Curitiba [14,15]

Curitiba, a city in southern Brazil, is known for its innovative urban planning and sustainable initiatives. While not exclusively solar-focused, its approach to urban development includes several elements related to renewable energy and environmental sustainability.

Key Features and Impacts:

- **Bus Rapid Transit (BRT) System:** Curitiba is renowned for its BRT system, a public transportation solution that reduces traffic congestion, energy consumption, and pollution.
- **Green Spaces and Parks:** The city has an abundance of green spaces and parks, providing residents with access to nature and reducing the urban heat island effect.
- **Waste Management:** Curitiba has implemented effective waste management practices, including recycling and composting, reducing landfill waste and its associated environmental impacts.
- **Solar Installations:** The city has gradually introduced solar installations on public buildings, harnessing solar energy for a cleaner energy mix.

Curitiba's sustainable initiatives showcase a holistic approach to urban development, where environmental and social well-being are central considerations.

These case studies reflect the diverse approaches that developing countries are taking to integrate solar energy and smart city concepts into their urban landscapes. While each context is unique, these examples demonstrate the potential of renewable energy adoption and sustainable urban planning to drive economic growth, improve quality of life, and contribute to a cleaner, more resilient future.

8 Opportunities and Future Outlook

The opportunities presented by solar energy adoption in developing countries are vast and hold the potential to drive transformative changes in multiple areas. The future outlook for solar energy in these regions is promising, with prospects for rural electrification, energy for productive uses, the creation of green jobs, and technological innovations that can revolutionize energy distribution.

8.1 Rural Electrification: Extending Solar Access to Remote Areas

Rural electrification remains a paramount goal in many developing countries. Solar energy offers a practical solution to extend electricity access to remote and underserved regions. Off-grid and decentralized solar solutions, including solar home systems and mini-grids, are already making a significant impact by providing reliable and sustainable power to communities that previously lacked access.

These initiatives not only improve the quality of life in rural areas by enabling lighting, communication, and access to information but also stimulate economic activities. They empower agricultural practices, enhance education and healthcare services, and promote small-scale industries, ultimately reducing the urban-rural development gap.

8.2 Energy for Productive Uses: Supporting Agriculture and Small Businesses

Solar energy's potential extends beyond basic electrification. It can be harnessed to support agriculture and small businesses, particularly in rural areas. Solar-powered irrigation systems, for example, enable farmers to efficiently water their crops, increasing agricultural productivity and income. Solar cold storage facilities enhance the shelf life of agricultural products, reducing post-harvest losses.

Furthermore, small and medium-sized enterprises (SMEs) can benefit from solar energy solutions, which offer reliable and cost-effective power sources. Solar water pumps, for instance, can be crucial for businesses in the food processing industry, helping them optimize their operations and reduce energy costs. These applications are vital for economic growth and job creation in developing regions.

8.3 Green Jobs: Opportunities for Employment and Entrepreneurship

The solar energy sector provides substantial opportunities for job creation and entrepreneurship. As solar technology becomes more affordable and accessible, the demand for skilled professionals in solar installation, maintenance, and manufacturing is on the rise. This workforce expansion stimulates economic growth and supports livelihoods in developing countries.

Moreover, the solar industry encourages entrepreneurship and local manufacturing, fostering economic self-reliance. Small-scale solar enterprises, such as solar panel assembly or distribution, can thrive and serve local markets. Additionally, solar-powered micro-businesses, such as phone charging stations, create income-generating opportunities in off-grid areas.

8.4 Technological Innovations: The Role of AI and Blockchain in Energy Distribution

The future of solar energy in developing countries is closely tied to technological innovations. Artificial intelligence (AI) and blockchain technology, in particular, are poised to revolutionize energy distribution and management.

- a. **AI for Energy Optimization:** AI systems can optimize energy generation, distribution, and consumption. Machine learning algorithms can predict energy demand and balance it with solar generation, ensuring efficient use of electricity. This technology is vital for smart grids and microgrids, especially in areas with intermittent energy sources.
- b. **Blockchain for Decentralized Energy Trading:** Blockchain technology facilitates peer-to-peer energy trading, enabling individuals and businesses to buy and sell excess solar-generated electricity directly to one another. This concept, known as decentralized energy trading, promotes energy self-sufficiency and enhances energy security in areas with unreliable grid connections.

The integration of AI and blockchain in solar energy management empowers consumers, improves grid resilience, and reduces energy losses during distribution. It also supports the transition to clean and sustainable energy sources.

The future outlook for solar energy in developing countries is characterized by a shift towards inclusive and sustainable development. It offers opportunities for electrifying rural areas, enhancing agricultural productivity, creating green jobs, and deploying cutting-edge technologies to optimize energy distribution. These developments not only contribute to the well-being of communities but also strengthen the resilience and economic viability of these regions, ensuring a brighter and more sustainable future.

9 Other studies and research

Renewable energy projects, particularly those in rural communities of developing nations, are crucial for addressing global energy needs and promoting sustainability. However, the acceptance and long-term viability of such projects depend on a complex interplay of factors. To shed light on this multifaceted issue, this review article explores a series of studies with a systems thinking perspective. By understanding these dynamics, we aim to provide valuable insights into how renewable energy initiatives can be more readily embraced and sustained within such contexts.

Table 1. Key research areas and topics related to solar energy in developing countries

Reference	Study Topic	Key Findings	Conclusion
[1]	Sustainability in solar energy projects	- Sustainability analysis minimizes negative impacts on environmental, social, and economic aspects. - LCA and MRIO have limitations. - IO analysis may have different results and impacts sustainability goals.	- Scientific frameworks like FISA are essential for decision-makers. - Accurate goal, scope, and indicators are crucial. - Solar energy is vital for meeting sustainable development goals.
[2]	Solar energy contribution to sustainable goals	- Solar energy supports SDGs through carbon mitigation, power capacity, low costs, and household power. - MBR Solar Park in Dubai is significant. - The park tests various solar technologies. - Aligns with Dubai's 2050 vision for renewable energy.	- Solar energy is essential for a sustainable future. - MBR Solar Park shows the feasibility of ambitious solar projects.
[3]	Environmental performance of solar energy systems	- PV systems' environmental impact varies; thin-film CIS has lower impacts. - Efficiency, area, and cost parameters differ among PV systems. - Flat plate systems are cost-effective in certain climates.	- Various PV technologies offer similar energy production and emissions reduction. - Flat plate systems are cost-effective in some climates.
[4]	Potential of solar energy in reducing emissions	- Recommendations to overcome barriers, including subsidies, feed-in tariffs, and loans. - International aid, tax credits, and skilled workforces are essential. - Carbon pricing can promote clean energy. - Raising awareness about environmental impacts is crucial.	- Positive approaches and political strategies are needed for solar energy development. - Subsidies, feed-in tariffs, and loans encourage renewable energy. - International cooperation and funding are essential. - Tax credits and carbon pricing promote clean energy. - Skilled workforces and R&D incentives are necessary for solar technology advancement. - Raising awareness about environmental impacts is critical.

[5]	Solar Energy and Rural Development in Developing Countries	<ul style="list-style-type: none"> - Promote gradual, step-by-step introduction of energy in rural areas. - Use "intermediate technology" that aligns with economic boundaries of poverty. - Establish rural energy centres for basic needs and education. - Create local government assistance programs for rural development. - Address rural unemployment through energy centres. 	<ul style="list-style-type: none"> - Development in rural areas should prioritize gradual energy introduction. - Technology should be suitable for labour surplus societies. - Rural energy centres can create jobs and improve rural life. - Healthy rural development is crucial for overall societal well-being.
[6]	Urban Planning for a Renewable Energy Future	<ul style="list-style-type: none"> - Reducing energy demand is a prime objective in the transition to renewable sources. - Urban factors play a crucial role in reducing demand. - Optimization of energy streams are essential for exergy optimization. - Renewable energy should fill the remaining demand at various scales. 	<ul style="list-style-type: none"> - Reducing energy demand is a primary step toward a renewable energy future. - Urban morphology and exergy optimization are key considerations. - Renewable energy should complement remaining energy needs at different scales. - Interdisciplinary research and application are crucial for sustainable urban development.
[7]	The role of socio-Culture in solar power adoption	<ul style="list-style-type: none"> - Age of household heads positively impact solar power adoption. - Older household heads are more likely to adopt solar technology. - Household income influences adoption; high-income households adopt more. - Higher education levels of household heads positively impact adoption. - Access to credit positively influences adoption. - Rural households are more likely to adopt solar power than urban ones. - Households without grid access are more likely to adopt solar power. - Adoption varies by development region. - Adoption also varies by ecological region. - Ethnic-caste status plays a significant role in adoption. 	<p>Socio-cultural factors, especially ethnic-caste differences and conflicts among ethnic groups, have a significant impact on solar power technology adoption. Policymakers should consider socio-cultural factors and promote equality through education and institutions to ensure equal access to modern energy technology.</p>
[8]	Social acceptance of solar energy in Finland	<ul style="list-style-type: none"> - Four states of willingness to adopt solar energy are identified: activated willingness, unconditional willingness, conditional willingness, and unwillingness. - Different customer segments are identified based on these states. - Patterns of 	<p>To accelerate the adoption of solar energy in Finland, it's essential to address the different states of willingness and customer segments with tailored information and support. Policies and strategies should consider pre-adoption and post-</p>

		social acceptance are categorized into adoption, acceptance in principle, rejection, and opposition.	adoption factors to encourage adoption across various customer segments.	
[9]	Causal-Loop Diagrams Related to the Acceptance of RES Projects		This section presents five causal-loop diagrams that show the factors that appear to predominantly influence the sustainability and acceptance of RES projects by rural communities. The diagrams were developed within the boundaries of five different livelihood capitals: social, human, physical, natural, and financial.	Understanding the complex interactions between various livelihood capitals is crucial for the success of renewable energy projects in rural communities. Interventions should be holistic, culturally sensitive, and consider multiple dimensions of the community. Involving the community, providing education, and ensuring access to financial services are key to project sustainability.
	Social Capital	Positive Relationships	Networks and trust influence community acceptance of RES projects.	Community acceptance depends on social capital.
	Human Capital	Skills and Education	Access to quality education and technologies enhances human capital. Lack of energy affects essential services.	Access to education and technologies is vital.
	Physical Capital	Infrastructure and Technology	Basic infrastructure is crucial for education, health, and income generation. Access to energy enhances community attractiveness.	Infrastructure is essential for development and project acceptance.
	Natural Capital	Environmental Quality	RES projects can have adverse effects on the natural environment. Direct and indirect impacts must be considered.	RES can affect the environment, which influences acceptance.
	Financial Capital	Monetary Resources	RES can generate income, but access to financial services is necessary. Payment models should minimize risk.	Financial resources and access to credit are vital for project success.

10 Conclusion

Developing countries face distinct challenges when embracing solar energy, but the promise of sustainable growth and progress is immense. The transformation to clean energy sources becomes increasingly feasible as smart cities emerge as pivotal actors in this transition. Advancements in technology, the implementation of supportive policies, and

collaborative efforts on an international scale have brought the potential for solar energy in developing nations into sharper focus. By effectively addressing these challenges and embracing the opportunities at hand, these countries are poised to lead the way towards a future that is both more sustainable and energy-secure.

Key Findings:

1. **Energy Transition in Developing Nations:** Developing countries are in a unique position to leapfrog conventional energy systems and shift directly to renewable sources like solar, unlocking sustainable and reliable power for their populations.
2. **Economic and Social Impact:** The adoption of solar energy in these regions not only benefits the environment but also stimulates economic growth, job creation, and social development by providing access to essential services.
3. **Smart Cities as Catalysts:** The development of smart cities acts as a catalyst, fostering innovation and efficiency, and making solar energy integration more effective and accessible.
4. **Technology and Infrastructure Advances:** Rapid technological progress and infrastructural development are driving solar energy adoption, reducing costs, and improving energy access for remote communities.
5. **Policy and International Collaboration:** Supportive policies and international collaborations are key enablers of solar energy growth, providing essential frameworks and investment opportunities.
6. **Resilience and Energy Security:** Solar energy enhances energy resilience, reducing vulnerability to supply disruptions and bolstering energy security.

In summary, these findings underline the tremendous potential of solar energy in developing countries, where the convergence of technological progress, smart city development, supportive policies, and international cooperation paves the way for a brighter and more sustainable future. As the world faces pressing energy and environmental challenges, these nations are poised to take a leading role in shaping a resilient, secure, and eco-friendly global energy landscape.

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