

SUSTAINABLE ENERGY MANAGEMENT IN DEVELOPING COUNTRIES: A REVIEW

Fawad Hussain Bhan¹, Ateeq U Rehman Bughio², Ali Adnan Bhutto³,
Shafique Ahmed Soomro^{*4}, Jawed Ali Thaheem⁵, Muhammad Raza Punjwani⁶,
Ali Zain Ul Abdeen⁷

^{1,2,*4,5,6}Faculty of Engineering Science and Technology, Department of Electrical Engineering, Indus University,
Karachi, 75850, Pakistan

⁷Manager Campus France Karachi Organization: Campus France, Karachi, 75850, Pakistan

¹fawadhussainbhan@gmail,²com,ateeq.rehman@indus.edu.pk,³aliadnanbhutto17@gmail.com,

⁴shafiq.soomro@indus.edu.pk,⁵jawed.thaheem@indus.edu.pk,⁶raza.punjwani@indus.edu.pk,

⁷zainqureshi340@gmail.com

DOI:<https://doi.org/10.5281/zenodo.21393574>

Keywords

Artificial Intelligence, Developing Countries, Demand Side Management, Energy Efficiency, Renewable Energy, Smart Grid, Sustainable Energy Management

Article History

Received: 01 January 2026

Accepted: 17 March 2026

Published: 31 March 2026

Copyright @Author

Corresponding Author: *

Shafique Ahmed Soomro

Abstract

Rapid population expansion, urbanization, restricted generation capacity and poor energy infrastructure imply that developing countries confront major challenges to supply the increasing energy demands. These challenges lead to regular power outages, substantial transmission and distribution losses and continuous reliance on fossil fuels. Sustainable energy management has become a necessity in the areas to improve energy efficiency, reliability and environmental sustainability. This study gives a comprehensive analysis on sustainable energy management in developing nations mainly focusing on renewable energy integration, smart grid technologies, demand side control and energy efficiency approaches. The research also emphasizes the growing importance of new technologies such as the Internet of Things (IoT) and artificial intelligence (AI) in today's energy systems. Also, there is a study of significant technological, economic and policy concerns specific to developing countries. The report finishes with a discussion of future research directions for enabling sustainable, secure, and efficient energy systems in growing regions.

1. INTRODUCTION

Energy is one of the most essential drivers of economic growth, industrial development and social progress. In emerging countries the rapid development in population, urbanization and industrial expansion have led to a substantial increase in the demand for electrical energy. But many of these countries have significant hurdles in servicing this expanding demand due to limited generation capacity, inadequate energy

infrastructure, and heavy dependence on fossil fuels.

An important problem in growing regions is the mismatch between energy supply and demand, causing frequent power outages, load shedding and poor quality of service.[1] In addition, the efficiency of power systems is diminished because of large transmission and distribution losses[2,3]. These problems not only harm household customers, but decrease industry output and slow

down economic progress. To address these difficulties, the concept of sustainable energy management has received much attention. It emphasizes sustainable generation, transmission and consumption of energy, with minimum environmental impact. Sustainable energy management also helps to integrate renewable energy sources[4,5] like solar, wind, and hydro power into current power systems. In recent years, new technologies, such as smart grids, Internet of Things (IoT), and artificial intelligence (AI), have played a key role in enhancing energy monitoring, control, and optimization. These technologies enable real-time data analytics, enhanced demand forecasting, and increased system reliability. However, developing countries still face a number of challenges such as financial constraints,[6,7,8] limited policy framework, lack of technical skills and inadequate infrastructure development. Therefore, a comprehensive understanding of sustainable energy management strategies and their implementation challenges is essential for improving energy security, efficiency, and sustainability in developing countries.[9,10] Against this background, this review paper provides an overview of sustainable energy management in developing nations, focusing on renewable energy integration, smart grid technologies, demand-side management, key implementation challenges, and future opportunities.

1.1 Importance of Sustainable Energy

The sustainable energy has become one of the most important components of the current power system development due to the increasing global energy demand, the worries about the environment and the restrictions of traditional energy resources. Sustainable energy is important not just from a technological point of view but also from an economic, environmental and social point of view and is a critical aim for developed and emerging countries.[11]

Why sustainable energy is important: It lowers dependency on fossil fuels such as coal, oil and natural gas[12]. These traditional sources of energy are not only limited but are also a major source of greenhouse gases which are the main drivers of

climate change and global warming. By changing to renewable energy sources such as solar, wind, hydro and biomass, governments can reduce carbon emissions and mitigate damage to the environment. Sustainable energy also greatly enhances energy security. Many developing countries are among the most heavily dependent on imported fuels, which is a heavy financial burden and exposes them to changes in the prices of global markets. Domestic renewable energy [14] resources are accessible and can be used to reduce our dependence on foreign energy imports and to increase our national energy independence. Another big one is economic progress. Efficient, reliable energy systems are critical to industrial expansion, job creation and infrastructure development. Sustainable energy solutions may also save long-term running expenses by reducing fuel use and improving system efficiency. The initial investment in renewable technology may be high but the long-term benefits in terms of cost savings and reliability far outweigh the initial investment.[13,14,15,16] In an environmental sense, there is a need for sustainable energy in order to cut down pollution and preserve natural habitats. Traditional means of producing energy release harmful gasses and pollutants that have a significant influence on air quality, water resources and human health. Renewable energy systems emit extremely little pollution, can be used for long time and are environment friendly.

Sustainable energy is also good for the growth of society and living quality. Education, health services, communications systems and living circumstances all improve with reliable energy. "In rural and remote locations, where the grid doesn't reach, off-grid renewable energy solutions like solar micro grids [17,18] can bring power. Finally, renewable energy encourages the development of technologies and innovations. The integration of smart grids, artificial intelligence and IoT based energy management systems is transforming old power systems into intelligent and automated networks, improving efficiency, monitoring and control.

In conclusion, sustainable energy is necessary because it ensures environmental conservation, energy security, economic stability, and social

development. It is therefore a pillar for future energy systems, particularly in underdeveloped countries.

1.2 Energy Crisis in Developing Countries

The developing countries have a more serious energy challenge than the developed countries. These problems are attributable to insufficient financial resources, aging infrastructure, poor energy planning and dependence on foreign fuels.

Typical problems are

- Insufficient capacity for electricity generation
- Frequent power cuts and outages
- High losses in transmission and distribution
- Voltage instability and low power quality
- Poorly designed energy management systems

In many emerging nations, power consumption is increasing far faster than supply, producing a chronic gap between supply and demand. This imbalance is not only a problem for consumers but industrial sectors, which suffer from reduced productivity, higher operating costs and slower economic growth. Foreign investment and industrial expansion are likewise discouraged by energy uncertainty.

1.3 Function of sustainable energy management

Sustainable energy management is essential for tackling the energy difficulties facing emerging countries. It is the systematic planning, control and optimization of operations of energy generation, distribution and consumption. The main aims are: Efficient use of energy resources
Reduce energy losses
Renewable energy systems
Integration
Enhanced grid reliability

Environmental footprint reduction
Countries can use sustainable energy management strategies that can dramatically enhance energy efficiency while lowering operational costs and environmental impact.

1.4 Recent Technologies in Energy Systems

Recent technological developments have converted conventional power systems into

intelligent and automated networks. Technologies such as Smart Grids, Internet of Things (IoT)[19], Artificial Intelligence (AI) and Machine Learning (ML) are playing an increasing role in shaping current energy systems.[20,21,22] These technologies allow: Energy monitoring in real time
Precise load forecasting
System automation and identification of faults
Efficient energy allocation
Intelligent decision making in power systems
In example, smart grid systems enable two-way communication between utilities and consumers, enhancing dependability and minimizing energy waste. IoT devices and smart meters also give real-time data that helps to optimize energy use patterns.

1.5 Implementation Challenges

There are several hurdles in the implementation of sustainable energy systems in poor nations despite technological developments. These are: High initial cost of renewable energy technologies.
Lack of technical expertise and qualified labor

1. Weak regulatory and policy frameworks
2. Limited facilities for R&D
3. Resistance to the adoption of new technology
4. Financial limitations and economic instability
5. These issues impede the move towards sustainable and efficient energy systems.

1.6 Objectives and Scope of the Review

The aim of this review article is to give a complete assessment on sustainable energy management in developing nations. The subject of the study is the evaluation of existing energy problems and the analysis of contemporary methods of increasing energy efficiency and reliability. The scope of this study is to: Integration of renewable energies (solar, wind, hydro) Applications and Technologies of Smart Grid Demand side management techniques Strategies for energy efficiency Role of Artificial Intelligence and Internet of Things in Power Systems Policy and economic issues The assessment aims at identifying the main research gaps and highlighting future potential for sustainable energy development.

1.7 Paper Structure

The rest of this paper is organized as follows: 2. The present energy scenario in developing countries is discussed. Section 3 describes the principles of sustainable energy management. Section 4 discusses renewable energy resources and their applications. Section 5 is dedicated to smart grid systems and recent technological advances. Section 6 deals with demand side management approaches. Section 7 outlines policy, economic and technical challenges. Finally, Section 8 gives findings and section 9 ideas for future research and conclusion.

2. OUTLOOK FOR ENERGY IN DEVELOPING COUNTRIES

2.1 An Overview of Energy Systems in Developing Countries

Developing countries are associated with a fast expanding energy demand and slowly growing energy infrastructure. Many of these countries have centralized power generation systems that are generally old, inefficient and unable to fulfill rising demand for electricity. This constant pressure on the energy sector in these locations causes volatility in the power supply and regular shortages. In

many developing regions, energy generation is heavily dependent on fossil fuels such as coal, oil and natural gas.[24] The integration of renewable energy is still restricted and in its early stage of contributing to the overall energy mix in several countries. The incongruence between the traditional and renewable energy sources results in long-term sustainability problems.

2.2 Supply/Demand Gap

The supply and demand mismatch of energy is one of the important concerns in the developing countries. The rapid growth of the demand for energy, resulting from population growth, urban expansion and industrial development, is far outstripping the growth in generation capacity. This gap leads to:

- Peak load shedding
- Power outages often occur
- Lower productivity of industry
- Increasing business costs

Utilities cannot fulfill peak demand in many circumstances and must resort to load management measures detrimental to customers and companies.

Table 1 Energy Challenges in Developing Countries

Challenge	Impact	Suggested Solution
Supply-Demand Gap	Power shortages	Capacity expansion
T&D Losses	Energy wastage	Smart grid
Fossil Fuel Dependence	High emissions	Renewable energy
Weak Infrastructure	Reliability issues	Grid modernization
Financial Constraints	Slow development	Investment support

2.3 Transmission and Distribution Losses

In poor countries, transmission and distribution losses are substantially larger than in affluent countries. These are the result of old infrastructure, inadequate maintenance, electricity theft and improper management of the grid. High T&D losses causes are System efficiency

cut, Higher-cost energy generating, National level energy waste [24] ,Cost to utilities companies Enhancing grid infrastructure and deploying sophisticated monitoring technologies are necessary to curtail such losses.

2.4 Reliance on Fossil Fuels

Many developing countries are very dependent on fossil fuels for energy generation. This dependence gives rise to a number of issues, including high costs for fuel imports, price instability in foreign markets, and environmental damage. Fossil fuel generation also contributes to: High carbon emission, Air pollution and health problems, Effects of climate change, Unrealistic energy systems. Today fossil fuels are the main source of energy but there is the increasing need to move to renewable energy sources.

2.5 Technical Limitations and Infrastructure

In many developing countries, energy infrastructure is generally aging with no contemporary automation and control systems. Power plants, transmission lines and distribution networks are often working beyond their design capacity. The major restrictions are Old, inefficient power-plants, Poor voltage regulation and grid stability, No sophisticated monitoring systems, Poor maintenance and technical knowledge. The overall reliability of the power supply is reduced by these limits.

2.6 Economic and Financial Constraints

A large-scale investment is needed to improve the energy sector. But, poor countries generally have no financial capacity. Power plants, renewable

energy projects and grid modernization are expensive to build, making it difficult to replace old systems. Economic issues that are common include: Restricted government financing, High debt load, Reliance on foreign investment, financial strain on subsidies. These restrictions are breaks on the shift to modern energy systems.

2.7 Environmental Effects

The extensive usage of fossil fuels in emerging countries has dire environmental effects. The generation of power leads to air pollution, greenhouse gases and environmental degradation. Major impacts are Higher CO₂ emissions, Poor air quality in cities, Pollution and health problems, Contribution to global climate change. These environmental challenges underscore the significance of cleaner and more sustainable energy. [2,26,27]

The energy future of the developing countries in general is characterized by the combination of the supply-demand mismatch, infrastructural limits, significant transmission losses, and fossil fuel dependence. These difficulties are interrelated and together they hamper the development of efficient and dependable energy systems. A holistic strategy involving renewable energy adoption, smart grid implementation, advanced energy management techniques and strong regulatory backing is needed to tackle these challenges.

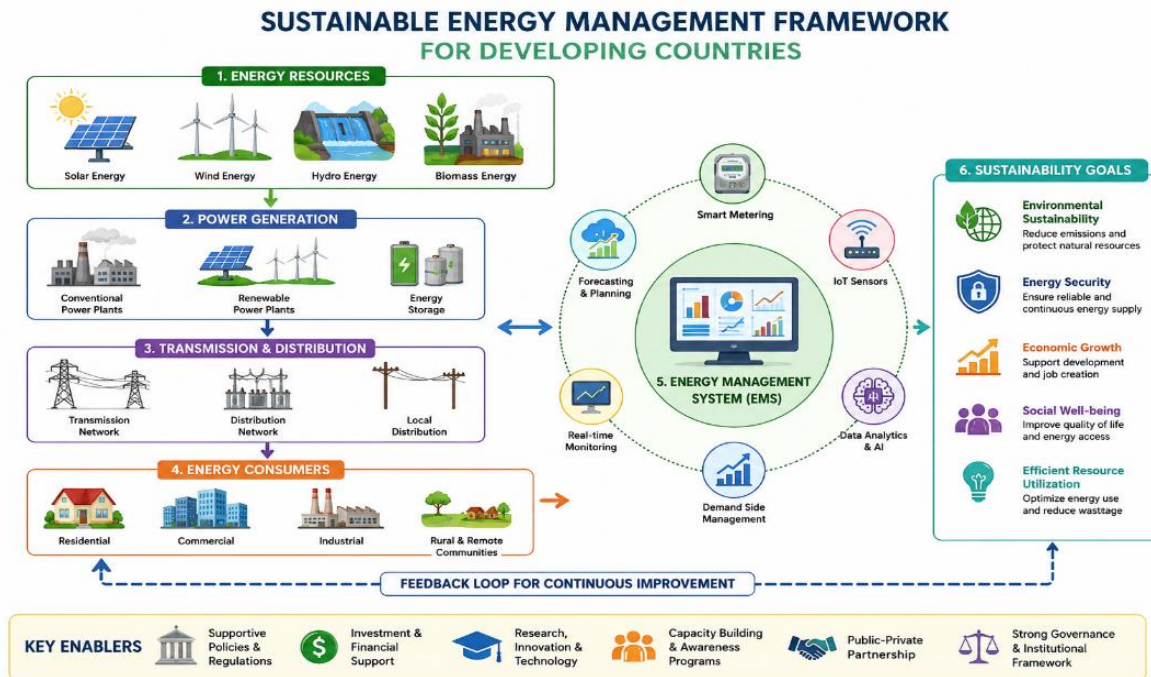


Figure 1 Sustainable Energy Management Framework for development Countries

3. Concept of sustainable energy management

3.1 An Overview of Sustainable Energy Management

Sustainable Energy Management (SEM) is the systematic planning, monitoring, controlling, and optimizing of energy resources to ensure the efficient, reliable, and ecologically responsible use of energy. It strives to achieve a balance between economic growth, security of energy supply and environmental sustainability, and to meet the expanding energy needs of society.

In particular, the sustainable management of energy is of great importance for the developing countries because of the rapid growth of population, urbanization, industrial expansion and the increasing use of electricity. Traditional energy management systems usually focus on power generation improvement, while sustainable energy management takes into account energy supply and energy efficiency[1]–[7]. It's designed to optimize energy resource usage, and to minimize waste, operating costs and environmental effects[8]–[12].

The growing concerns on climate change, emissions of green house gases[28,29,30] and exhaustion of fossil fuel sources have further added to the significance of sustainable energy management all over the world. As such, governments, utility companies, industry and researchers are actively researching creative techniques to increase energy efficiency and to integrate renewable energy supplies into existing electricity

3.2 Sustainable Energy Management Principles

The creation and operation of modern energy systems are guided by several basic concepts of sustainable energy management.

3.2.1 Energy Efficiency

Energy efficiency means using less energy to keep up the functioning of a system. This includes the use of efficient technology, equipment and operating methods that reduce energy losses in generation, transmission, distribution and consumption.

Table 2 : Comparison of Energy Sources in Developing Countries

Energy Source	Efficiency (%)	Environmental Impact	Availability	Cost Level	Suitability for Developing Countries
Coal	30-40%	Very High CO ₂ emission	High	Medium	Low (environmental concerns)
Natural Gas	45-55%	Moderate emissions	Medium	Medium	Medium
Hydropower	85-90%	Very low emissions	Location-based	High initial cost	High (where water resources exist)
Solar PV	15-22%	Zero emissions	Very High (sunlight)	Reducing cost	Very High
Wind Energy	30-45%	Very low emissions	Location-based	Medium	High
Biomass	20-30%	Moderate emissions	High in rural areas	Low	Medium

3.2.2 Integration of Renewable Energy

One of the basic principles of sustainable energy management is to combine renewable energy sources, such as solar, wind, hydro and biomass. Renewable resources enable us to rely less on fossil fuels and to create a more sustainable world.[31,32,33]

3.2.3 Protection of the Environment

The goal of sustainable energy systems is to reduce environmental consequences by minimizing greenhouse gas emissions, air pollution and resource depletion. The notion underpins international initiatives to combat climate change and promote sustainable development.[34]

3.2.4 Energy Security

Energy security is the continual availability of energy supplies at an affordable price. Sustainable energy management increases system resilience and decreases sensitivity to fuel shortages and price volatility.

3.2.5 Economical Feasibility

The energy system has to be economically viable as well, if it is to be sustainable. Energy management strategies should offer long term financial benefits through efficiency improvements, cost reductions of operations and optimization of resource consumption

3.3 Goals of Sustainable Energy Management

The main objectives of sustainable energy management are to optimize the overall efficiency of energy production, transmission, distribution

and utilization assuring long-term environmental and economic sustainability. It is dedicated to lowering energy losses in the transmission and distribution operations to make the most use of available resources. A further goal of sustainable energy management is to strengthen the reliability, stability and security of energy systems so as to assure a continuous and reliable supply of power to users. Enhancement of the integration and penetration of renewable energy sources, such as solar, wind and hydropower, into the energy mix is another significant goal, to reduce dependence on fossil fuels.[33-40] It also tries to reduce the environmental effect by reducing greenhouse gas emissions, pollution and conserving natural resources. Sustainable energy management promotes economic growth and social development by creating jobs, increasing energy availability and fostering industrial development. It also aims to optimize energy consumption and production patterns with the use of sophisticated technology, smart energy systems and effective

resource allocation, assuring a balanced and sustainable energy future..

Achieving these objectives helps to develop resilient and sustainable energy systems that can satisfy future energy needs.

3.4 Elements of Sustainable Energy Management

Efficient energy use is achieved through numerous interwoven parts that form sustainable energy management.[41]

3.4.1 Power generation

Energy generation is the production of electricity from renewable and traditional energy sources. Sustainable energy management promotes the progressive replacement of the fossil fuel based generation with cleaner renewable technology.

3.4.2 Distribution and Transmission

The transmission and distribution system carries electricity from power plants to the end users. Proper management of these systems reduces technical losses and enhances grid reliability.[42]

Table 3 Energy Losses in Power System Stages (Developing Countries Average)

Stage of Energy System	Description	Average Loss (%)	Major Issues
Power Generation	Conversion losses in plants	35-45	Old thermal plants, low efficiency
Transmission	Long-distance electricity transfer	5-8	Weak infrastructure
Distribution	Delivery to consumers	10-20	Technical + theft losses
End-use Consumption	Inefficient appliances	15-25	Lack of energy-efficient devices

3.4.3 Energy use

Energy is consumed by the household, commercial, industrial and agricultural sectors. Energy Monitoring and Control Energy monitoring and control is required to improve the overall system efficiency.

3.4.4. Energy Monitoring and Management

Modern energy management systems use advanced monitoring tools to gather real-time data on energy generation and consumption. This information underpins educated decision-making and operational optimization.[43]

Table 4 Renewable Energy Potential vs Installed Capacity in Developing Regions

Region	Solar Potential (kWh/m ² /year)	Installed Solar Capacity (GW)	Wind Potential (GW)	Installed Wind Capacity (GW)	Utilization Level
South Asia	1800–2200	60–80	150–200	40–60	Low–Moderate
Africa	2000–2500	20–40	100–150	10–25	Very Low
Middle East	2000–2400	30–50	80–120	15–30	Low
Latin America	1600–2100	50–70	120–180	35–55	Moderate

3.5 Renewable Energy and Sustainable Energy Management

Renewable energy is vital for sustainable energy management due to its environmental and economic benefits. Solar, wind, hydroelectric and biomass energy sources are all clean alternatives to conventional fossil fuels. The integration of renewable energy leads to:

- Reduction of greenhouse gases emissions.
- More energy security.
- Diversification of energy sources.
- Sustainable throughout the long run.
- Less reliance on imported fuels.

Renewable energy technologies provide several chances to improve electricity availability in poor countries, especially in distant and neglected areas.

3.6 Strategies for Energy Management

Many strategies are used for improving energy management performance.

- Energy Conservation
- Minimizing wasteful energy use through behavioral and technical advances.
- Demand-side management (DSM)
- Balance supply and demand for electricity by managing consumer demand.
- Managing Peak Loads
- Reducing electricity consumption during high demand periods to increase system stability.

- Energy Audit
- Examine energy usage patterns to find potential for improvements in efficiency.
- Forecasting of Load
- Forecasting future electricity demand for planning and operational purposes.

3.7 Advantages of Sustainable Energy Management

There are many benefits of implementing sustainable energy management.

- Benefits to the Environment
- Lower carbon emissions.
- Better air quality.
- Natural resources conservation.
- Economic Advantages
- less expensive energy
- Enhanced operating efficiency.
- Reduced fuel consumption.
- Social Benefits
- Enhanced access to electricity.
- Better quality of life.
- Support for the sustainable development goals.
- Technical Advantages
- Enhanced grid reliability.
- Enhanced energy monitoring
- Better system performance.

3.8 Challenges of Sustainable Energy Management

It has some problems for the effective application but it has benefits:

- High upfront investment costs.
- Lack of technological expertise.
- Regulatory and policy impediments.
- Infrastructure constraints
- Intermittent nature of renewable energy sources.
- Public awareness, lack of. Addressing these difficulties would need concerted efforts by governments, utility companies, corporations and research organizations.

Sustainable energy management is a holistic method for reliable, efficient and environmentally conscious energy systems.[42-46] Developing nations can tackle energy difficulties and spur economic development and environmental sustainability by embracing renewable energy sources, boosting energy efficiency, and deploying modern management practices.

4. Renewable Energy Resources

Renewable energy resources are an important component of sustainable energy management systems in developing countries. These resources are extracted from natural processes which are continuously renewed, such as solar radiation, wind flow, hydrological cycles and conversion of organic matter. The transition towards renewable energy-based systems has been faster due to the increasing strain on fossil fuel-based energy systems and environmental concerns such as greenhouse gas emission and climate change. In developing countries, the move towards renewable energy is not just an environmental imperative but also an economic and infrastructural need. Many areas are plagued by inadequate grid infrastructure, high transmission losses and intermittent power delivery.[47-48] Therefore, decentralized renewable energy systems have emerged as a viable option for boosting energy access, energy security and sustainable development goals.

The availability of resources, technological maturity, cost-efficiency and integration capabilities into existing energy systems determine

the performance and practicality of renewable energy technologies. The following sections give a technical review of the major renewable energy resources.

Solar energy is the most abundant and fastest-growing renewable energy supply in developing regions. Countries within the global sunbelt have high levels of solar irradiation, providing good grounds for photovoltaic (PV) and solar thermal systems. Photovoltaic (PV) cells, which convert solar radiation into energy using semiconductors, can be used in modest household systems or big utility-scale solar farms. The continuously reduction in PV module price, together with improvement in conversion efficiency, has considerably improved the economic feasibility of solar energy systems.

Solar energy, however, has intrinsic intermittency because of diurnal and seasonal changes. This fluctuation means that energy storage systems or hybrid configurations have to be implemented to mitigate the reliability. System design must also address performance degradation owing to temperature impacts, dust deposition and ambient factors. The efficiency of solar energy systems is normally 15% to 23% , and the capacity factor is 18% to 25% , depending on where the system is located and how it is configured .

A mature renewable technology, wind energy employs aerodynamic rotor systems to transform the kinetic energy of atmospheric airflows into electrical energy. Wind energy viability is highly dependent on the local wind speed distribution that is typically advantageous in areas like coastal areas, broad plains and high terrains. In underdeveloped countries, wind energy has demonstrated great potential in areas with continuous wind corridors, but it remains sporadic because of infrastructure and budgetary restrictions.

However , wind turbines are not 100 % operationally efficient . Wind speed varies , turbine design varies , and ability to feed into the grid varies . Average capacity factors are 25 to 45 percent, making wind an intermediate reliability source of power, albeit variable. The unpredictable nature of wind patterns presents one of the primary technical hurdles, demanding advanced

forecasting systems and grid stabilizing methods. Also in project development, spatial limitations and environmental factors such impacts on birds and the creation of noise must be considered.

Hydropower is one of the most established and stable renewable energy technologies, particularly in developing countries with extensive river systems and water resources. It works on the idea of turning gravitational potential energy of water into mechanical and electrical energy. Hydropower systems are highly efficient, frequently reaching 85-90% efficiency. They are important in base-load electric generation and grid stability.

Hydropower[53,54] generation, however, is largely site specific and depends on hydrological factors such as rainfall patterns, river flow constancy and topographical gradients. Large-scale hydropower projects have tremendous generation capacity but significant environmental and social repercussions, including ecosystem damage, sedimentation, and people displacement. Small and micro-hydropower systems give more environmentally sustainable options, particularly for rural electrification, although their contribution to national energy supply remains small.

Biomass energy is obtained from organic matter such as agricultural wastes, animal waste and forestry by-products. It is particularly significant in

rural energy systems where modern energy infrastructure is scarce. Biomass can be used in different forms, such as solid combustion, biogas production and liquid biofuels. Traditional biomass[55] use is still prevalent in developing nations but with low energy efficiency and severe health risks from indoor air pollution. Anaerobic digestion and biomass gasification are modern biomass technologies that enable better energy conversion efficiency and lower environmental impact. The effectiveness of energy conversion depends a lot on the technology: older systems are at 10-20%, while sophisticated biogas systems reach more than 50%. The sustainability of biomass energy[56], however, depends on the appropriate management of resources to avoid deforestation and land degradation.

From a systems approach, renewable energy resources have to be evaluated not individually but as an integrated energy portfolio. Each resource has complementary characteristics: solar energy has high scalability but intermittent output, wind energy has complementary generation profiles, hydropower provides grid stability and base-load support, and biomass provides dispatchable energy suitable for rural and backup applications. The integration of these resources through hybrid energy systems and smart grid technology is necessary for reliable and sustainable energy supply in emerging countries.

Table 5 Technical Comparison of Renewable Energy Resources in Developing Countries

Parameter	Solar	Wind	Hydropower	Biomass
Resource Availability	Very High	Medium	Location-specific	High (rural)
Efficiency Range	15-23%	25-45%	80-90%	10-60%
Capacity Factor	18-25%	25-45%	40-90%	20-80%
Reliability	Medium	Medium	Very High	Medium
Capital Cost	Medium	High	Very High	Low-Medium

Operational Cost	Very Low	Low	Low	Medium
Environmental Impact	Very Low	Very Low	Moderate-High	Moderate-High
Scalability	Very High	High	Medium	Medium

Table 6 shows the global trend in renewable energy capacity increase for the period 2021–2025. The results suggest a steady and quick increase in total installed renewable capacity, mainly due to the expansion of solar energy. [49,50,51]The biggest growth contribution comes from solar power compared to wind and hydro power, due to the decreased cost of technology and

higher efficiency of photovoltaic systems. Hydropower is important but its proportion of new capacity expansions is falling due to geographical constraints and environmental concerns. Overall, the table shows a significant global movement toward renewable energy systems led by solar, especially in developing nations.

Table 6 : Global Renewable Energy Capacity Growth Trend (Recent Data)

Year	Total Renewable Capacity (GW)	Solar Share	Wind Share	Hydro Share	Key Observation
2021	~3060 GW	40%	27%	25%	Hydro still dominant legacy source
2022	~3250 GW	44%	28%	24%	Solar begins rapid expansion
2023	~3600 GW	48%	29%	22%	Solar overtakes hydro growth rate
2024	~4448 GW	55%	30%	20%	Rapid global scaling of renewables
2025	~5149 GW	58%	31%	19%	Solar becomes dominant source

The table. 7 demonstrates that solar and wind energy are now the most cost competitive sources of power with LCOE values that are far lower than those of fossil fuels. Hydropower is still cost effective, albeit with a significant initial

investment, while biomass has a middling cost performance. Renewable energy technologies are generally becoming more economically viable for the developing countries.

Table 7 Summary (LCOE Comparison)

Energy Source	LCOE (USD/kWh)	Cost Trend	Economic Viability
Solar PV	0.03 – 0.08	Rapidly decreasing	Very High
Onshore Wind	0.03 – 0.07	Stable decreasing	Very High
Hydropower	0.05 – 0.12	Stable	High
Biomass	0.06 – 0.15	Moderate	Medium
Fossil Fuels	0.07 – 0.20	Increasing	Low (future risk)

Hydropower has the highest efficiency and reliability and is excellent for base-load generating as seen in this table. Wind energy has a modest performance with variability while solar energy has

a lower capacity factor due to intermittency. Shown in Table 8 Biomass has variable efficiency depending on the type of technology, and can be used for rural systems as well as backup systems.

Table 8 Energy Efficiency and Capacity Factor Comparison

Energy Source	Conversion Efficiency	Capacity Factor	Reliability Level
Solar PV	15-23%	18-25%	Medium
Wind	30-45%	25-45%	Medium
Hydropower	80-90%	40-90%	Very High
Biomass	20-60%	50-80%	Medium-High

The comparison reveals that solar and wind energy are associated with the lowest environmental impacts Shown in table 9 .whereas hydropower has moderate to high ecological repercussions owing to disturbance of the ecosystem. The impact

of biomass is dependent on the type of system (traditional or modern). Renewable energy is usually far less harmful to the environment than fossil fuels.

Table 9 Environmental Impact Index of Renewable Energy Systems

Energy Source	CO ₂ Emissions	Land Use Impact	Ecosystem Impact	Pollution Level
Solar	Very Low	Medium	Low	Very Low
Wind	Very Low	Low	Low-Medium	Very Low
Hydropower	Low	High	High	Low
Biomass	Medium	Medium	Medium-High	Medium

This table shows 10. that solar energy is the most suited alternative for the developing countries because of its great availability and scalability. Wind energy works in some areas but hydropower

is quite reliable but has geographical limitations Biomass is ideal for mostly rural areas but needs updating for better sustainability.

Table 10 suitability Index of Renewable Energy Sources for Developing Countries

Criteria	Solar Energy	Wind Energy	Hydropower	Biomass Energy
Resource Availability	Very High	Medium	Location-specific	High (rural areas)
Installation Cost	Medium	Medium-High	High	Low-Medium
Operational Cost	Very Low	Low	Low	Medium
Energy Efficiency	Medium (15-23%)	Medium (25-45%)	Very High (80-90%)	Medium (20-60%)
Reliability	Medium	Medium	Very High	Medium
Scalability	Very High	High	Medium	Medium
Environmental Impact	Very Low	Very Low	Moderate-High	Moderate
Rural Applicability	Very High	Low-Medium	Medium	Very High
Grid Integration	Medium	Medium-Low	Very High	Medium
Overall Suitability	Very High	High	Very High	Medium High

Results reveal that renewable energy systems significantly boost energy security by decreasing reliance on imports and increasing price stability Shown in table .11 For developing countries,

renewables are a crucial element of energy independence, providing long-term sustainability and less susceptibility to the vagaries of global markets than fossil fuels.

Table 11 Renewable Energy Role in Energy Security

Energy Aspect	Fossil Fuels	Renewable Energy Systems
Import Dependency	High	Low
Price Stability	Low	High
Supply Security	Vulnerable	Resilient
Long-term Sustainability	Low	Very High
Climate Risk	High	Very Low

The table shows 12. that modern energy systems are based on the integration of various renewable sources. The complementary nature of solar, wind, hydropower and biomass improve reliability .

Storage systems and smart grids ensure stability. The results confirm the importance of hybrid energy systems in sustainable energy management.

Table 12 Hybrid Energy System Model (Modern Approach)

Component	Function	Benefit in Developing Countries
Solar PV	Daytime generation	Rural electrification
Wind Power	Complementary supply	Grid balancing
Hydropower	Base-load stability	Reliable supply
Biomass	Backup generation	Rural energy security
Battery Storage	Load balancing	Grid stability
Smart Grid	Monitoring & control	Efficient distribution

5. SMART GRID SYSTEMS AND MODERN TECHNOLOGIES

5.1 Overview of Smart Grid Technology

The idea of the smart grid represents a major advance in the design, operation and management of electrical power systems. Traditional power grids operate on a one-way transmission model, from generation to consumption. Smart grids utilize advanced digital communication, sensing and control technologies to create a bidirectional, intelligent and adaptive energy network. This

transformation is especially important for developing countries where aging infrastructure, high transmission and distribution losses and growing energy demand require urgent and innovative solutions[57-58] A smart grid is an electricity supply network that uses digital technology and automation for the monitoring and control of the generation, transmission, distribution and consumption of electrical energy in real time. Smart grids are characterized primarily by the ability to

communicate in two directions between utility and consumer, enabling dynamic changes in supply and demand of electricity. This capability greatly improves system efficiency, decreases operational losses and increases the reliability of power delivery. The application of smart grid technology in developing countries provides a solution to the structural weaknesses of existing

power systems. Smart grids, through automation of grid operations, remote monitoring and integration of renewable energy sources can help address the persistent problems of voltage instability, load shedding, energy theft and inefficient energy distribution that plague energy systems in many developing regions.

Table 13 Comparison of Traditional Grid vs Smart Grid

Communication	One-way	Two-way (bidirectional)
Monitoring	Manual / limited	Real-time automated
Fault Detection	Slow, manual	Automated, fast
Energy Flow	Unidirectional	Bidirectional (prosumers)
Consumer Role	Passive consumer	Active participant
Renewable Integration	Difficult	Highly compatible
Self-healing	Not available	Available
Data Collection	Periodic/manual	Continuous/automated

5.2 Key Components of Smart Grid Infrastructure

The smart grid consists of several interconnected components, which together form an intelligent energy management system. These components include the whole power system from generation and transmission to distribution and end-use consumption.

5.2.1 Advanced Metering Infrastructure (AMI)

One of the important building blocks of a smart grid is an Advanced Metering Infrastructure (AMI). AMI encompasses smart meters,

communication networks and data management systems that together enable two-way, real-time communication between consumers and utilities. Smart meters are the successor to conventional electromechanical meters and offer detailed, time-stamped data on energy consumption.[59-60] This data supports dynamic pricing, remote disconnection and reconnection and automatic outage detection. The deployment of AMI is particularly impactful in developing countries as it reduces electricity theft and unauthorized connection, which are major contributors to non-technical losses.

Table 14 Smart Meter Benefits and Their Impact in Developing Countries

Benefit Area	Description	Impact in Developing Countries
Theft Detection	Identifies unauthorized tapping	Reduces T&D losses significantly
Real-time Billing	Accurate consumption data	Improved revenue collection
Demand Forecasting	Historical usage patterns	Better load planning
Outage Management	Automatic fault reporting	Faster restoration times
Consumer Awareness	Usage feedback to consumers	Encourages energy conservation

5.2.2 SCADA and Energy Management Systems (EMS)

Supervisory regulate and Data Acquisition (SCADA) systems are used to centrally regulate

and monitor the power system components such as generators, transformers, and switching equipment in real-time. • When connected with Energy Management Systems (EMS), SCADA

provides utilities with the ability to optimize power flow, manage contingencies and respond quickly to system problems. Modernization of the control centers by SCADA and EMS is very essential to enhance the operational reliability of the power systems through manual or semi-automated operations in developing countries.

5.2.3 Communication Networks

The backbone of every smart grid system is reliable and secure communication infrastructure. Smart grid communication networks encompass fiber optic cables, power line communication (PLC), wireless sensor networks (WSN), cellular networks (4G/5G), and satellite-based systems. In developing countries, wireless and cellular communication technologies provide practical and cost-effective solutions for linking distributed energy assets and distant metering stations in rural and remote places where the installation of physical cables is economically or geographically difficult.

5.2.4 Distributed Energy Resources (DERs)

Smart grids are built to handle Distributed Energy Resources (DERs) including rooftop solar panels, small wind turbines, battery storage systems and electric vehicles (EVs). Unlike centralized power plants, DERs are installed closer to the point of

consumption, thereby reducing transmission losses and improving local energy security. The opportunity for DERs in developing nations is huge for rural electrification and off-grid energy access, especially for populations that are far away from the main grid.

5.3 Impact of Artificial Intelligence and Machine Learning

In modern energy systems, Artificial Intelligence (AI) and Machine Learning (ML) have surfaced as disruptive technologies. They can sift through huge amounts of data, spot complicated patterns, and forecast future outcomes. This is changing the way power grids are controlled, serviced and fine-tuned. In underdeveloped countries, AI and ML are realistic solutions to overcome operational inefficiencies and improve reliability of energy supply in limited human resources. The use of AI in energy systems covers a range of areas such as load forecasting, fault detection, renewable energy projection, energy optimization, and demand-side management. Machine learning algorithms have been shown to perform better than traditional statistical techniques in prediction and optimization applications in the energy sector. These algorithms include artificial neural networks (ANNs), long short-term memory (LSTM) models, support vector machines (SVMs) and reinforcement learning techniques.

Table 15 :AI and Machine Learning Applications in Energy Systems

Application	AI/ML Technique Used	Benefit
Load Forecasting	Neural Networks, LSTM	Accurate demand prediction
Fault Detection	Support Vector Machines	Early fault identification
Energy Optimization	Reinforcement Learning	Reduced operational costs
Renewable Forecasting	Random Forest, Deep Learning	Improved solar/wind prediction
Anomaly Detection	Clustering, Autoencoders	Theft and loss detection
Grid Stability	Genetic Algorithms	Optimized power flow

5.3.1 AI-based Load Forecasting

Accurate forecasting of loads is critical to efficient planning of power generation and distribution. Traditional forecasting methods based on regression models are limited in capturing the nonlinear and complicated linkages in energy consumption trends. Artificial intelligence (AI) based forecasting models, especially deep learning

architectures such as LSTM networks and convolutional neural networks (CNNs), have shown considerable improvements in accuracy for short-, medium- and long-term load forecasting. For emerging countries, where energy demand is rapidly and unpredictably increasing, AI-powered forecasting helps utilities in better planning of

generation capacity and reducing the incidence of load shedding. [61]

5.3.2 Artificial Intelligence for Predictive Maintenance and Fault Diagnosis

The main causes in underdeveloped nations are power outage and energy loss due to equipment failure and fault detection. AI algorithms trained on past sensor data can detect anomalous patterns in voltage, current and temperature prior to equipment failures. This allows utilities to shift from reactive to predictive maintenance, eliminating unplanned outages and increasing the lifespan of grid equipment. [62,63] Support vector machines, random forests and autoencoders are some of the machine learning approaches that have been effectively employed for fault classification and anomaly detection in the transmission and distribution systems.

5.4 Internet of Things (IoT) in Energy Systems

The Internet of Things, or IoT, is a network of physical devices that are embedded with sensors,

software and other technologies to connect and exchange data with each other and other systems over the internet. IoT technology in energy systems offers real-time monitoring, automated control and data-driven decision-making across the full power system value chain. The implementation of IoT in the energy infrastructure is a crucial enabler for smart grid functioning and sustainable energy management.[64-65] IoT devices are being applied in energy systems including smart meters, voltage and current sensors, remote terminal units (RTUs), programmable logic controllers (PLCs), weather monitoring stations and smart inverters for renewable energy systems. These devices produce continuous streams of operational data which are sent to central management platforms for analysis, visualization and control. The synergy of IoT, cloud computing and data analytics provides a good infrastructure for intelligent energy management

Table 16: IoT Devices and Their Applications in Energy Management

IoT Device	Function	Data Generated	Application
Smart Meters	Consumption monitoring	Usage patterns	Billing, DSM
Sensors (Grid)	Voltage/current monitoring	Power quality data	Grid stability
SCADA Systems	Remote control	Operational data	Grid automation
Weather Stations	Climate monitoring	Solar/wind data	Renewable forecasting
Smart Inverters	PV system management	Generation data	Solar integration

There are various advantages of IoT based energy monitoring systems in underdeveloped nations. First, they can reduce the requirement for actual site visits, by enabling remote monitoring of distributed assets. Secondly, they offer detailed usage data that enables precise billing and loss detection. Third, IoT systems facilitate the integration of small-scale renewable energy installations, such rooftop solar panels and mini-grids, into the larger energy management framework. With the decreasing cost of IoT hardware and the increasing availability of mobile internet connectivity in underdeveloped nations,

IoT-based energy management is becoming more reachable and inexpensive.

5.5 Block chain Technology for Energy Systems

Block chain technology was initially designed for financial transactions, but it is now being investigated for use in energy systems.[66] A block chain is a distributed, decentralized ledger, allowing transactions to be recorded in a transparent, secure and immutable way. Block chain has many creative uses in the energy sector, such as peer-to-peer (P2P) energy trading, decentralized energy management, secured metering and invoicing, and transparent

renewable energy certification. Block chain-based peer-to-peer energy trading platforms in underdeveloped nations have a specific potential for communities with distributed solar or mini-grid systems. With a block chain network, prosumers with excess energy from rooftop solar panels can sell directly to nearby consumers without a centralized utility middleman. This generates new economic opportunities for small-scale energy producers and increases the efficiency of local energy delivery. However, the widespread deployment of block chain in the energy systems in developing nations is hindered by the unavailability of high-speed internet infrastructure and the legislative frameworks needed to regulate decentralized energy markets.

5.6 Microgrids and Off-Grid Systems

Microgrids are small-scale energy systems that can run either in parallel with the main grid or independently as autonomous energy networks. A typical microgrid consists of distributed generation sources such as solar panels or tiny wind turbines, energy storage devices such as batteries and sophisticated control systems that regulate the balance between local generation and consumption. Microgrids are of special importance to developing nations because they can deliver a stable supply of power to rural and distant areas which are not connected to the main grid.

Smart microgrid controllers optimize the dispatch of local generation, battery storage and power quality inside the microgrid by using advanced algorithms such as AI, IoT-based monitoring etc. This capacity also makes microgrids a resilient, self-contained energy option for locations with poor or no grid infrastructure. Solar-powered microgrids have already been successful in rural communities in Sub-Saharan Africa, South Asia, and Latin America, which means they could play a part in speeding up energy availability in the developing world. When connected to the main grid, the integration of current communication and control technology in microgrids also allows them to participate in broader grid management activities such as demand response programs and frequency regulation services.[67] This makes

microgrids a versatile part of a contemporary, adaptable and sustainable energy system.

5.7 Cybersecurity Issues in Smart Grid

The rising digitization of power systems using smart grid technologies creates substantial cybersecurity threats. With energy infrastructure becoming more interconnected and dependent on digital communication networks, it is increasingly exposed to cyberattacks, data breaches and hostile meddling. These threats present a considerable barrier to the safe and reliable operation of smart grid systems in poor nations, where cybersecurity frameworks and technical competence are generally insufficient. Some common types of cyber security threats in smart grid environments are illegal control system access, metering data manipulation, denial-of service attacks on communication networks, and intrusion of SCADA systems. A successful cyberattack on a smart grid can result in large scale blackouts, economic losses and endanger public safety. Thus, the implementation of smart grids in underdeveloped nations must be complemented by strong cybersecurity measures, such as network segmentation, data encryption, intrusion detection systems and frequent security audits. International standards such as IEC 62351 and NIST SP 800-82 offer guidance on cybersecurity in energy systems. However, the application of these standards in underdeveloped nations is hindered by financial restrictions, lack of technical knowledge and the lack of clear regulatory requirements. Therefore, in addition to technical solutions, capacity building, policy development and international cooperation are needed to address cybersecurity in smart grid development.

5.8 Challenges in Implementation of Smart Grid in Developing Countries

Smart grid technologies provide vast potential to improve energy systems in poor nations, but there are a number of serious barriers to their deployment. These difficulties are both technical and non-technical, calling for concerted action by governments, utilities, technology providers and international development groups.[68]

Table 17 Challenges of Smart Grid Implementation in Developing Countries

Challenge	Description	Possible Solution
High Capital Cost	Infrastructure investment is large	Public-private partnerships
Cybersecurity Risk	Digital systems are vulnerable	Encryption, security protocols
Lack of Expertise	Shortage of skilled workforce	Training and capacity building
Interoperability	Incompatible legacy systems	Open standards adoption
Connectivity	Poor internet infrastructure	Wireless/cellular networks
Regulatory Gap	Lack of smart grid policies	Updated energy regulations

One of the main hurdles to deployment in underdeveloped nations is the high capital cost of smart grid infrastructure. The adoption of modern metering infrastructure, communication networks and control systems demands large upfront investment that many utilities in poor nations cannot afford without external financial backing. International development banks and donor organizations are key sources of finance for smart grid projects in low-income countries through concessional loans, grants and technical assistance programs. The other important barrier is the shortage of competent technical workers. Smart grid systems need skills in areas such as power electronics, communication engineering, data analytics and cybersecurity. These skills are in limited supply in many developing nations and the training and education systems have not yet changed to generate graduates with the transdisciplinary abilities needed for smart grid operation and maintenance. Investing in technical education and professional training programs is thus an essential complement to smart grid infrastructure investment. Smart grid technology and state-of-the-art energy management systems are an important gateway for the transformation of developing countries' power sectors. By incorporating smart metering infrastructure, SCADA systems, AI and machine learning, IoT devices, blockchain platforms, and microgrid technologies, developing countries may significantly enhance the efficiency, dependability, and sustainability of their energy systems. These technologies solve many of the basic problems of traditional power grids, including significant transmission and distribution losses, lack of good fault detection, limited use of renewable energy sources, and lack of proper customer interaction. However, the full potential of smart grid

technology in underdeveloped nations can only be realized if major constraints including high capital costs, cybersecurity threats, lack of technical skills, insufficient communication infrastructure, and bad regulatory frameworks are overcome. To successfully adopt smart grids as a foundation for sustainable energy management in developing regions, a comprehensive and coordinated approach is necessary. This approach should involve technological deployment, capacity building, policy change, and international cooperation.

6. Challenges and Constraints for Sustainable Energy Management in Developing Countries

The shift towards sustainable energy management in developing nations is limited by a complex interplay of technical, economic, institutional and environmental issues. Despite major advances in renewable energy technologies, smart grids and digital energy management systems, in terms of efficiency and cost-effectiveness, their large-scale deployment has been constrained by the lack of infrastructure, weak regulatory frameworks, financial constraints and operational uncertainties. These difficulties have a direct impact on the stability of power systems, energy security, investment attractiveness and the realization of SDG 7 to enable access to affordable, dependable, sustainable and modern energy for all.

6.1 Technical Challenges in Incorporating Renewable Energies

The integration of renewable energy resources into the conventional power systems has various technological hurdles due to the fact that most of the renewable sources are intermittent and weather dependent. The power generation

variations are difficult to match loads and control frequency due to the highly variable nature of solar photovoltaic (PV) and wind energy both in time and space. Inverter-based renewable energy systems have little or no mechanical inertia, unlike conventional thermal power plants. This reduces system stability and makes it more vulnerable to frequency variations following disruptions.

Voltage regulation in distribution networks with substantial renewable energy penetration is another important topic. Weak distribution systems are characterized by reverse power flow, voltage increases, harmonic distortion and more reactive power demand. The problems demand the implementation of advanced voltage control techniques, dynamic reactive power

compensation, flexible AC transmission systems (FACTS) and intelligent inverter control strategies. Grid congestion is another key worry. Many developing countries have existing transmission networks that were initially constructed for centralized fossil fuel generation, rather than geographically scattered renewable energy resources. This leads to operational issues such as transmission bottlenecks, increased line losses and poor power quality. The lack of synchronized phasor measurement units (PMUs), wide-area monitoring systems (WAMS) and advanced supervisory control and data acquisition (SCADA) systems limits the ability to monitor the grid in real-time and flexibility of operation

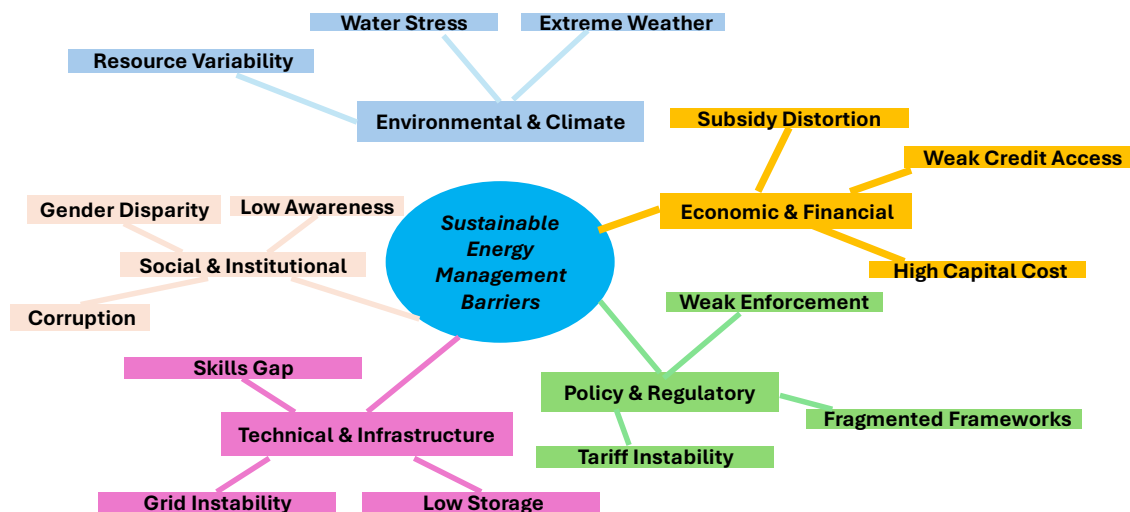


Figure 2 Multi-dimensional Barrier Framework

6.2 Energy Storage and Grid Flexibility

The intermittency of renewable energy generation enhances the importance of flexible power systems, coupled with effective energy storage technology. Battery Energy Storage Systems (BESS), pumped hydro storage, compressed air energy storage (CAES), hydrogen storage and thermal energy storage are considered as important enablers of renewable energy integration to a greater extent.

However, the deployment of energy storage in underdeveloped nations is hindered by high capital costs, limited domestic manufacturing capability, short battery lifecycles in harsh environmental conditions and inadequate recycling infrastructure. Lithium-ion batteries are the dominant choice for present applications but problems with crucial mineral supply chains, degradation mechanisms, fire safety and end-of-life management continue to limit broad deployment.

In addition, the lack of market mechanisms to compensate storage systems for ancillary services, peak shaving, spinning reserve, black-start capability and frequency regulation decreases

investment incentives. Hence, governmental reforms and reorganization of the power market are necessary to unlock the full potential of energy storage technology.

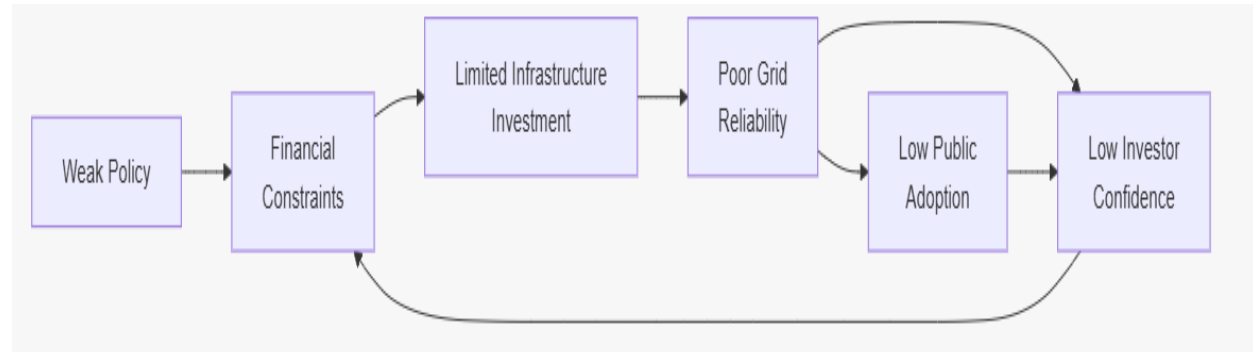


Figure 3

6.3 Smart Grid Implementation Challenges

Smart grids are a key component of sustainable energy management by facilitating two way communication, distributed intelligence, demand side management and real-time energy optimization. However, the technological challenge of application of smart grid technologies in developing nations is very high. One of the main challenges is the limited implementation of Advanced Metering Infrastructure (AMI), intelligent electronic devices (IEDs) and communication protocols according to international standards like IEC 61850. Many of the existing utilities still have manually run substations with limited automation, which makes it difficult to monitor and diagnose faults in real-time. Another significant worry that has been raised is cybersecurity. The digitalization of the energy infrastructure is developing and exposes the power systems to cyber threats, ransomware attacks, data breaches and malicious control operations. Multi-layer security architectures are needed to safeguard smart grids including encryption, intrusion detection systems, blockchain-based authentication, secure communication protocols, and artificial intelligence-based anomaly detection. Another major difficulty is interoperability, as smart grid components are often supplied by multiple manufacturers with diverse communication standards. Therefore, standardization and

interoperability are a must for seamless integration and sustainable operational reliability[68-69].

6.4 Economic and Investment Challenges

Financial constraints are among the greatest impediments to the implementation of renewable energy. Although the levelized cost of electricity (LCOE) from solar PV and wind energy has declined significantly over the past decade, the total system cost of integrating renewables is still large because of the investments required in transmission infrastructure, energy storage, digital communication networks, and grid modernization. Investment risks are often significant in developing countries due to political instability, currency devaluation, inflation and unpredictable regulatory regimes. These issues drive up the cost of financing and deter both domestic and overseas investors. In addition, energy pricing in many emerging economies are excessively subsidized, which erodes utility earnings and restricts investment in infrastructure upgrades. Investor trust is further eroded by the lack of well-designed carbon pricing systems, renewable energy auctions and long-term power purchase agreements (PPAs)

6.5 Policy, regulatory and institutional challenges

Effective sustainable energy management will depend on clear energy policies and robust

institutional governance. But many developing countries continue to have fragmented legislative frameworks, overlapping institutional mandates, lengthy project approval procedures and uneven regulatory enforcement. Grid codes must be updated to reflect inverter-based generation, distributed energy resources (DERs), electric vehicles (EVs) and prosumers. Poor coordination of planning between energy ministries, utilities, regulators and environmental agencies often result in project delays and poor allocation of resources. Moreover, the lack of energy data hinders integrated resource planning and evidence-based policy-making. Reliable forecasting of power consumption, renewable energy generation and climate implications requires comprehensive national energy databases supported by modern digital platforms.

6.6 People and Technology Readiness

Successful adoption of sustainable energy solutions demands highly trained engineers, data scientists, cybersecurity professionals and power system operators. Unfortunately many developing countries suffer from a lack of competent professionals able to design, operate and maintain innovative renewable energy systems. The energy sector invests relatively little in research and development (R&D), restricting domestic innovation and increasing reliance on foreign technology. Poor co-operation between universities, research institutes, business and government further inhibits the commercialization of technologies and information transfer. Capacity development activities, focused training programs and stronger university-industry collaboration are important to enhance local technical skills and underpin long-term energy transition goals.

6.7 Resilience to Climate and Environmental

Climate change adds further operational uncertainties to sustainable energy systems. Higher temperatures also decrease the efficiency of photovoltaic conversion and increase the need for electricity for cooling, while variations in wind regimes and hydrological cycles affect the availability of renewable energy. Extreme weather

events such as floods, cyclones, droughts and heatwaves can damage transmission lines, substations and renewable energy installations, diminishing system resilience. Future energy infrastructure therefore has to integrate climate-resilient design concepts, probabilistic risk assessment, resilient microgrids, distributed generation, and adaptive asset management systems to reduce service interruptions during extreme events. Future research must be directed towards developing AI-driven energy management systems that can integrate renewable forecasting, demand response, distributed optimization and predictive maintenance into cohesive operational frameworks. Machine learning and deep learning algorithms can improve short-term demand forecasting, renewable power prediction and fault detection and hence increase grid dependability. Promising areas of research for developing countries are emerging technologies such as digital twins, blockchain-enabled peer-to-peer energy trading, vehicle-to-grid (V2G) systems, transactive energy markets, and hydrogen-based energy storage. Moreover, future sustainable energy management research should focus on multi-objective optimization strategies that minimize operational cost, carbon emissions and energy losses while maximizing reliability and resilience simultaneously. Overcoming these multi-dimensional constraints calls for comprehensive planning combining technical innovation, new regulatory frameworks, financial reforms, enhanced digital infrastructure and international collaboration. Such an integrated approach can help developing countries to speed renewable energy deployment, increase energy security, boost grid resilience and accomplish long-term sustainable development goals.

7. Policies and Strategies for Sustainable Energy Management

7.1 Enhancing Energy Policies and Regulatory Settings

A strong regulatory framework is key to accelerate the roll out of sustainable energy in developing countries. Governments need to create transparent licensing procedures, solid investment policies and long-term renewable energy targets in

order to cut investor uncertainty. Regulatory agencies need to regularly update grid codes to enable the integration of distributed energy resources (DERs), energy storage systems, electric vehicles (EVs) and smart grid technology.

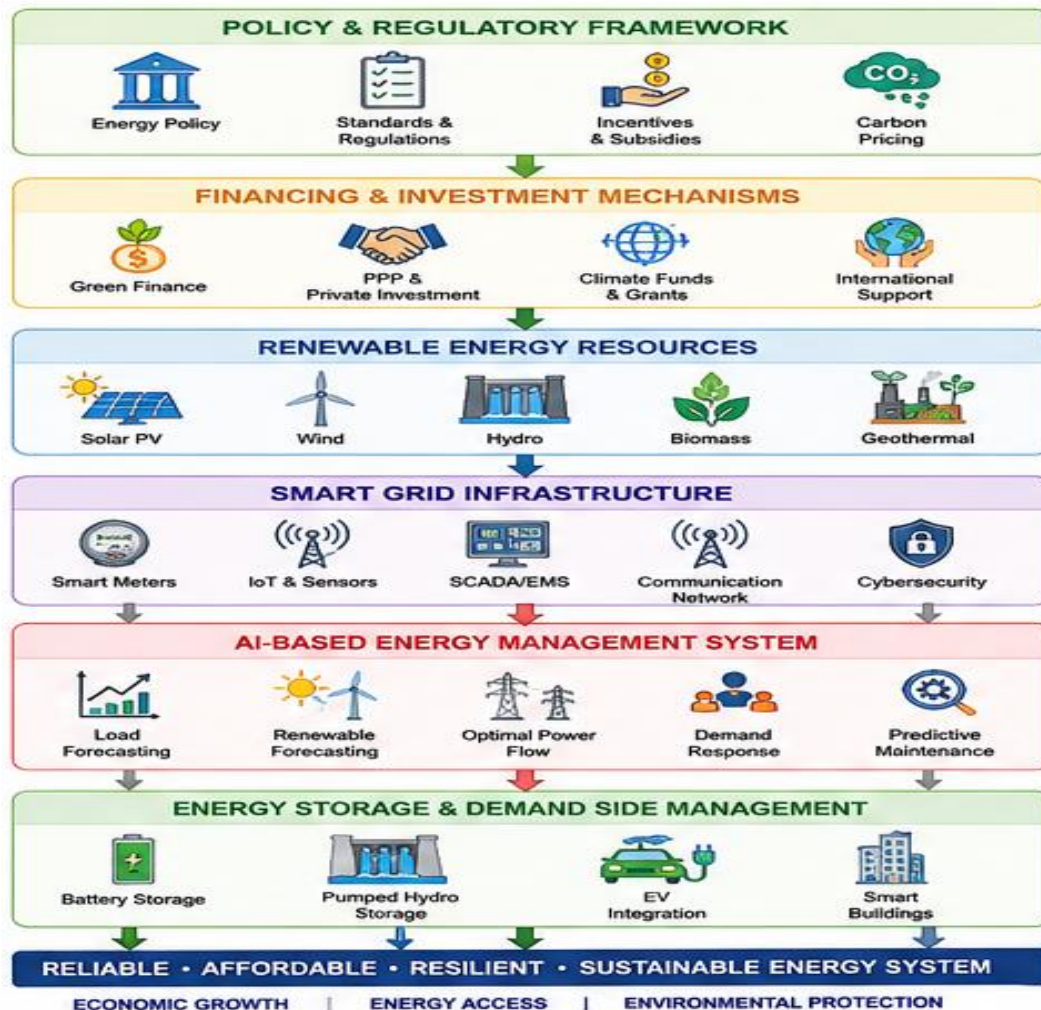
Additionally, removing inefficient fossil fuel subsidies and adopting carbon pricing systems can improve the competitiveness of renewable energy technology. [71]

Table 18 Comprehensive Strategies for Sustainable Energy Management in Developing Countries

Strategy	Technology /Approach	Objective	Key Components	Advantages	Challenges	Performance Indicators	SDGs Supported	Future Research
Renewable Energy Integration	Solar PV, Wind, Hydro, Biomass, Geothermal	Increase renewable energy penetration	Distributed Generation (DG), Inverters, Grid Connection	Reduced CO ₂ emissions, energy security	Intermittency, forecasting uncertainty	Renewable penetration (%), CO ₂ reduction, LCOE	SDG 7, 13	Hybrid renewable systems, offshore wind, floating PV
Smart Grid Modernization	AMI, SCADA, PMU, WAMS, FACTS	Improve grid reliability and monitoring	Smart meters, communication network, automation	Real-time monitoring, lower losses, self-healing grid	High capital cost, interoperability	SAIDI, SAIFI, voltage stability, power quality	SDG 7, 9	AI-enabled autonomous smart grids
Energy Storage Systems (ESS)	Li-ion, Flow Battery, Pumped Hydro, CAES, Hydrogen	Balance renewable intermittency	BESS, EMS, Battery Management System (BMS)	Frequency regulation, peak shaving	Battery degradation, recycling, high cost	Storage capacity (MWh), round-trip efficiency (%)	SDG 7, 12	Green hydrogen, second-life batteries
Artificial Intelligence (AI)	Machine Learning, Deep Learning, Reinforcement Learning	Intelligent decision-making	Forecasting, optimization, anomaly detection	Improved forecasting accuracy, predictive	Data availability, explainability	MAE, RMSE, prediction accuracy	SDG 9	Explainable AI (XAI), federated learning

				mainte nance					
Internet of Things (IoT)	Smart Sensors, Wireless Communication	Real-time monitoring	IoT gateways, sensor networks	Continuous monitoring, automated control	Cybersecurity, communication reliability	Data latency, packet loss, network uptime	SDG 9	Edge AI, 6G-enabled smart grids	
Demand Response (DR)	Dynamic Pricing, Load Control	Reduce peak demand	Smart appliances, smart meters	Lower operational cost, peak reduction	Consumer participation	Peak Load Reduction (%), Load Factor	SDG 7	AI-based demand response optimization	
Microgrids	Grid-connected & Islanded Systems	Rural electrification	PV, Wind, Battery, Diesel Backup	High reliability, energy access	Protection coordination	Reliability Index, Energy Availability	SDG 7, 11	Community microgrids, resilient microgrids	
Electric Vehicles (EVs)	V2G, Smart Charging	Sustainable transportation	Charging stations, BESS	Reduced emissions, grid flexibility	Charging infrastructure	EV penetration, charging efficiency	SDG 11, 13	Vehicle-to-Grid optimization	
Policy & Regulation	Feed-in Tariff, Net Metering, Carbon Tax, Renewable Portfolio Standard	Accelerate renewable deployment	Regulatory agencies, incentives	Investment attraction, market growth	Policy inconsistency	Renewable investment, installed capacity	SDG 7, 17	Adaptive policy frameworks	
Financial Mechanisms	Green Bonds, PPP, Climate Funds, Carbon Finance	Support infrastructure investment	Public-private partnerships	Reduced financing risk	Limited funding access	ROI, LCOE, project completion rate	SDG 8, 17	Innovative climate finance	
Cybersecurity	Blockchain, Encryption, IDS	Secure smart grid operation	Authentication, secure communication	Data integrity, resilience	Sophisticated cyberattacks	Detection rate, response time	SDG 9	Quantum-resistant cybersecurity	

Capacity Building	Training, R&D, University-Industry Collaboration	Develop skilled workforce	Technical education, research centers	Improved technical expertise	Limited funding	Number of trained professionals, R&D expenditure	SDG 4, 9	Digital learning platforms
Climate Resilience	Climate Risk Assessment, Resilient Grid Design	Improve system resilience	Disaster management, adaptive planning	Reduced outage risk	Extreme weather	Grid resilience index, recovery time	SDG 13	Climate-adaptive power systems

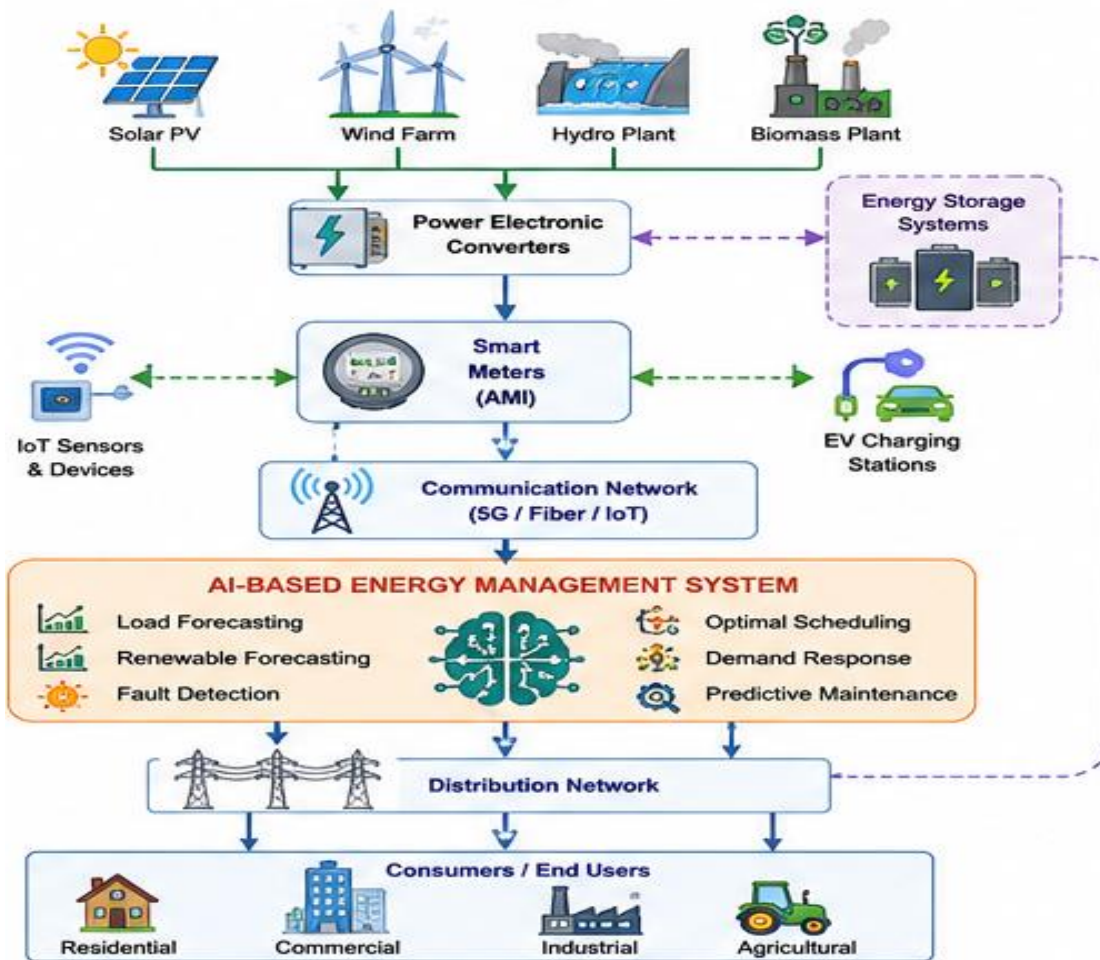


Integrated Sustainable Energy Management Framework

7.2 Boosting Investment and Innovative Finance Mechanisms

The high capital cost of renewable energy projects continues to be one of the most significant impediments in underdeveloped countries. Governments should encourage green financing instruments, such as green bonds, climate funds, concessional loans, and blended finance models,

to mitigate investment risks. PPPs can attract private funding for renewable energy projects and alleviate governments' financial constraints. International agencies such as the World Bank, Asian Development Bank (ADB), and Green Climate Fund (GCF) can also play an important role in providing technical assistance and financial support.

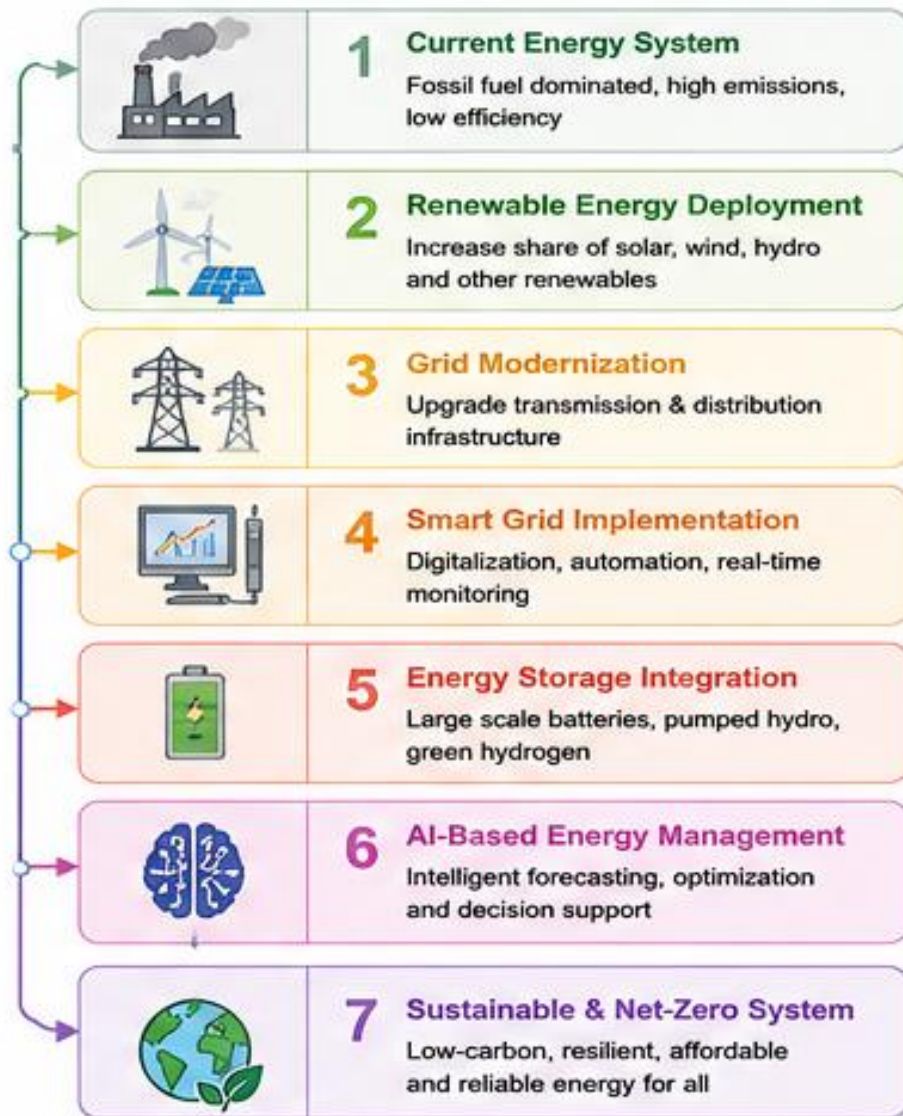


Smart Grid Architecture for Sustainable Energy Management

7.3 Modernization of Power Systems Using Smart Grid Technologies

Updating the power infrastructure is key to enhancing system reliability and incorporating fluctuating renewable energy resources. The investment should be on Advanced Metering Infrastructure (AMI), Supervisory Control and Data Acquisition [71-72,75] (SCADA), Phasor

Measurement Units (PMUs) and Wide Area Monitoring Systems (WAMS). These technologies enhance real-time monitoring, fault detection, demand response and overall grid resilience. Also, distributed energy management systems can improve power flow and reduce transmission losses.

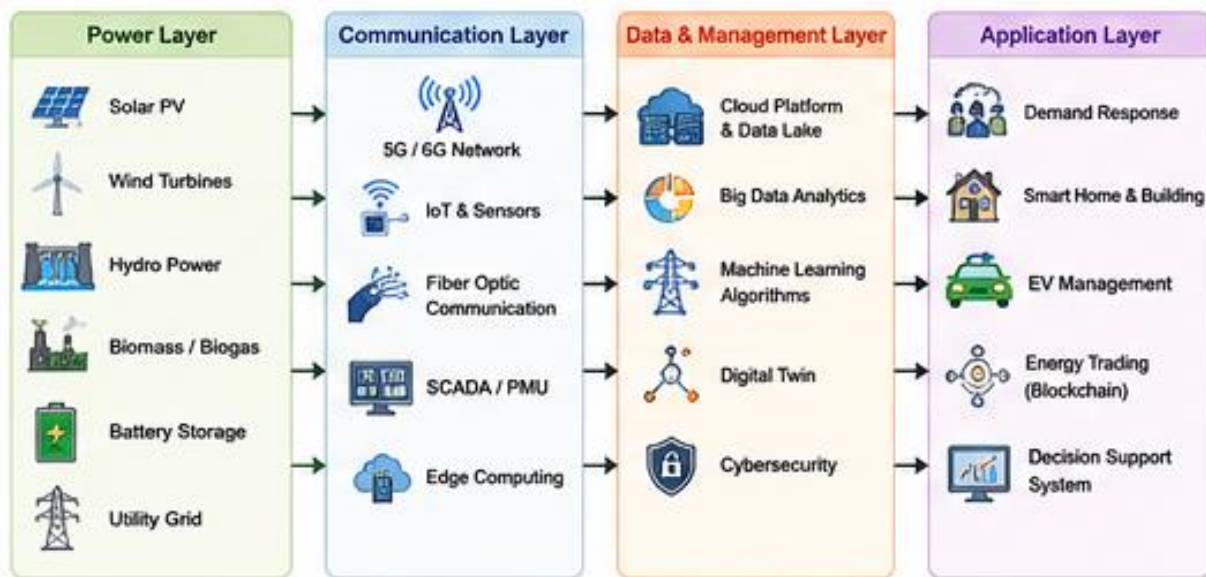


Roadmap for sustainable Energy Transition

7.4 Digital Technologies and Artificial Intelligence Integration

Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), Digital Twins and Big Data Analytics are changing sustainable energy management. AI based forecasting models increase renewable energy projection, load forecasting and energy scheduling. Machine

learning techniques allow for predictive maintenance of power system components, minimizing equipment breakdowns and maintenance expenses. IoT-enabled sensors allow for real-time monitoring of dispersed energy resources, while blockchain technology can enable secure peer-to-peer electricity trading and transparent energy transactions.



Multi layer Smart Energy Management Architecture

7.5 Introduction of Advanced Energy Storage Systems

Critical for mitigating renewable energy intermittency are energy storage systems. Battery Energy Storage Systems (BESS), pumped hydro storage, compressed air energy storage (CAES), thermal energy storage, and green hydrogen technologies enhance grid flexibility and dependability. Future work should aim at reducing battery costs, improving life cycle performance, and creating battery recycling technologies to promote sustainable deployment.

7.6 Capacity Building and Human Resource Development

Developing countries need trained individuals who can develop, operate and maintain modern energy systems. Governments should foster university-industry collaboration, invest in technical education and develop specialized training programmers in renewable energy, power systems, cybersecurity and artificial intelligence. More R&D can also speed up technological innovation and localization of renewable energy technology.

7.7 Expanding Energy Access with Decentralized Energy Systems

Decentralized energy solutions, such as solar household systems, hybrid renewable microgrids and community-based mini-grids, can provide major benefits to remote and rural populations. These solutions decrease reliance on centralized infrastructure while increasing access, reliability and resilience of electricity. Hybrid solar PV, wind, biomass, diesel backup and battery storage systems provide dependable electricity for off-grid applications.

7.8 International Cooperation and the Sustainable Development Goals

Strong international cooperation is required to achieve sustainable energy management. Technology transfer, sharing of information, and financial aid from international organizations can speed up the adoption of renewable energy in developing countries. These activities directly contribute to fulfilling the United Nations Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action).

8. Research Gaps and Outlook

In spite of the significant evolution of sustainable energy management over the past decade, the literature reveals substantial research gaps that still hinder the extensive deployment of sustainable energy systems in developing countries. In recent years, the transition from the evaluation of individual renewable energy technologies towards integrated energy management has been a trend, but the transition is not yet complete as most investigations are still based on individual components such as photovoltaic (PV) systems, wind turbines, battery storage, or policy mechanisms rather than the whole energy ecosystem. Recent systematic reviews conclude future research needs to integrate physical infrastructure, digital technologies, cyber systems and social and policy dimensions into unified energy-management frameworks. A key limitation observed in the present literature is the absence of integrated sustainable energy management frameworks. Most of the published studies optimize a single objective, e.g., minimizing the electricity cost, maximizing the renewable energy penetration, or reducing the greenhouse gas emissions, without considering energy security, system resilience, environmental sustainability, affordability, and social acceptance simultaneously. Hence, many proposed solutions work in laboratory or simulation settings but are difficult to translate into practice within energy systems in developing countries with unreliable grids, financial constraints, weak regulatory institutions, and fast-growing electricity demand. Recent review studies recommend the development of integrated cyber-physical-social energy management models to coordinate renewable generation, storage, smart grids and policy interventions.

The second critical gap is the limited practical deployment of artificial intelligence (AI)-based energy management systems. Recent advances in machine learning, deep learning, reinforcement learning and explainable AI have greatly improved renewable energy forecasting, demand prediction, fault diagnosis, battery management and optimal scheduling. However, most of the reported AI applications are limited to simulation

environment on benchmark datasets. Transferability to developing countries is limited by poor quality operational data, limited sensing infrastructure, inadequate communication networks, and insufficient computational resources. Recent reviews explicitly stress the need for research in AI for developing economies to focus on solutions that are specifically designed for low-resource environments, rather than simply transferring methods developed for high-income countries. Another key research gap is linked to the integration of renewable energy in existing electrical grids. Despite the rapid growth in renewable energy capacity, solar and wind generation are inherently intermittent, as they are dependent on weather conditions. High penetration of variable renewable energy will result in voltage fluctuations, frequency instability, reverse power flow, congestion and reduced system inertia. Most of the current studies have focused on renewable energy forecasting rather than on developing adaptive grid-management strategies that could jointly coordinate distributed energy resources, battery storage, electric vehicles, [76]flexible loads and demand-response programs. Recent surveys thus point to grid flexibility and smart energy management as among the top research priorities for future smart grid development. Optimization of hybrid renewable energy systems (HRES) is also still insufficiently studied. Hybrid systems combining solar PV, wind turbines, biomass, diesel generators, battery energy storage and hydrogen storage are increasingly seen as solutions for rural electrification as they improve reliability and reduce fossil fuel use. However, a large number of optimization studies are based on deterministic mathematical models that do not consider the uncertainty associated with weather variability, electricity demand, component degradation, and fuel-price fluctuation. Furthermore, optimization objectives tend to focus on economic performance while ignoring environmental impacts, system resilience, lifecycle sustainability, and community acceptance. Future work should therefore consider stochastic optimization, uncertainty analysis and multi-objective decision-making

techniques to improve practical design of hybrid renewable energy systems.

Yet, there remain significant gaps of knowledge in the energy storage space. Today, lithium-ion batteries are dominating commercial renewable energy storage due to their high energy density and declining costs. However, the long-term sustainability of these batteries is still hindered by issues such as raw-material availability, degradation, thermal safety, recycling, and environmental impacts. Emerging alternatives, such as sodium-ion batteries, flow batteries, compressed-air energy storage, thermal storage, pumped hydro storage, and green hydrogen, have attracted increasing research interest. However, comparative assessments, taking into account technical performance, lifecycle cost, environmental impacts, and regional suitability, are still limited. Thus, comprehensive comparative

studies on storage technologies are needed to identify optimal storage technologies for different climatic and economic conditions in developing countries. Moreover, digitalization and interoperability are still poorly considered in many studies on sustainable energy management. Smart grids are increasingly using advanced metering infrastructure, Internet of Things (IoT) devices, cloud computing, blockchain and digital twins to enable real-time monitoring and decentralized energy management. However, interoperability between heterogeneous devices, cybersecurity, data privacy and communication standards are still major obstacles to widespread implementation. Recent surveys have emphasized cybersecurity and standard communication architectures as important research priorities for future smart-grid deployment.

Table 19 Major research gaps in sustainable energy management

Research area	Current status	Research gap	Future research priority
Integrated energy management	Mostly technology-specific studies	Lack of holistic optimization frameworks	Multi-sector integrated energy management
Artificial intelligence	Strong simulation-based research	Limited field implementation in developing countries	Low-resource AI, explainable AI, edge AI
Renewable energy integration	High renewable penetration studies	Grid instability and intermittency	Adaptive smart-grid control
Hybrid renewable systems	Extensive sizing studies	Limited uncertainty analysis	Stochastic and multi-objective optimization
Energy storage	Lithium-ion dominates literature	Limited comparison of emerging storage technologies	Hybrid storage and green hydrogen
Smart grids	Rapid technological development	Interoperability and cybersecurity issues	Secure cyber-physical energy systems

The durability of sustainable energy systems in response to fluctuating climatic circumstances has not been adequately examined, in addition to technological constraints. Many energy system optimization models presume stable weather conditions and rely on historical climate data; however, climate change is currently modifying solar irradiance, wind patterns, hydrological cycles, and the incidence of extreme weather events. These alterations directly affect renewable energy production, transmission systems, and power consumption. Recent evaluations highlight

that climate-resilient energy planning must integrate uncertainty analysis, climate projections, and adaptive operational techniques instead of depending exclusively on historical meteorological data. Despite the growing focus on resilience evaluation, standardized approaches for evaluating the long-term operation of renewable-rich power systems under future climatic scenarios remain absent.

A significant research need pertains to life-cycle sustainability assessment (LCSA). Numerous published studies assess renewable energy

technology by singular indicators, like levelized cost of electricity (LCOE), energy efficiency, or carbon emissions. Although these indicators are significant, they offer but a limited comprehension of sustainability. A thorough evaluation must encompass environmental effects, economic viability, technical dependability, resource use, recyclability, and societal acceptance over the complete life cycle of energy systems. Lithium-ion batteries enhance renewable energy integration but pose issues related to lithium extraction, reliance on essential minerals, recycling efficacy, and end-of-life waste management. Likewise, photovoltaic modules and wind turbine blades will produce escalating amounts of trash in the forthcoming decades, necessitating circular economy techniques that are now underrepresented in existing research.

The implementation of circular economy ideas in sustainable energy management is an increasing research goal. Most studies focus on energy generation and operational performance, neglecting material recovery, remanufacturing, recycling technologies, and sustainable supply chains. Future sustainable energy systems must be constructed in accordance with circular economy principles that reduce resource depletion and environmental impacts by extending product life, reusing components, implementing enhanced recycling, and recovering key materials. Such strategies are especially crucial for developing nations where waste management infrastructure is inadequate and resource efficiency is vital for sustained energy security.

Contemporary literature also exposes significant deficiencies in policy and governance. Many developing nations have implemented renewable energy regulations, such as feed-in tariffs, renewable portfolio standards, tax incentives, and auction processes. Nonetheless, policy execution frequently suffers from inconsistency due to regulatory ambiguity, institutional deficiencies, insufficient financial frameworks, and constrained technical expertise. Current research typically assesses particular policy instruments in isolation, neglecting the interplay between governance quality, institutional coordination, market reforms, private-sector involvement, and

international financial assistance. As a result, frameworks for evidence-based policy that can facilitate long-term sustainable energy transitions are still inadequately created. Recent theme evaluations underscore the necessity of integrating digital technologies, including artificial intelligence and machine learning, with policy design to enhance planning, forecasting, and decision support in developing countries. A subsequent constraint pertains to data availability and interoperability. Advanced energy management systems rely on high-quality operational data received from smart meters, weather stations, distributed sensors, and communication networks. Nonetheless, numerous developing nations persist in encountering disjointed databases, uneven data standards, inadequate monitoring infrastructure, and suboptimal interoperability across energy management systems. These limitations diminish the efficacy of artificial intelligence, machine learning, and digital twin technologies, as algorithm performance is heavily reliant on data quality. Recent systematic evaluations regularly highlight data scarcity, interoperability, privacy protection, and cybersecurity as significant obstacles hindering the large-scale deployment of intelligent energy management systems.

The research also underscores the necessity for increased focus on energy justice and social inclusion. Sustainable energy transitions should not be assessed exclusively based on technological efficiency or economic performance. Equitable access to inexpensive and dependable power, gender equality, community engagement, and the enhancement of local capacities are all critical factors for long-term sustainability. Nonetheless, social aspects are inadequately reflected in engineering-focused energy management studies. Subsequent research should thus incorporate socioeconomic variables alongside engineering optimization models to guarantee that technology advancements foster inclusive and fair growth. [73] These research gaps indicate that future sustainable energy management must transition from technology-specific optimization to interconnected, intelligent, resilient, and human-centered energy systems. Future research must

integrate renewable energy technology, sophisticated energy storage, artificial intelligence, Internet of Things (IoT), blockchain, digital twins, smart grids, and evidence-based policy into cohesive cyber-physical energy systems. Recent systematic evaluations suggest that forthcoming

research should emphasize decentralized energy management, reinforcement learning for real-time optimization, federated learning for privacy-preserving coordination, and explainable AI to enhance transparency and confidence in decision-making.

Country	Major Renewable Energy Resource	Current Progress	Key Research Gap	Future Priority	Research
India	Solar, Wind, Biomass	Rapid renewable capacity expansion and smart-grid deployment	Grid flexibility, energy storage integration, AI-based demand forecasting, coal dependence	AI-enabled Management Systems (EMS), Vehicle-to-Grid (V2G), green hydrogen, long-duration storage [1]	Energy Systems
China	Solar, Wind, Hydropower	Global leader in renewable energy deployment and manufacturing	Renewable curtailment, transmission congestion, regional power imbalance	Digital twin technology, ultra-high-voltage transmission, AI-based grid optimization	
Brazil	Hydropower, Bioenergy, Wind, Solar	Diversified renewable energy mix with strong bioenergy sector	Hydropower vulnerability to climate change, transmission expansion	Climate-resilient power systems, hybrid renewable systems, battery storage [1]	
Bangladesh	Solar Biomass PV,	Successful Solar Home Systems and rural electrification	Limited grid capacity, low renewable penetration, financing constraints	Rooftop solar, battery storage, AI-based microgrid management, distributed generation [2]	
Pakistan	Solar, Wind, Hydropower	Growing utility-scale solar and hydropower	Grid instability, transmission losses, weak policy implementation	Smart grids, hybrid renewable systems, demand-side management	
Kenya	Geothermal, Wind, Solar	Global leader in geothermal energy and mini-grids	Rural electrification, storage integration, financing	Green hydrogen, AI-enabled microgrids, climate-resilient energy planning [3]	
Nigeria	Solar, Gas, Hydropower	Large renewable potential but limited deployment	Poor grid infrastructure, energy access deficit, investment barriers	Decentralized renewable systems, mini-grids, digital energy management	
South Africa	Solar, Wind	Expanding Renewable Energy Independent Power Producer	Coal dependency, aging grid infrastructure	Battery Energy Storage Systems (BESS), grid modernization, just energy transition [3]	

		Programme (REIPPPP)		
Ethiopia	Hydropower, Wind	Hydropower- dominated electricity generation	Climate vulnerability and limited diversification	Solar-hydro hybrid systems, regional grid integration
Indonesia	Geothermal, Solar, Biomass	Significant geothermal potential	Slow renewable deployment, fossil-fuel subsidies	Geothermal optimization, carbon capture, integrated energy planning

9. Conclusions and Recommendations

Sustainable energy management is a crucial element of sustainable development strategies in developing nations, where escalating energy demand, population growth, urbanization, industrialization, and climate change exert considerable strain on current energy systems. This review critically evaluated recent advancements in sustainable energy management by analyzing renewable energy technologies, energy efficiency methods, smart-grid development, energy storage systems, policy frameworks, and emerging digital technologies. The literature indicates that the shift from fossil fuel-based energy systems to renewable and low-carbon [74] alternatives is crucial for decreasing greenhouse gas emissions, enhancing energy security, improving electricity access, fostering economic growth, and attaining long-term environmental sustainability.

The research indicated that developing nations have considerable renewable energy resources, especially solar, wind, hydropower, biomass, and geothermal energy, which provide major prospects for diversifying national energy portfolios. Countries like China and India have achieved significant advancements in utility-scale renewable energy generation, bolstered by robust policy frameworks, technological innovation, and substantial investments. Brazil has effectively harnessed hydropower and biofuels to diminish reliance on fossil fuels, whilst Kenya has established itself as a global frontrunner in geothermal power production. Bangladesh has exemplified the efficacy of decentralized solar household systems in enhancing rural electrification, whereas Pakistan, Nigeria, and many Sub-Saharan African nations persevere in

augmenting solar photovoltaic installations to mitigate ongoing electricity deficits. Notwithstanding these accomplishments, the integration of renewable energy is inconsistent among developing nations due to variations in economic capability, institutional quality, infrastructural development, and policy execution. The results also suggest that sustainable energy management encompasses more than just the implementation of renewable energy technologies. Efficient energy management necessitates the amalgamation of renewable energy sources with energy efficiency initiatives, sophisticated energy storage technologies, smart power systems, and conducive regulatory frameworks. Contemporary sustainable energy systems are increasingly defined by distributed generation, bidirectional power flows, demand-side management, electric mobility, and decentralized energy markets. As a result, conventional centralized power systems are progressively transforming into intricately interconnected and digitally enhanced smart energy systems that necessitate advanced monitoring, forecasting, optimization, and control methods. This research identifies that technological constraints constitute a primary obstacle to sustainable energy management in developing nations. Renewable energy sources, like solar photovoltaic and wind power, are intrinsically intermittent due to their reliance on meteorological conditions and seasonal fluctuations for electricity output. The extensive integration of fluctuating renewable energy may consequently compromise grid stability by causing voltage variations, frequency aberrations, reverse power flow, and congestion in electricity transmission networks. Moreover, numerous

developing nations persist in utilizing antiquated transmission and distribution infrastructure that was initially designed for centralized fossil fuel power generation rather than for decentralized renewable energy production. The absence of contemporary grid infrastructure considerably restricts the incorporation of renewable energy and diminishes overall system reliability. Energy storage technologies have become essential for sustainable energy management, as they offer operational flexibility and enhance the reliability of renewable energy systems. Lithium-ion batteries presently prevail in commercial applications due to their elevated energy density and decreasing costs; nonetheless, issues regarding resource availability, degradation, thermal safety, recycling, and environmental effects persistently limit their long-term viability. Innovative technologies, including sodium-ion batteries, solid-state batteries, redox-flow batteries, thermal energy storage, compressed air energy storage, pumped hydro storage, and green hydrogen, are anticipated to assume progressively significant roles in facilitating future low-carbon energy systems. However, comparative analyses assessing the technical efficacy, lifecycle sustainability, economic viability, and environmental consequences of these technologies in developing-country contexts are still scarce. The review underscores the transformational impact of digital technologies on contemporary energy management. Artificial intelligence (AI), machine learning (ML), deep learning, digital twins, block chain, cloud computing, and the Internet of Things (IoT) are fundamentally transforming the monitoring, control, and optimization of energy systems. These technologies provide precise renewable energy forecasting, astute demand prediction, predictive maintenance, fault detection, autonomous grid management, and decentralized energy trading. Nonetheless, their execution in developing nations is hindered by deficient digital infrastructure, restricted technical proficiency, inadequate interoperability, cybersecurity issues, and limited access to high-quality operational data. Therefore, digital transformation must be regarded as a fundamental element of future sustainable energy policies

rather than a discretionary technological improvement. In addition to technological obstacles, this analysis highlighted other economic, institutional, and policy-related problems that persistently hinder sustainable energy transitions. Significant capital investment demands, restricted access to green financing, unpredictable investment climates, insufficient institutional capacity, disjointed regulatory frameworks, erratic policy execution, and a lack of technical proficiency persist as substantial barriers in numerous developing nations. Despite the implementation of various renewable energy incentives by different governments, such as feed-in tariffs, renewable portfolio standards, tax incentives, and competitive auctions, the efficacy of these policies significantly fluctuates due to the quality of governance and institutional capacity. Consequently, enduring policy stability, transparent regulatory frameworks, and efficient institutional coordination are vital precondition for expediting renewable energy implementation and enticing private-sector investment.

The analysis further indicates that sustainable energy management ought to be assessed using multidimensional sustainability indicators instead of exclusively depending on technical or economic performance criteria. Future decision-making frameworks should incorporate environmental sustainability, lifecycle assessment, greenhouse gas emissions, resource efficiency, energy justice, affordability, gender inclusion, community participation, and climate resilience. Likewise, aspects of the circular economy—such as material recovery, battery recycling, photovoltaic waste management, and sustainable supply chains—must be essential elements of future renewable energy systems to guarantee enduring environmental sustainability.

The examination of contemporary literature suggests that forthcoming sustainable energy systems will progressively transition towards integrated cyber-physical energy networks, distinguished by decentralized renewable energy production, sophisticated control systems, enhanced energy storage, real-time digital surveillance, and data-driven policymaking. Integrated approaches can significantly enhance

energy security, operational efficiency, climate resilience, and economic competitiveness, while facilitating the attainment of the United Nations Sustainable Development Goals, specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

Based on the findings of this review, several strategic recommendations are proposed to accelerate sustainable energy management and facilitate the transition toward low-carbon and climate-resilient energy systems in developing countries. These recommendations target governments, policymakers, researchers, energy utilities, the private sector, and international organizations, recognizing that successful energy transitions require coordinated efforts across multiple stakeholders.

Governments should establish long-term, stable, and transparent energy policies that encourage renewable energy deployment while reducing dependence on fossil fuels. Policy consistency is essential for attracting domestic and foreign investment, minimizing regulatory uncertainty, and supporting the large-scale integration of renewable energy technologies. Governments should also strengthen institutional capacity by improving regulatory frameworks, streamlining project approval processes, and promoting coordinated planning among energy, environmental, industrial, and financial sectors. Furthermore, increasing public investment in transmission infrastructure, rural electrification, and modern smart-grid systems will be critical for improving electricity reliability and expanding energy access.

Policymakers should prioritize the modernization of national electricity networks through the deployment of smart-grid technologies, advanced metering infrastructure, and digital energy management systems. The integration of battery energy storage systems, pumped hydro storage, and emerging green hydrogen technologies should be encouraged to enhance grid flexibility and improve the reliability of renewable energy generation. Financial mechanisms, including feed-in tariffs, renewable energy auctions, green bonds,

carbon pricing, tax incentives, and blended finance, should be strengthened to reduce investment risks and improve the economic competitiveness of clean energy projects.

Research institutions and universities should focus on developing integrated sustainable energy management frameworks that combine renewable energy technologies, artificial intelligence, machine learning, Internet of Things (IoT), blockchain, digital twins, and advanced optimization algorithms. Future research should move beyond technology-specific studies and adopt multidisciplinary approaches that simultaneously evaluate technical performance, economic feasibility, environmental sustainability, climate resilience, and social impacts. Greater emphasis should also be placed on life-cycle assessment, circular economy principles, battery recycling, photovoltaic waste management, and the sustainable use of critical raw materials to improve the long-term sustainability of renewable energy systems.

Electricity utilities should accelerate investments in smart-grid infrastructure, digital monitoring platforms, demand-side management programs, and distributed energy resources to improve operational efficiency and facilitate higher shares of renewable energy integration. The adoption of predictive maintenance, real-time monitoring, and AI-assisted operational control can significantly reduce system losses, improve equipment reliability, and enhance electricity quality. Utilities should also encourage decentralized energy systems, community microgrids, and distributed generation to improve electricity access in remote and underserved regions.

The private sector should play a more active role in accelerating sustainable energy transitions through investments in renewable energy projects, clean technology innovation, energy-efficient manufacturing, and digital energy solutions. Public-private partnerships should be strengthened to facilitate technology transfer, reduce investment barriers, and accelerate commercialization of emerging technologies such as green hydrogen, advanced battery storage, and carbon-neutral industrial processes. Industrial sectors should adopt comprehensive energy

management systems based on international standards such as ISO 50001 to improve energy efficiency and reduce greenhouse gas emissions. International organizations, multilateral development banks, and climate finance institutions should continue supporting developing countries through technical assistance, concessional financing, knowledge transfer, and capacity-building initiatives. International collaboration is particularly important for facilitating access to advanced renewable energy technologies, digital infrastructure, research networks, and climate-resilient energy planning tools. Expanding global partnerships can help reduce technological disparities between developed and developing countries while accelerating progress toward the Sustainable

Development Goals (SDGs) and the Paris Agreement targets.

Finally, future sustainable energy management should prioritize inclusive development by integrating energy justice, gender equality, community participation, and equitable access into national energy planning. Policies should ensure that vulnerable populations benefit from renewable energy investments through affordable electricity, employment opportunities, and local capacity development. A transition toward sustainable energy systems should therefore be evaluated not only by technological performance and economic returns but also by its contribution to social well-being, environmental protection, and long-term sustainable development.

Stakeholder	Key Recommendations	Expected Outcomes
Governments	Develop stable renewable energy policies, strengthen institutions, modernize transmission infrastructure, and promote rural electrification.	Increased renewable energy deployment, improved energy security, and enhanced investor confidence.
Policymakers	Expand green financing, renewable energy auctions, smart-grid programs, and supportive regulatory frameworks.	Faster clean-energy transition and improved policy effectiveness.
Research Institutions	Develop AI-based energy management systems, hybrid renewable energy optimization models, life-cycle sustainability assessment, and climate-resilient energy planning tools.	Innovative, efficient, and sustainable energy management solutions.
Electricity Utilities	Invest in smart grids, battery energy storage systems (BESS), advanced metering infrastructure, and demand-side management.	Improved grid stability, operational efficiency, and renewable energy integration.
Private Sector	Increase investment in renewable energy technologies, digitalization, and energy-efficient industrial processes through public-private partnerships.	Accelerated technology commercialization, job creation, and economic growth.
International Organizations	Support climate finance, technology transfer, capacity building, and international research collaboration.	Enhanced technical capacity and accelerated sustainable energy transition in developing countries.
Local Communities	Promote community participation, decentralized energy systems, and public awareness programs.	Improved energy access, social acceptance, and inclusive sustainable development.

The shift to sustainable energy management in emerging nations necessitates a holistic and cohesive strategy that encompasses more than only increasing renewable energy production. This review emphasizes that long-term energy sustainability relies on the efficient integration of renewable energy sources, sophisticated energy storage systems, smart-grid technologies, digital advancements, and conducive policy frameworks within robust and adaptable energy systems. Governments ought to provide solid legislative frameworks, enhance institutional capabilities, and foster investment in clean energy infrastructure, while promoting public-private partnerships and international cooperation to expedite technology transfer and capacity development.

Future research should focus on creating integrated sustainable energy management frameworks that incorporate artificial intelligence, machine learning, Internet of Things (IoT), digital twins, blockchain, and advanced optimization techniques to improve system reliability, operational efficiency, and renewable energy integration. Simultaneously, increased focus must be directed towards life-cycle sustainability assessment, circular economy initiatives, climate-resilient energy strategies, and energy justice to guarantee that technological progress fosters environmental conservation, resource efficiency, and equitable socioeconomic advancement. Sustainable energy management must be acknowledged as a multifaceted strategy that concurrently tackles technological, economic, environmental, institutional, and social concerns. Developing nations can expedite their transition to secure, cheap, and low-carbon energy systems by implementing evidence-based policies, promoting technical innovation, enhancing regional and international collaboration, and investing in resilient energy infrastructure. These coordinated initiatives will enhance energy accessibility and economic competitiveness while significantly contributing to the attainment of the United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action), thus fostering a

more sustainable, inclusive, and climate-resilient future.

REFERENCES

- ur Rehman, A., Sanjari, M. J., Elavarasan, R. M., & Jamal, T. (2026). Sustainability-aligned pathways for energy transition: A review of low-carbon energy network solutions. *Renewable and Sustainable Energy Reviews*, 226, 116428.
- Berha, A., & Khemani, S. (2026). Unreliable Electricity in Developing Countries. *Development Research*.
- Hossain, M. K., Molla, A. S., Chowdhury, P., Tanvir, F. A., & Farrok, O. (2026). Transforming sustainable energy through microgrids: Bangladesh perspectives. *Energy Conversion and Management*: X, 101585.
- Basaran, K., Siano, P., Abdelkader, M., Candan, A. K., Kivi, M. M., Sakib, N., ... & Lazaroiu, G. C. (2026). A comprehensive survey of distributed optimization methods and technological enablers for sustainable energy communities. *Energy*, 139983.
- Park, M. H., Yeo, S., Kim, J. H., Choi, J. H., & Lee, W. J. (2026). Comprehensive review on recent progress in renewable and sustainable energy applications in shipping industry, and suggestions for future developments. *Renewable and Sustainable Energy Reviews*, 225, 116152.
- Prajapati, P., Guo, R., Cai, A., & Prashad, R. (2026). Navigating the energy transition in India: challenges and opportunities towards sustainable energy goal. *Water-Energy Nexus*, 9, 1-18.
- ur Rehman, A., Sanjari, M. J., Elavarasan, R. M., & Jamal, T. (2026). Sustainability-aligned pathways for energy transition: A review of low-carbon energy network solutions. *Renewable and Sustainable Energy Reviews*, 226, 116428.
- Ji, T., Wang, S., Wang, J., & Zhang, J. (2026). Beyond technology: Role of technology-organization-environment-human factors in autonomous driving adoption for new energy vehicles. *Journal of Retailing and Consumer Services*, 88, 104552.

- Shaikh, A. K., Khan, I., Amjad, F., & Dilbar, S. (2026). Exploring challenges and solutions for smart grid integration in Oman. *Energy Exploration & Exploitation*, 01445987251405489.
- Khandakar, M., et al. (2025). Sustainable energy transition towards decarbonization among developing countries: A systematic literature review. *Frontiers in Sustainability*, 6, 1641299.
- Qian, Y., Xu, Z., Qin, Y., & Gou, X. (2025). A critical review on the multidimensional complexity of sustainable energy development. *Applied Energy*, 394, 126194. <https://doi.org/10.1016/j.apenergy.2025.126194>
- Prajapati, P., Guo, R., Cai, A., & Prashad, R. (2026). Navigating the energy transition in India: challenges and opportunities towards sustainable energy goal. *Water-Energy Nexus*, 9, 1-18.
- Mustafa, S., Long, Y., & Rana, S. (2024). Role of domestic renewable energy plants in combating energy deficiency in developing countries. End-user perspective. *Energy Reports*, 11, 692-705.
- Chu, S., & Majumdar, A. (2012). Opportunities and challenges for a sustainable energy future. *nature*, 488(7411), 294-303.
- Tester, J. W., Drake, E. M., Driscoll, M. J., Golay, M. W., & Peters, W. A. (2012). *Sustainable energy: choosing among options*. MIT press.
- Afgan, N. H., Al Gobaisi, D., Carvalho, M. G., & Cumo, M. (1998). Sustainable energy development. *Renewable and sustainable energy reviews*, 2(3), 235-286.
- Hatzigrygiou, N., Asano, H., Irvani, R., & Marnay, C. (2007). Microgrids. *IEEE power and energy magazine*, 5(4), 78-94.
- Saeed, M. H., Fangzong, W., Kalwar, B. A., & Iqbal, S. (2021). A review on microgrids' challenges & perspectives. *IEEE access*, 9, 166502-166517.
- Madakam, S., Ramaswamy, R., & Tripathi, S. (2015). Internet of Things (IoT): A Literature. *Journal of computer and communications*, 3, 164-173.
- Chu, W., Calise, F., Duić, N., Østergaard, P. A., Vicidomini, M., & Wang, Q. (2020). Recent advances in technology, strategy and application of sustainable energy systems. *Energies*, 13(19), 5229.
- Chu, W., Calise, F., Duić, N., Østergaard, P. A., Vicidomini, M., & Wang, Q. (2020). Recent advances in technology, strategy and application of sustainable energy systems. *Energies*, 13(19), 5229.
- Østergaard, P. A., Duic, N., Noorollahi, Y., & Kalogirou, S. A. (2021). Recent advances in renewable energy technology for the energy transition. *Renewable Energy*, 179, 877-884.
- Nobilo, M., Salehi, S., & Nilsson, H. (2026). Lifetime analysis of hydro turbines with focus on fatigue damage in a renewable energy system—A review. *Renewable and Sustainable Energy Reviews*, 228, 116578.
- Yakymchuk, A., Baran-Zgłobicka, B., & Woruba, R. M. (2026). Advanced Energy Collection and Storage Systems: Socio-Economic Benefits and Environmental Effects in the Context of Energy System Transformation. *Energies*, 19(2), 309.
- Bordes, A., Huret, M., Rivot, E., Andrieux, C., Doray, M., Edeline, E., ... & Olmos, M. (2026). Disentangling the influence of density dependence, size dependence and environmental effects on fish population dynamics. *Journal of Animal Ecology*.
- Ahmed, Z. (2026). The dual environmental impact of AI technologies: Analyzing direct effects vs. economic growth dynamics. *Technological Forecasting and Social Change*, 224, 124480.
- Marlina, L., Fan, X., Afifah, S., Liaw, S. K., Kishikawa, H., & Yeh, C. H. (2026). Performance evaluation of high speed optical wireless communication in 1064 nm band under environmental effects. *Journal of Optics*, 28(1), 015701.
- Namakka, M., Rahman, M. R., & Bakri, M. K. B. (2026). Waste biomass pellets for green energy production-A sustainable alternative for energy security. *Renewable and Sustainable Energy Reviews*, 226, 116315.

- Doğan, B., Hossain, M. R., Khalfaoui, R., Nassani, A. A., & Ghosh, S. (2026). Navigating Chinese green deals through green investment, green technology, and green energy development: a race for sustainability or greenwashing?. *Financial Innovation*, 12(1), 67.
- Ye, X., Zeng, W., Guan, X., Zhang, T., & Guo, L. (2026). Green energy and chemicals from biomass via thermo-photo catalysis: Fundamentals, progress, and opportunities. *Coordination Chemistry Reviews*, 546, 217041.
- Thekkan, M. J., & Nandagopal, A. (2026). Review on multiport dual active bridge converters for integration of renewable energy sources. *Energy Reports*, 15, 109076.
- Çaloğlu Büyükselçuk, E., & Turan, H. (2026). Evaluation of Barriers to the Integration of Renewable Energy Technologies into Industries in Türkiye. *Processes*, 14(2), 307.
- Dashti, N., & Bagriyanik, M. (2026). Switching over-voltages and mitigation methods in sustainable power systems with renewable energy integration. *Renewable and Sustainable Energy Reviews*, 226, 116220.
- Intergovernmental Panel on Climate Change. (2023). *Climate Change 2023: Synthesis Report*. IPCC. <https://www.ipcc.ch/report/ar6/syr/>
- International Energy Agency. (2024). *World Energy Outlook 2024*. IEA. <https://www.iea.org/reports/world-energy-outlook-2024>
- Dincer, I., & Acar, C. (2020). *Smart energy systems for a sustainable future*. Elsevier.
- International Energy Agency. (2023). *Electricity market report 2023*. <https://www.iea.org/reports/electricity-market-report-2023>
- International Energy Agency. (2024). *World energy outlook 2024*. <https://www.iea.org/reports/world-energy-outlook-2024>
- International Renewable Energy Agency. (2023). *World energy transitions outlook 2023: 1.5°C pathway*. <https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023>
- International Renewable Energy Agency. (2024). *Renewable capacity statistics 2024*. <https://www.irena.org/Publications/2024/Mar/Renewable-Capacity-Statistics-2024>
- Lund, H., Østergaard, P. A., Connolly, D., & Mathiesen, B. V. (2022). Smart energy and integrated energy systems. *Energy*, 245, 123201. <https://doi.org/10.1016/j.energy.2022.123201>
- Organisation for Economic Co-operation and Development. (2022). *Financing the green transition: Towards a sustainable future*. <https://www.oecd.org>
- REN21. (2024). *Renewables 2024 global status report*. <https://www.ren21.net/reports/global-status-report/>
- Siano, P. (2022). Demand response and smart grid technologies: A review. *Renewable and Sustainable Energy Reviews*, 158, 112104. <https://doi.org/10.1016/j.rser.2022.112104>
- United Nations Environment Programme. (2023). *Emissions gap report 2023*. <https://www.unep.org/resources/emissions-gap-report-2023>
- United Nations Industrial Development Organization. (2021). *Industrial energy efficiency accelerator*. <https://www.unido.org>
- U.S. Department of Energy. (2023). *Energy management best practices guide*. <https://www.energy.gov>
- World Bank. (2023). *Tracking SDG 7: The energy progress report 2023*. World Bank. <https://trackingsdg7.esmap.org/>
- Al-Owaidhani, A., Al-Sharafi, A., Al-Buraiki, A. S., Khalifa, A. E., & Yilbas, B. S. (2026). Techno-economic perspectives on hydrogen production systems via using renewable energy resources: A comprehensive review. *International Journal of Hydrogen Energy*, 219, 153984.

- Jahandideh, M., Mahmoudi, A., Rashidi, S., Valipour, M. S., & Zirak, S. (2026). Leveraging renewable energy for mitigating greenhouse gas emissions in Iran. *Energy Conversion and Management*, X, 101632.
- Liu, Z., Chen, Z., Letchmunan, S., Huang, Y., Senapati, T., & Pamucar, D. (2026). A linear Diophantine fuzzy hybrid decision support system for sustainability evaluation of renewable energy resources. *Engineering Applications of Artificial Intelligence*, 167, 113731.
- Wang, Z., Liu, X., Gu, W., Cheng, L., Wang, H., Liu, J., ... & Shen, Y. (2026). Power-to-Hydrogen-to-Power as a pathway for wind and solar renewable energy utilization in China: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, 226, 116195.
- De Keyser, J., Fuentes, P. O., Hayes, D. S., & Habersack, H. (2026). A review of hydropower in Central Asia: Past, present, and future. *Renewable and Sustainable Energy Reviews*, 226, 116239.
- Zhang, J. S., Niu, W. J., Li, J. B., Zhang, J., Zhou, B., Fu, X. Y., & Feng, Z. K. (2026). A novel intelligent interval prediction framework for daily generation of hydropower reservoir. *Renewable Energy*, 125816.
- Namasivayam, S. K. R., Sivasuriyan, K. S., Priyanka, S., Lavanya, M., Sowmya, R., Varshan, G. A., ... & Avinash, G. P. (2026). A critical review of green nanomaterials enhanced cleaner biohydrogen production and high efficiency storage from aquatic biomass-A sustainable utilization of nanotechnology in energy generation pathway from the lignocellulosic biomass. *International Journal of Hydrogen Energy*, 198, 152810.
- Akhlishah, Z. N., Ong, H. C., Lee, H. V., & Tan, Y. H. (2026). Environmental impacts of biomass energy: A life cycle assessment perspective for circular economy. *Renewable and Sustainable Energy Reviews*, 226, 116363.
- Zhang, Z., Rath, S., Xu, J., & Xiao, T. (2026). Federated learning for smart grid: A survey on applications and potential vulnerabilities. *ACM transactions on cyber-physical systems*, 10(1), 1-26.
- Rasoulnia, M., Yaghoubi, E., Yaghoubi, E., Hussain, A., & Kamwa, I. (2026). A comprehensive systematic and bibliometric review of technologies and measurement tools for power quality events detection, classification, and fault location in smart grids. *Renewable and Sustainable Energy Reviews*, 226, 116302.
- Banik, S. (2026). A Comprehensive Survey of Intrusion Detection in Advanced Metering Infrastructure: Toward Scalable Data-Driven Security in Smart Grids.
- Rahat, M. K., Asraf, M. S., Junaid, A., & Islam, M. S. (2026). Communication infrastructure for secure smart meter networks in electric utilities. *Saudi Journal of Engineering and Technology*, 11(5), 450-461.
- Ali, A., Ullah, M., & Khan, M. T. (2026). Impact of artificial intelligence-based predictive analytics on improving academic performance in Pakistani universities: The moderating role of digital literacy. *Spectrum of Engineering Sciences*, 4(3), 167-178.
- Alnnale, T. (2026). Predictive Governance in Digital Enterprises: An LSTM-Enhanced Deep Learning Framework for Economic Optimization of IT Incident Management Using Enriched Process Logs. *Al-Farooq Journal of Sciences*, 2(3), 86-113.
- Liew, N., Pattnaik, S., Kures, A. O., Park, K., & Pinsky, E. (2026). Transforming Global Supply Chains with Artificial Intelligence, Machine Learning, and Next-Generation Technologies. In *Next Generation Entrepreneurship: Convergence of Innovation, Technology, and Society* (pp. 207-234). Cham: Springer Nature Switzerland.
- Cota, A. F., Perboli, G., Guglielmi, P., Munoz, A. M., Aznar, G. F., Alfonso, I. M. T., ... & Salazar, P. (2026). The future of electric mobility between technology, business acceptance and policy making: lessons learned from the INCIT-EV project. *IEEE Access*.

- Häyriinen, M. (2026). The role of IoT-enabled data analytics in optimizing renewable energy systems.
- Sharma, G., & Oum Kumari, R. (2026). Optimizing Solar Energy Systems Through IoT, Metadata, and Blockchain Technologies. In *Distributed Ledger Technology in Communication: Integration of IoT, Blockchain and Metadata* (pp. 99-110). Cham: Springer Nature Switzerland.
- Bakare, M. S., Abdulkarim, A., Guntreddi, V., Madugu, I. S., Ibrahim, O., Owonikoko, W. O., & Alasinrin, B. A. (2026). Intelligent battery charge-discharge control in off-grid microgrids using hybrid GEP-fuzzy techniques. *Next Energy*, 11, 100584.
- Pilakkat, D., Balasubramanian, K., & Rajendran, S. R. (2026). Digital Twins Beyond Monitoring: A Survey on Predictive Control, Cybersecurity, and Storage Integration in PV-Enabled Smart Grids. *IEEE Access*.
- Shaikh, A. K., Khan, I., Amjad, F., & Dilbar, S. (2026). Exploring challenges and solutions for smart grid integration in Oman. *Energy Exploration & Exploitation*, 01445987251405489.
- Işık, C., Ongan, S., Aydın, R., & İmamoğlu, İ. K. (2026). Economic, environmental, social, and governance (ECON-ESG) strategies for sustainable development: theory and a holistic evidence from Germany. *Business Strategy and the Environment*, 35(4), 5133-5157.
- Rodaro, C., Caputo, A., Sarfo, C., & Kargina, M. (2026). Enterprising strategies for Sustainable Development Goals: a bibliometric and systematic literature review. *Journal of Enterprising Communities: People and Places in the Global Economy*, 20(1), 33-58.
- Panwar, D. (2026). Modernizing Power Grids for High Renewable Penetration: Challenges and Control Innovations. In *EPJ Web of Conferences* (Vol. 351, p. 01007). EDP Sciences.
- Shafique Ahmed Soomro, Jawed Ali Thaheem, Muhammad Raza Punjwani, Syed Ahsan Raza, & Adil Noor Soomro. (2026). PAKISTAN RENEWABLE ENERGY GENERATION EVOLUTION FROM 1947 TO PRESENT. *Spectrum of Engineering Sciences*, 4(3), 1-12. Retrieved from <https://www.thesesjournal.com.medicalsciencesreview.com/index.php/1/article/view/2140>
- Muhammad Raza Punjwani, Jaweed Ali Thaheem, Muhammed Ahsan Niaz, Ali Zain Ul Abdeen, Shafique Ahmed Soomro, & Mansoor. (2026). RENEWABLE AND SUSTAINABLE ENERGY SYSTEMS FOR A LOW-CARBON FUTURE: SOURCES, SUSTAINABILITY DIMENSIONS, AND FUTURE CHALLENGES. *Spectrum of Engineering Sciences*, 4(4), 1003-1014. Retrieved from <https://thesesjournal.com.medicalsciencesreview.com/index.php/1/article/view/2524>
- Hussain, S., Ahmed, I., Faisal, M., Abdeen, A. Z. U., Soomro, S. A., Thaheem, J. A., & Punjwani, M. R. A COMPREHENSIVE REVIEW OF SMART GRID AND RENEWABLE ENERGY INTEGRATION IN PAKISTAN.
- Shafique Ahmed Soomro, Sarfraz Hussain, Muhammad Raza Punjwani, Irfan Ahmed, Adil Noor Soomro, Jawed Ali Thaheem, & Ali Zain Ul Abdeen. (2026). A REVIEW OF SOLAR-POWERED ELECTRIC VEHICLE CHARGING STATIONS: TECHNOLOGIES, CHALLENGES, AND FUTURE TREND. *Spectrum of Engineering Sciences*, 4(5), 1406-1428. Retrieved from <https://thesesjournal.com.medicalsciencesreview.com/index.php/1/article/view/2849>.
- I. Mir, A. Ahmad, N. Sallih, N. Bheel, M. Ali, and A. Farouk, 'Results in Engineering A review on life cycle assessment of different pipeline materials', *Results Eng.*, vol. 19, no. July, p. 101325, 2023, doi: 10.1016/j.rineng.2023.101325.

- N. Bheel et al., 'Heliyon Effect of wheat straw ash as cementitious material on the mechanical characteristics and embodied carbon of concrete reinforced with coir fiber', *Heliyon*, vol. 10, no. 2, p. e24313, 2024, doi: 10.1016/j.heliyon.2024.e24313.
- N. B. Abdul Salam Buller, Mohsin Ali, Tariq Ali, 'Effect of silica fume on fracture analysis, durability performance and embodied carbon of fiber-reinforced self-healed concrete', *Theor. Appl. Fract. Mech.*, vol. 130, p. 104333.
- M. Ali, 'Valorization of sewage sludge ash in alkali-activated materials: A comprehensive review of material properties, reactivity, and future sustainable applications', *Chemosphere*, vol. 391, no. August, p. 144724, 2025, doi: 10.1016/j.chemosphere.2025.144724.
- M. Ali, A. Kumar, S. H. Rizvi, S. Ali, and I. Ahmed, 'Effect of Polyester Fiber on Workability Property of High Strength Concrete', *Quaid-e-Awam Univ. Res. J. Eng. Sci. Technol.*, vol. 18, no. 02, pp. 102–108, 2020, doi: 10.52584/qj.1802.15.
- M. Ali, A. Kumar, S. Hussain, and N. Bheel, 'Effect of polyester fiber on compressive strength and split tensile strength properties of high strength concrete', vol. 44, no. 1, pp. 159–170, 2025.
- M. Hussain, 'Effect of Waste Glass Powder Particle Size on Flow and Compressive Strength of Slag-Based Alkali-Activated Materials', vol. 4, no. 5, pp. 328–347, 2026.
- M. Ali et al., 'A review on chloride induced corrosion in reinforced concrete structures: lab and in situ investigation', *RSC Adv.*, vol. 14, no. 50, pp. 37252–37271, 2024, doi: 10.1039/d4ra05506c.
- B. Abdul et al., 'FACTORS CAUSING DELAYS AND COST OVERRUNS IN CONSTRUCTION PROJECTS IN PAKISTAN', vol. 7, no. 5, pp. 242–257, 2026.
- A. Rehman, S. Tariq, and M. Ali, 'Spectrum of Engineering Sciences EFFECT OF NAOH MOLARITY ON THE MECHANICAL PROPERTIES OF CORN COB ASH-BASED GEOPOLYMER MORTAR USING LOCALLY AVAILABLE FINE AGGREGATES , A REVIEW Spectrum of Engineering Sciences', vol. 3138, 2026.
- S. S. Abdul Rehman, Mohsin Ali, 'EFFECT OF NAOH MOLARITY ON THE COMPRESSIVE STRENGTH OF CORN COB ASH-BASED GEOPOLYMERS WITH LIMESTONE POWDER ADDITIVES Spectrum of Engineering Sciences', *Spectr. Eng. Sci.*, vol. 3138, pp. 888–904.
- A. H. S. U. N. Ali Mohsin , Faizan Noor, Rashid Ali 3, 'Spectrum of Engineering Sciences EXPERIMENTAL STUDY ON HIGH-CALCIUM ALKALI-ACTIVATED BASED MORTAR Spectrum of Engineering Sciences', *Spectr. Eng. Sci.*, vol. 3138, no. May 2026, pp. 383–397, 2026.