Journal of Energy Research and Reviews

Volume 16, Issue 8, Page 23-43, 2024; Article no.JENRR.120675
ISSN: 2581-8368

The State-of-the-Art Review on Wind and Photovoltaic Solar Hybrid Renewable Energy and Its Impending Potential in Eastern and Southern Africa

M. Chambalile [a,b*], B. Su [a] and F. Illo [a]

[a] *Jiangsu University, China.*
[b] *Lusaka City Council, Zambia.*

Authors' contributions

This work was carried out in collaboration among all authors. Author MC conceptualized the study, did formal analysis, performed methodology and wrote, original draft. Author BS conceptualization the study, did the methodology, formal analysis and visualization. Author FI conceptualized the study, performed methodology and wrote, original draft. all authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jenrr/2024/v16i8365

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here:
https://www.sdiarticle5.com/review-history/120675

Review Article

Received: 22/05/2024
Accepted: 30/07/2024
Published: 08/08/2024

ABSTRACT

Hybrid renewable energy, combining wind and solar sources, is crucial globally, notably in Africa, addressing electricity shortages and complementing each other's performance. However, both sources are intermittent, challenging grids without sufficient storage capacity. Many countries invest in these systems for sustainable electricity, especially in rural Africa. This paper reviews

---

**Corresponding author: E-mail: chambalile93@gmail.com;*

Cite as: *Chambalile, M., B. Su, and F. Illo. 2024. "The State-of-the-Art Review on Wind and Photovoltaic Solar Hybrid Renewable Energy and Its Impending Potential in Eastern and Southern Africa". Journal of Energy Research and Reviews 16 (8):23-43. https://doi.org/10.9734/jenrr/2024/v16i8365.*

Photovoltaic solar and wind hybrid systems, analysing integration, opportunities, and technologies for enhanced energy output. It examines design, technologies, and policies from the last decade, with case studies from Kenya, South Africa, and China, and forecasts developments in Southern and Eastern Africa.

Keywords: Renewable energy; photovoltaic solar; wind energy; hybrid energy; Africa.

ABBREVIATION

PV : Photovoltaic
CFD : Computational Fluid dynamics
BIPV : Bifacial Photovoltaic
CO2e : Carbon Dioxide Emission
LP : Linear Programming
PSO : Particle Swarm Optimization
MPC : Model Predictive Control
LCOE : Leveled Cost of Energy
LCA : Life Cycle Assessment
AC : Alternative Current
DC : Direct Current

1. INTRODUCTION

The renewable energy sector is advancing with new technologies and applications [1]. Photovoltaic (PV) solar energy has roots dating back to Alexandre Edmond Becquerel in the 19th century, with Charles Fritts creating the first working solar cell in the 1880s. Wind energy has historical origins dating back centuries. Research in 2019 highlighted the growing use of renewable energy worldwide, as detailed in Table 1, showing rapid adoption of PV solar and wind systems, accounting for 19% of global energy production in 2012 and increasing since then. The study emphasizes the global installation and impact of renewable energy sources, particularly PV solar, surpassing wind capacity globally [2].

Between 2019 and 2023, renewable energy has advanced significantly. New hybrid technologies harness kinetic energy from multiple sources and utilize hybrid materials for electricity generation [4]. Integrating various renewable sources seamlessly, wind and PV solar are popular choices [5,6] in hybrid systems. Research in PV solar and wind hybrid systems has addressed integration, energy storage, design, and environmental impact challenges, showing potential as supplementary power sources. These systems reduce lifecycle costs and ensure a reliable electricity supply. They promise a sustainable energy future, with ongoing advancements projected. Fig. 2 predicts global electricity generation, expecting a 20% increase by 2027 compared to 2022 capacity. Fig. 1 depicts global renewable energy usage by region in 2022, with China leading and other regions progressing.

Hybrid systems show higher efficiency compared to single-source energy systems. Fig. 3 displays power production trends over the years for wind, solar, and hydro systems, reflecting their electricity outputs. Fig. 4 from 2015 research directly compares solar, wind, and hybrid systems, highlighting the superior energy output of hybrid configurations [7].

Hybrid systems combining solar and wind energy maximize energy production and ensure reliable electricity. They are particularly beneficial in regions with intermittent wind availability due to low speeds and environmental factors [9]. Fig. 5 depicts a hybrid system integrating wind and PV solar energy sources, controlled through a unit that also manages energy storage in batteries.

Recent advancements in power electronic semiconductor devices have greatly enhanced electrical power conversion in PV solar and wind hybrid systems [59-62]. These innovations have improved system reliability, efficiency, and overall quality. New hybrid energy system modelling software incorporates industrial process enhancements and photovoltaic module efficiency, considering energy regulations, component interactions, and power flow management for consistent energy. Customization and automation of controllers have streamlined operations and reduced maintenance needs. Efficient AC and DC applications further boost performance [55-58].

This study addresses the data gap on hybrid PV solar and wind systems, summarizing significant developments and opportunities for model enhancements. It reviews the current state of these systems, their applications, policies, and prospects in Africa, and key related research. The paper includes:

a) Introduction and research rationale
b) Methodology and literature review of optimization approaches for PV solar and wind hybrid systems

c) Global state of the art with case studies from China and East Africa
d) The potential of hybrid systems in Southern and Eastern Africa
e) Summary of key findings

1.1 Wind Modeling

To harness wind energy, modelling techniques for wind turbines are crucial, and categorized into analytical, empirical, and computational fluid dynamics (CFD) simulations [11,12]. These approaches are combined for balanced assessments, from initial design to detailed aerodynamic studies and blade design refinement. The choice of model depends on research goals, detail needed, resources, and system complexity [13,14].

1.2 Challenges in Wind Modeling

Wind behaviour prediction and enhancing wind energy systems face challenges, especially in modelling. Key issues include turbulence for load predictions, requiring advanced models; wake effects downstream affecting performance and turbulence; terrain complexity influencing wind characteristics for optimal layouts; accurate wind data collection considering topography and obstructions; crucial for mitigating project risks and enabling data-driven decisions.

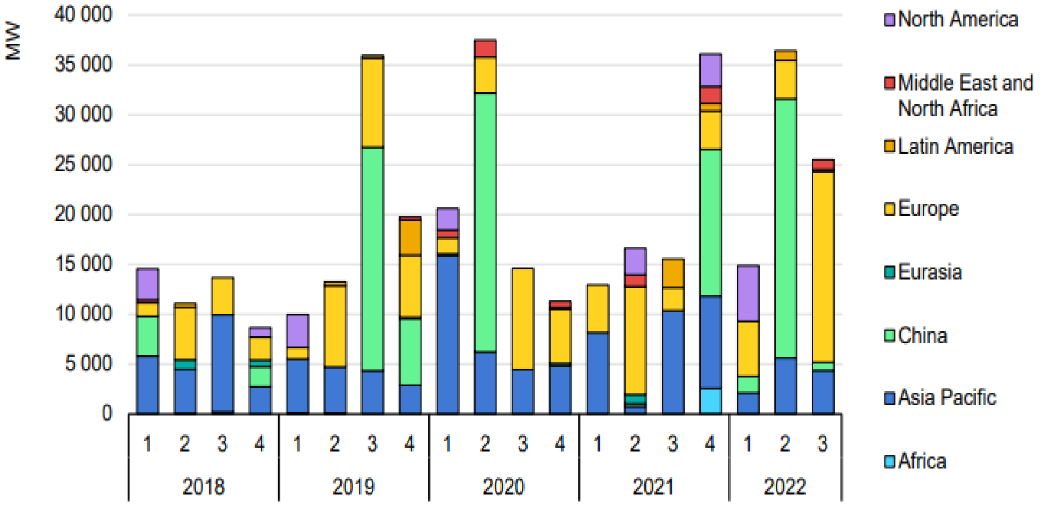


Fig. 1. Renewable capacity auctioned by region

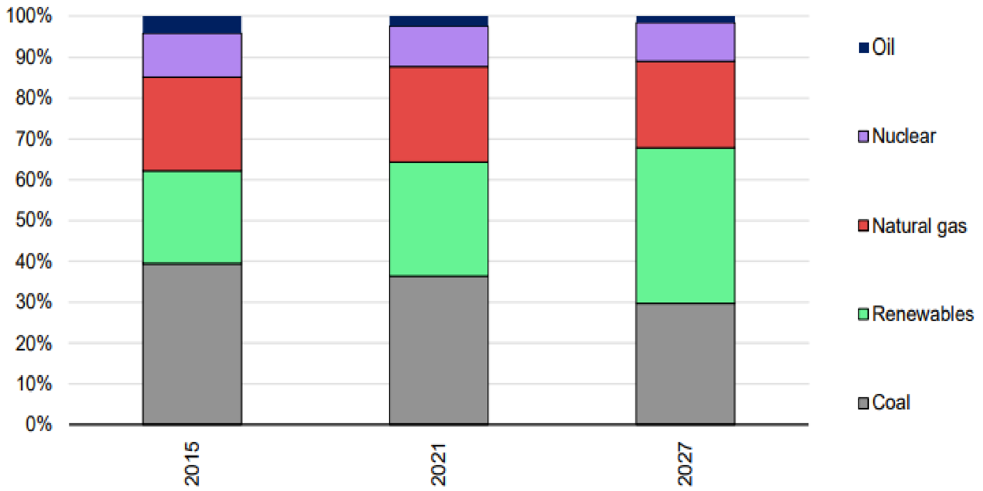


Fig. 2. Electricity generation prediction 2015- 2027

Table 1. Indication of global renewable energy potential [3]

Global indication of renewable energy by year	2009	2010	2011	2012	2013	2014	2015	2016
Annual investigation in renewable energy (USD)	160	211	257	244	232	270	286	241
Gross instillation capacity	1,230	1,320	1,360	1,470	1578	1712	1849	2017
Hydroelectric energy	915	945	970	990	1018	1055	1064	1096
Wind energy	159	198	238	283	319	370	433	487
Photo electricity	23	40	70	100	138	177	227	303
Solar thermal energy	160	185	232	255	373	406	433	456
Ethanol production	76	86	86	83	87	94	98	99
Biodiesel production	17.8	18.5	21.4	22.5	26	29.7	30.3	30.8
Countries goals	89	98	118	138	144	164	173	176

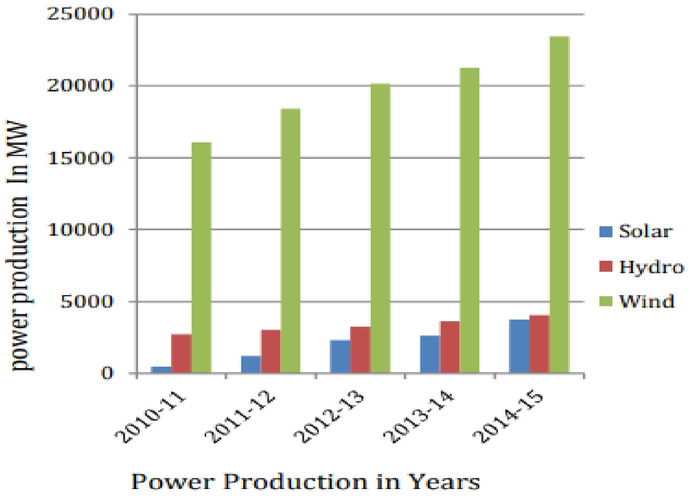


Fig. 3. Power produced by (wind/solar/hydro) system [8]

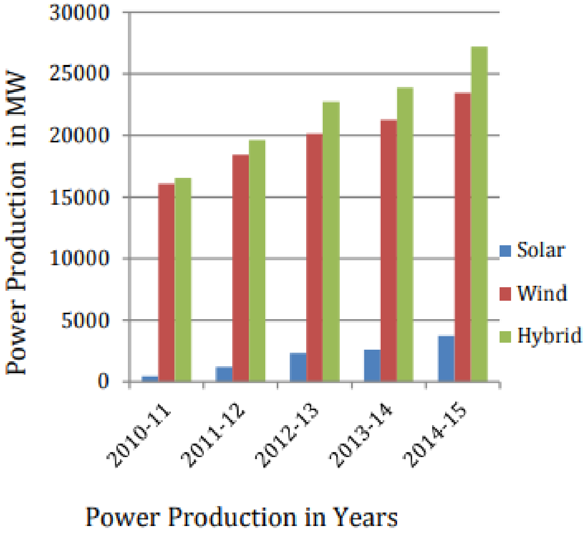


Fig. 4. Solar, wind and hybrid system [8]

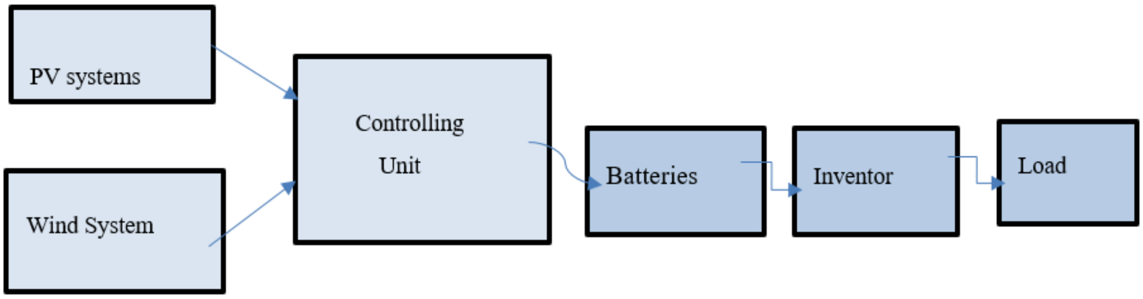


Fig. 5. Schematic of a solar-wind hybrid system [10]

Table 2. Modeling approaches for wind turbines [14-16]

Model	Description	Characteristics
Analytical Models	Constructed on theoretical principles and mathematical equations these models are aimed to simplify the complex aerodynamic and mechanical behaviour of wind turbines while providing quick and computationally efficient solutions. Suitable for preliminary design assessments and quick performance estimates [15].	1. Simplified representation of aerodynamic forces and moments using blade element momentum theory (BEM). 2. Basic consideration of factors like wind speed, turbine geometry, and airfoil characteristics. 3. Limited accuracy for capturing complex flow phenomena, wake effects, and three-dimensional flows.
Empirical Models	Rely on statistical relationships derived from experimental data and field measurements. These models are developed by analyzing the performance data of operational wind turbines under varying conditions. Useful for system performance prediction and validation against real-world data [17].	1. Calibration based on empirical data to account for various operating conditions. 2. Ability to handle non-linear and time-varying effects that analytical models might not capture. 3. Limited ability to extrapolate beyond the range of data used for calibration.
Computational Fluid Dynamics (CFD) Simulation	CFD simulations are advanced numerical methods that solve the governing equations of fluid flow over wind turbine components. CFD models use complex computational algorithms to simulate the aerodynamic behaviour of wind turbines in three-dimensional space, providing detailed insights into flow patterns and performance [18].	1. High-fidelity representation of aerodynamic interactions and turbulent flows. 2. Ability to study complex geometries, such as wind turbine blades with varying twist and airfoil shapes. 3. Consideration of three-dimensional effects, wake interactions, and turbine-turbine interactions.

1.3 Advances in Wind Harvest Modeling

Recent advancements in wind modelling techniques [19] enhance precision, effectiveness, and applicability across domains. Key trends include expanding offshore wind farms to capitalize on stronger, reliable ocean winds. This growth involves larger turbine designs with increased capacity [20-24]. Fig. 6 illustrates the modelling of floating turbines. The innovation of floating wind turbines expands wind energy deployment into deep-water locations, extending wind power capabilities [25]. Fig. 7 demonstrates a wave converter system, showing how kinetic energy from turbine blades efficiently converts into electrical energy.

Fig. 6. Lifting operation powered by wind turbines [26]

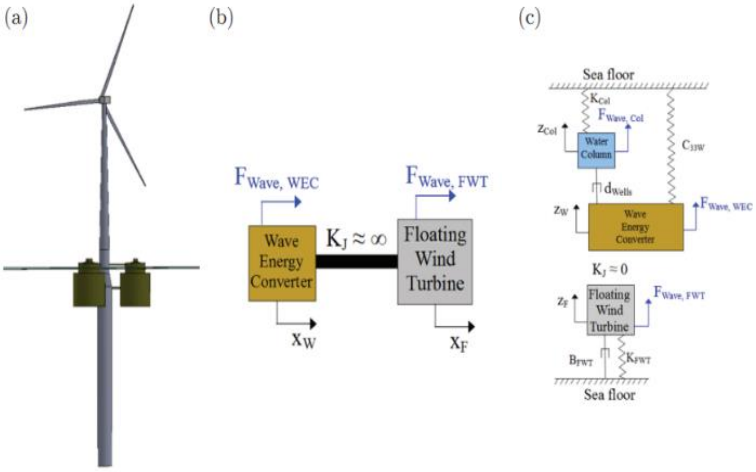


Fig. 7. wave energy converter array integrated with a floating wind turbine

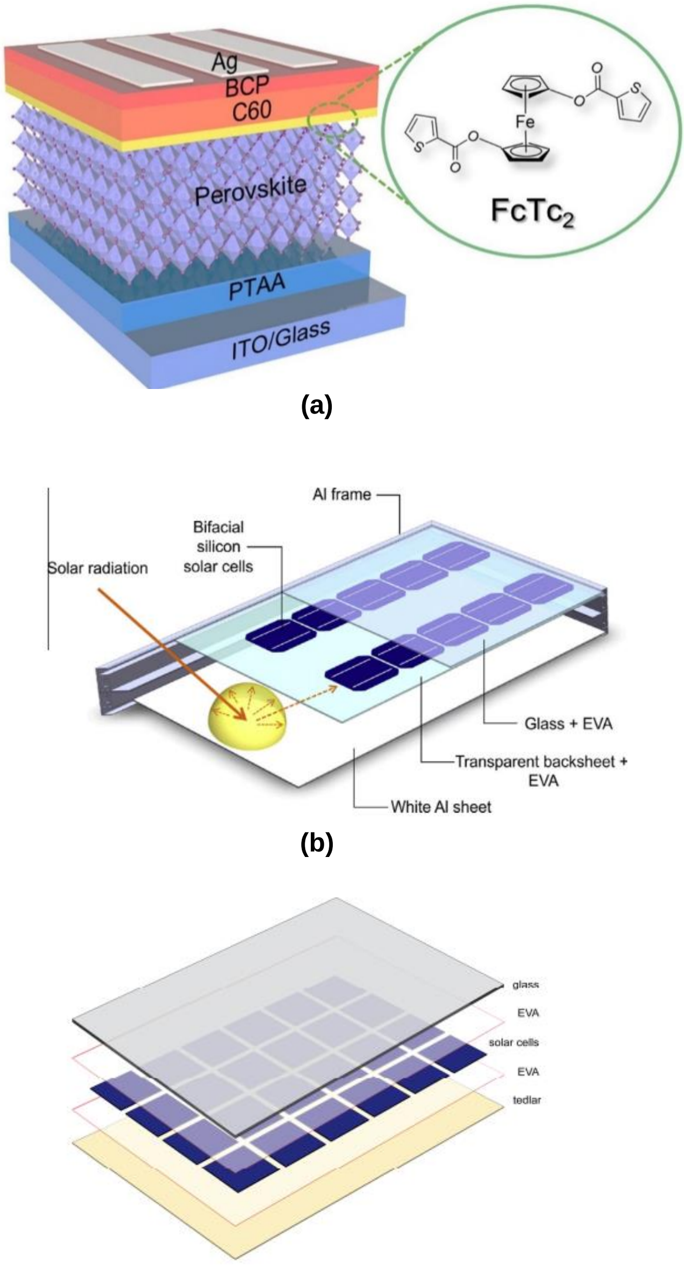
It includes (a) an Illustration of an onshore turbine array linked to the floating wind turbine via hinged linkages. (b) Surge-mode free body diagram of a single wind energy converter and floating wind turbine. (c) Effective heave-mode free body diagram of a single wind energy converter and floating wind turbine.

1.4 Solar Modeling

Modelling photovoltaic solar panels involves using single-diode, dual-diode, or other electrical models to understand their behaviour. The single-diode model simplifies with a diode, current source, and resistor, considering recombination and resistances. The dual-diode model adds accuracy by including another diode for recombination losses, crucial under variable conditions. Complex models detail specific cell phenomena, chosen based on precision needs and data complexity. Key factors affecting PV performance include temperature, shading causing hotspots and uneven current, and spectral mismatch with sun spectrum changes. Accurate modelling integrates these for reliable power predictions.

1.5 Solar Advancements

Recent solar advancements include improved model accuracy and streamlined parameter extraction. Methods use AI and complex algorithms for parameter extraction, advanced electrical models account for surface effects in high-efficiency cells, and commercial software like double-diode models are enhanced. Integrating meteorological data boosts forecast precision, crucial for grid-connected systems. Validation with extensive solar installation data ensures real-world accuracy, standardizing methodologies and enhancing transparency via open-source tools. These advances support sustainable energy progress with more reliable forecasts and optimized solar systems.



(a)

(b)

(c)

Fig. 8. Advancements in structures of solar models

Perovskite solar cells show promise over silicon-based ones with higher efficiency, flexibility, and lower production costs. They don't need optional layers or vacuum energy levels for high performance [26]. Bifacial solar panels maximize energy generation by reflecting and absorbing light from various surfaces [27,28]. Building integrated Photovoltaics (BIPV) integrates solar cells into building elements like windows and roofs, enabling electricity generation without compromising aesthetics [29].

2. PV SOLAR AND WIND HYBRID

Integrated modelling optimizes wind and solar hybrid systems by simulating dynamic interactions between energy sources using time-series data. It incorporates wind turbine power curves, solar panel output, and factors like irradiance and temperature. A hybrid system controller adjusts power output based on resource availability, load demands, and storage capacity, employing measures like power smoothing and ramp rate management. Energy storage, such as batteries, ensures a consistent power supply, with the model accounting for charging and discharging behaviour. Grid interaction considers voltage stability and frequency regulation, assessing overall grid performance. The techno-economic analysis evaluates the levelized cost of electricity (LCOE) and financial viability, guiding optimal system placement and configuration.

These models aid policymakers, grid operators, and developers by enhancing renewable energy integration. They optimize energy generation, system stability, and efficiency through wind turbines and PV solar panels. Wind power, stronger at night, complements daytime solar peaks, reducing storage needs and ensuring stable electricity output [14].

2.1 Enhanced Energy Generation and Grid Integration

A hybrid system combining wind and solar energy maximizes energy production year-round, efficiently utilizing available capacity. It supplements with the alternative source during low wind or solar periods, ensuring continuous power supply. Integration into the grid enhances stability and meets energy demands effectively [31].

2.2 Energy Storage Integration

Energy storage, such as batteries, enhances the performance of wind PV solar hybrid systems by storing surplus electricity for later use during periods of low resources, improving overall efficiency and supply-demand balance [32].

2.3 Optimization Techniques

Optimization approaches like Linear Programming (LP), Integer Linear Programming, Genetic Algorithms, Particle Swarm Optimization, Dynamic Programming, Fuzzy Logic, and Model Predictive Control are crucial for maximizing PV-wind-based hybrid energy systems' effectiveness and commercial viability [10].

2.4 Necessities for PV Solar Wind Hybrid System Optimization

The succeeding requirements of the system optimization of a wind and solar hybrid can be shown in Table 3. Which shows some main requirements, describing them in detail such as data, load, and configuration system and energy model.

2.5 Steps for Hybrid System Design and Planning

Hybrid system design and planning involves defining objectives and requirements, conducting a site assessment, selecting appropriate technologies, and performing system sizing and design. This is followed by an economic analysis to estimate costs and develop financial models, simulation and optimization to test and refine system performance, and risk assessment and mitigation to identify and address potential issues. An implementation plan is then developed, including project planning, procurement, and obtaining necessary permits. The system is installed and commissioned, ensuring it meets performance and safety standards. Finally, a monitoring and maintenance plan is established to track performance, conduct regular maintenance, and make adjustments for optimal operation.

2.6 Sustainability Assessment

Analyzing wind and PV solar energy's lifecycle impacts is crucial for assessing sustainability, and evaluating societal and environmental acceptability. It includes renewable electricity production efficiency, greenhouse gas emissions, land and water use, and societal implications, with geographic variations impacting emissions, energy costs, and efficiency. Social impacts were qualitatively assessed alongside these metrics to prioritize sustainable development, highlighting significant CO2e emission differences across technologies (Fig. 10).

Community engagement is crucial in wind-solar hybrid projects, impacting local perceptions and generating employment [34,35,36]. Safety risks during construction and operational phases also need consideration [37]. Photovoltaic technology faces challenges in storage and variable solar irradiation [38]. Turbine damage risks occur at high wind speeds and operational limits at low speeds. Economic viability depends on location, resource availability, energy demand, financing, and policy support [39]. Levelized Cost of Energy (LCOE) assesses competitiveness against fossil fuels [33,39]. Energy storage integration enhances economic feasibility by optimizing energy use and reducing grid reliance. Project scale, location, and supportive policies influence overall viability amid local electricity prices and market dynamics.

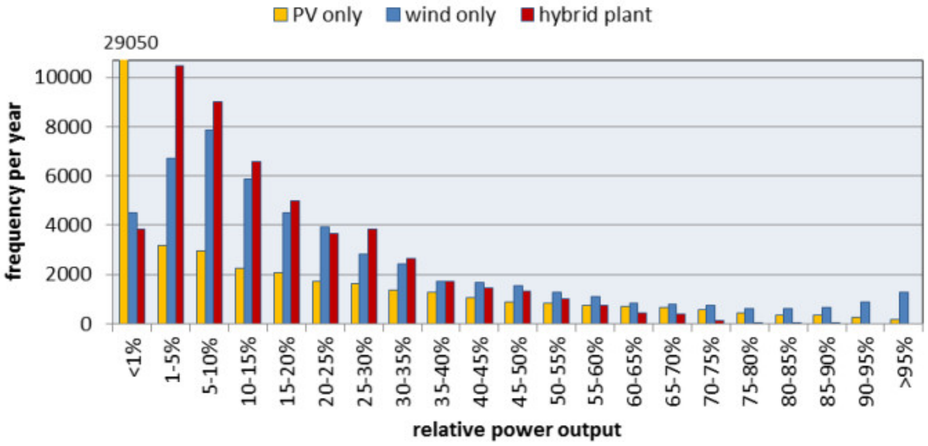


Fig. 9. Comparison of energy output of wind, solar and a hybrid plant [30]

Table 3. Requirements for PV solar and wind hybrid system

Requirements	Description
Meteorological data	1. Analysis of the area's meteorological features. 2. Information on the resources of the sun and wind. 3. Calculate weather data on a minute, hourly, or daily basis.
Load profile	For design optimisation purposes, load demand averages on an hourly or daily basis are typically used.
System configuration	When there is more solar than wind on site, the hybrid system is set with a supreme PV system and a lower wind system share.
Energy system model	These models are used to locate issues and find solutions through various computing techniques.

Table 4. Outlines the phases for designing and planning hybrid energy systems, focusing on solar photovoltaic and wind optimization methodologies [10]

Segments	Scheme and scheduling
Segment 1	Determination of the weather's condition
Segment 2	Analysis of demand for electricity
Segment 3	Configuration of a hybrid system
Segment 4	Creation of hybrid systems models
Segment 5	Utilizing simulation and optimization for sizing analysis
Segment 6	Analysis of the system's operations

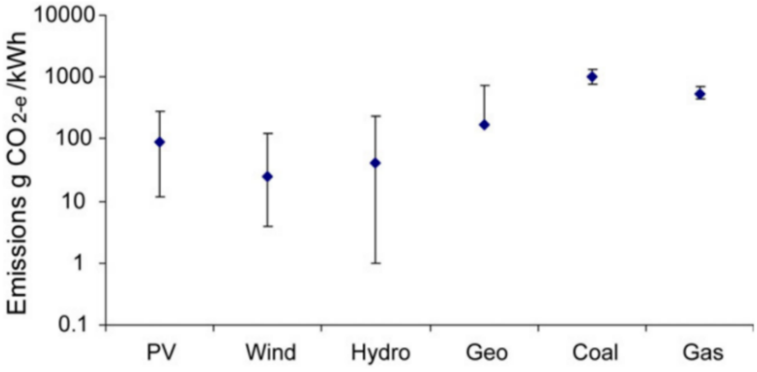


Fig. 10. Carbon dioxide released throughout electricity generation [33]

The ongoing operational and maintenance costs, including labour, spare parts, and servicing, are crucial in sustaining wind PV solar hybrid systems. Assessing their sustainable grid integration involves evaluating environmental, social, and economic impacts, ensuring effective electricity supply while maintaining grid stability and reliability. Considerations for sustainable grid integration of wind PV solar hybrid systems [40].

i. Grid Stability and Reliability
ii. Demand Response and Flexibility
iii. Energy Storage Integration
iv. Grid Infrastructure Upgrades
v. Grid Code Compliance
vi. Transmission and Distribution Losses
vii. Ancillary Services
viii. Economic Implications
ix. Grid Planning and Expansion

A life cycle assessment (LCA) of wind-solar energy evaluates environmental impacts from extraction to disposal [40].

3. STATE OF ART HYBRID ENERGY SYSTEM TECHNOLOGICAL DEVELOPMENT

The demand for clean energy drives hybrid system deployment. Community engagement, global participation, and corporate initiatives enhance renewable adoption. International collaborations accelerate technology advancements. Government incentives stimulate investment. Innovations improve system performance and reliability. Challenges include energy generation variability and policy uncertainties, requiring improved forecasting and grid strategies.

3.1 Case Study

3.1.1 Developments in China

As of September 2021, China has become a global leader in the development of wind and PV solar renewable energy. The country has made significant strides in expanding its renewable energy capacity and reducing its dependence on fossil fuels. Table 5 highlights developments in PV solar and wind energy technologies in China [41].

China advances with wind and PV solar hybrid power plants, combining turbines and panels on-site for stable energy. Distributed systems integrate rooftop solar with small wind turbines in urban and rural areas, providing renewable energy to buildings. Solar-wind hybrids aid agriculture, enhancing water pumping for irrigation and livestock. Off-grid areas benefit from wind PV solar, improving energy access and rural life. China prioritizes grid integration with smart grid tech and energy storage, supporting low-carbon energy transition through R&D in system configurations and control strategies.

3.2 Developments in East and Southern Africa

Over the past decade, African countries have made strides in promoting renewable energy. Many nations have set ambitious targets and implemented policies to attract investments, including innovative financing mechanisms like feed-in tariffs and power purchase agreements. Despite challenges and heavy reliance on coal, Africa demonstrates a growing interest in renewable energy compared to China.

Fig. 11 shows Africa's energy sources, dominated by coal with wind at its lowest. Technological advancements are improving wind and PV solar system efficiency, and expanding Africa's renewable energy market [44]. Adoption varies across countries due to local factors and policies [45]. Evolution in these technologies is crucial for enhancing energy access, economic growth, and environmental preservation. Leading countries in hybrid wind and PV solar include Kenya, South Africa, and Morocco [46]. In South Africa, a smart-house energy management strategy uses hybrid solar PV-wind-battery systems connected to the grid (Fig. 2), optimizing electricity supply (Table 6) with intelligent demand control [9,47,48].

Several off-grid projects in Africa combine wind turbines and solar panels to create hybrid power systems, supplying electricity to communities without access to the main grid [49]. In regions with limited water access, wind-solar water pumps are deployed, using renewable energy to pump water for agricultural and community needs, as depicted in Fig. 13 [50]. Hybrid wind-solar street lighting systems are installed in African cities, using renewable energy to power LED streetlights and reduce carbon emissions [51]. Remote communities utilize wind PV solar hybrid systems as standalone power solutions for lighting and essential services [51]. South Africa and Kenya explore PV solar and wind hybrid applications in agriculture, as illustrated in Fig. 13.

Table 5. Wind solar energy advances in China

Innovation	Description
Installed Capacity	China has the largest installed capacity and industry of both wind and PV solar energy in the world.
Wind Energy	A major player in the wind energy sector, with a vast number of onshore and offshore wind farms. Key provinces such as Inner Mongolia, Hebei, and Shandong have significant onshore wind capacity.
Solar energy	China is also a global leader in PV solar energy. The country has a substantial number of solar installations, including utility-scale solar farms, rooftop solar systems, and solar parks. Provinces like Jiangsu, Shandong, and Henan are among the leading regions for solar energy deployment [1].
Global Climate Commitments	China has made significant climate commitments and aims to peak its carbon emissions by 2030 and achieve carbon neutrality by 2060. As a result, the country has been intensifying efforts to quicken the deployment of renewable energy sources.
Manufacturing	China is a major manufacturer of wind turbines and solar panels, supplying not only its domestic market but also exporting to various countries. The country's manufacturing capabilities have contributed to cost reductions and increased accessibility to renewable energy technologies worldwide [42].
Grid Integration Policy	Actively working on grid integration to accommodate the increasing share of renewable energy in its electricity mix. The government has been investing in smart grid technologies and energy storage solutions to enhance grid stability and flexibility.
Policies	China has implemented numerous incentives with the goal of the growth of renewable energy. Some aspects can be seen through feed-in tariffs, subsidies, and favourable regulations to support wind and solar projects.
Research and Innovation	China has been investing in research and innovation to improve the efficiency and performance of wind and solar technologies. This includes developing advanced materials, innovative PV cell designs, and new wind turbine technologies [43].

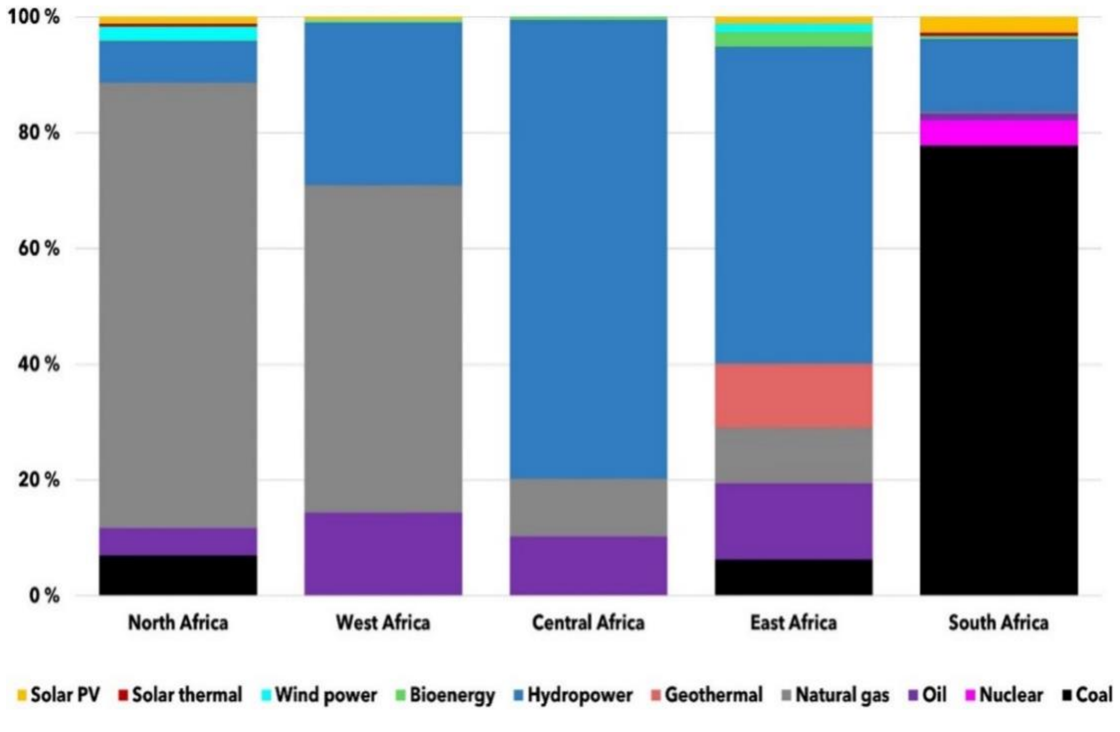


Fig. 11. Africa's electricity source as of 2020 [44]

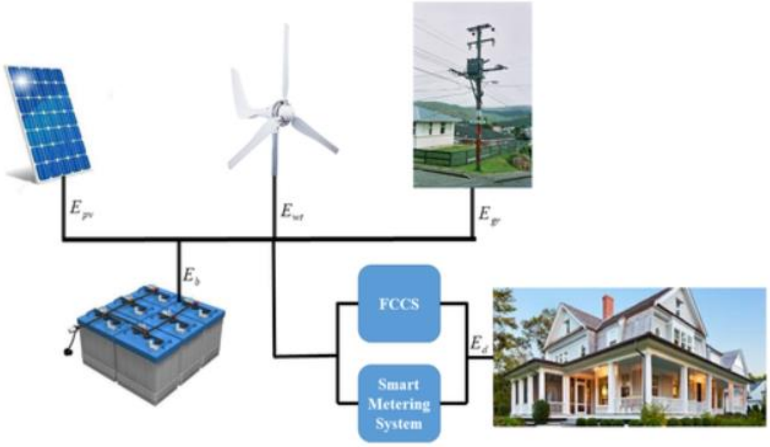


Fig. 12. PV solar and wind system prototypical of the projected optimization of residential load

Table 6. Day-to-day electricity demand, wind speed and solar generation

Daily Time Hour	Energy demand Kwh	Wind speed m/s	Solar irradiance W/mm	Daily Time Hour	Energy demand kwh	Wind speed m/s	Solar irradiance w/mm
00:00	0.6	0.82	0	12:00	0.84	1.766	494.023
01:00	1.72	1.665	0	13:00	0.62	2.576	494.023
02:00	0.46	0.998	0	14:00	0.56	2.017	494.023
03:00	0.9	0.956	0	15:00	4.34	2.282	494.023
04:00	2.18	2.549	0	16:00	7.02	3.116	494.023
05:00	5.72	2.558	0	17:00	2.82	2.626	494.023
06:00	6.98	2.775	15.418	18:00	2.48	3.427	43
07:00	4.82	3.754	119.344	19:00	8.48	2.972	0
08:00	1.44	2.948	233.282	20:00	3.66	2.543	0
09:00	4.24	2.828	336.534	21:00	3	2.336	0
10:00	1.16	2.87	438.693	22:00	2.58	1.863	0
11:00	4.6	2.522	482.247	23:00	0.68	1.231	0

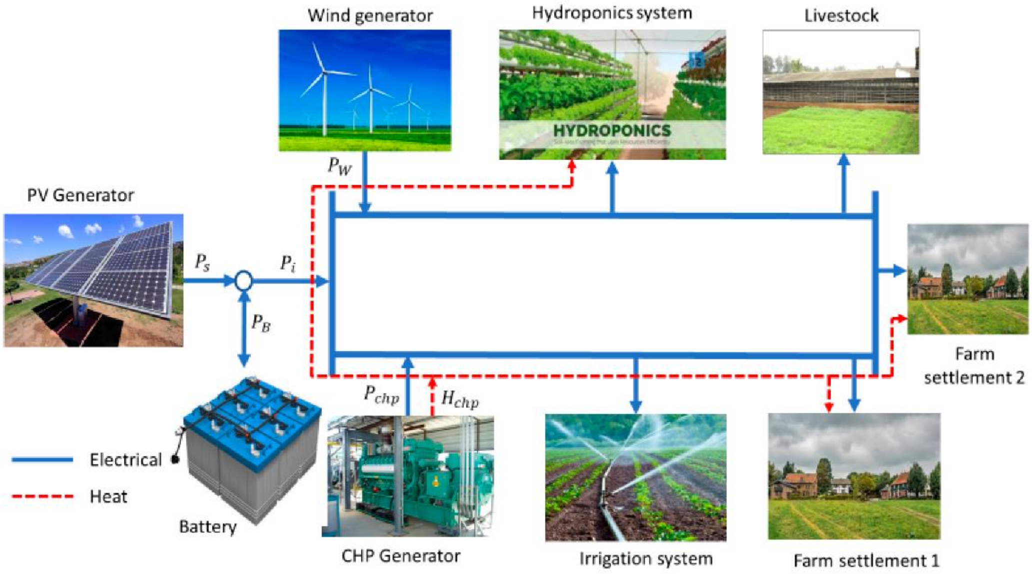


Fig. 13. Diagram of a prototype set up of hybrid PV solar/ wing and battery system [32]

Table 7. Comparison of renewable energy policies in Kenya [53] and China [54]

Policies	China	Kenya
Feed-in tariffs	Producers of renewable energy are guaranteed a fixed price for the power they produce, which is frequently set above market rates. This promotes investment in renewable energy.	Offering long-term agreements and assured pricing for power produced. These regulations seek to increase investment and encourage the use of renewable energy sources [53].
Renewable Portfolio Standards (RPS)	A national RPS that requires electricity producers to source a specific proportion of their energy from renewable sources. According to the RPS, a predetermined percentage of power must be produced using renewable resources, such as wind, solar, hydro, and biomass.	To fulfil their obligations for renewable energy, utilities and power providers are often subject to these regulations, which encourage them to engage in renewable energy projects [46]
Regulatory Frameworks and Incentives	The government provides a range of financial incentives and subsidies to encourage the creation and implementation of renewable energy projects these include Tax reductions, low-interest loans, and grants are a few examples of these incentives.	To aid in the development of renewable energy projects, governments and international organizations have developed green energy funds and finance channels.
Research and Development Support	This includes supporting businesses engaged in renewable energy projects and sponsoring research organizations.	The government gives funding to researchers about renewable energy.
Renewable Energy Access and Grid Integration	This involves upgrading the power grid to accommodate more intermittent renewable sources and promoting distributed energy systems.	Due to the vast rural areas with limited or no access to the main grid, several African countries have focused on off-grid renewable energy solutions, such as small-scale solar systems and mini-grids.
Climate and Environmental Policies	China has become a significant issuer of green bonds, allowing investors to fund environmentally friendly projects, including renewable energy developments.	Many countries are members of international agreements and have developed national climate action plans that include targets for renewable energy adoption and emissions reduction.

3.3 Renewable Energy Policies Advancement Comparison between China and East Africa

China and East Africa are advancing sustainable energy initiatives. Examining renewable energy policies provides insights into the status of wind, solar, and PV industries. East African countries each pursue distinct strategies based on their energy needs, resources, and policy priorities. Similar patterns and programs for renewable energy development exist across the continent, as seen in Kenya's energy ministry and compared to China in Table 7 [46,52].

4. PV SOLAR AND WIND SYSTEM POTENTIAL IN AFRICA

4.1 Climate Investigation

Africa's climate, wind, PV solar, and energy sustainability present both opportunities and challenges. Its vast landmass and diverse climates offer great potential for wind and solar energy development. PV solar energy thrives with abundant sunlight in North, West, and parts of East Africa, boasting high solar irradiation levels. Wind resources are favourable in the Horn of Africa, coastal areas, and Southern Africa, suitable for both onshore and offshore projects. Challenges include limited financing, inadequate infrastructure, bureaucratic hurdles, and political instability, hindering energy access.

4.2 Challenges

Africa faces challenges in securing sustainable electricity due to limited infrastructure, insufficient investment in power plants, and reliance on fossil fuels, leading to supply issues and climate impacts. Political instability complicates energy delivery. Financing barriers hinder renewable projects, but mechanisms like green bonds and partnerships could help. Clear policies with incentives are crucial [63-66]. Grid stability needs investments in smart technologies for wind and solar integration. Climate change worsens challenges, impacting energy production. Renewable adoption enhances resilience, needing capacity building and global cooperation for Africa's energy future.

4.3 Opportunities

Africa's vast renewable energy potential supports off-grid solutions for energy access in remote areas. Integrating wind and solar PV in hybrid systems enhances grid stability and energy production. Regional cooperation and cross-border projects promote resource sharing and boost energy security. Increased research and development investment can drive technology advancements suited to Africa's unique environmental and energy needs, as shown in Fig. 14.

Sterl, S., et al. [55], highlighting Somalia's leading solar capacity and Kenya's wind capacity. Renewable energy holds transformative potential for Africa's energy system, fostering sustainable growth and mitigating climate change impacts. Enhancing regulatory frameworks, funding mechanisms, and technological innovation is crucial for Africa to maximize the benefits of renewable energy, promoting economic development, job creation, and environmental conservation.

4.4 Recent Technological Advancements in Hybrid Systems

Recent technological advancements in hybrid systems encompass a variety of fields, including automotive technology, renewable energy, and computing. Here are some notable examples:

4.5 Automotive Hybrid Systems

Toyota's Hybrid Synergy Drive: Toyota's ongoing improvements in hybrid technology have led to the development of the latest iteration of their Hybrid Synergy Drive. This system uses a combination of a gasoline engine and electric motor to optimize fuel efficiency and performance. The Toyota Prius, for example, achieves over 50 miles per gallon (mpg) due to advancements in battery technology, regenerative braking, and more efficient power management systems.

Plug-in Hybrid Electric Vehicles (PHEVs): Innovations in PHEVs, such as the Chevrolet Volt and Mitsubishi Outlander PHEV, allow for longer electric-only ranges. These vehicles combine larger battery packs with the ability to recharge from an external power source, significantly reducing reliance on gasoline for short trips [67,68].

4.6 Renewable Energy Hybrid Systems

Hybrid Solar-Wind Systems: Hybrid renewable energy systems that combine solar panels and wind turbines are becoming increasingly efficient. Companies like Siemens Gamesa are developing hybrid energy parks that utilize both solar and wind power to provide a more stable and continuous energy supply. These systems can offset the intermittency of one energy source with the other, enhancing overall energy reliability.

Hybrid Energy Storage Systems: Integrating different types of energy storage systems, such as lithium-ion batteries with supercapacitors or flow batteries, can balance the benefits of high energy density and quick discharge capabilities. This approach is used in grid storage applications to stabilize the grid and provide backup power during peak demand times.

4.7 Computing and Information Systems

Hybrid Cloud Computing: Companies like Microsoft, Amazon, and Google are advancing hybrid cloud computing platforms, which combine on-premises data centers with public and private cloud resources. These systems allow organizations to scale their IT infrastructure flexibly, optimize costs, and enhance data security. Microsoft's Azure Arc and AWS Outposts are examples of services that enable seamless integration and management of hybrid cloud environments.

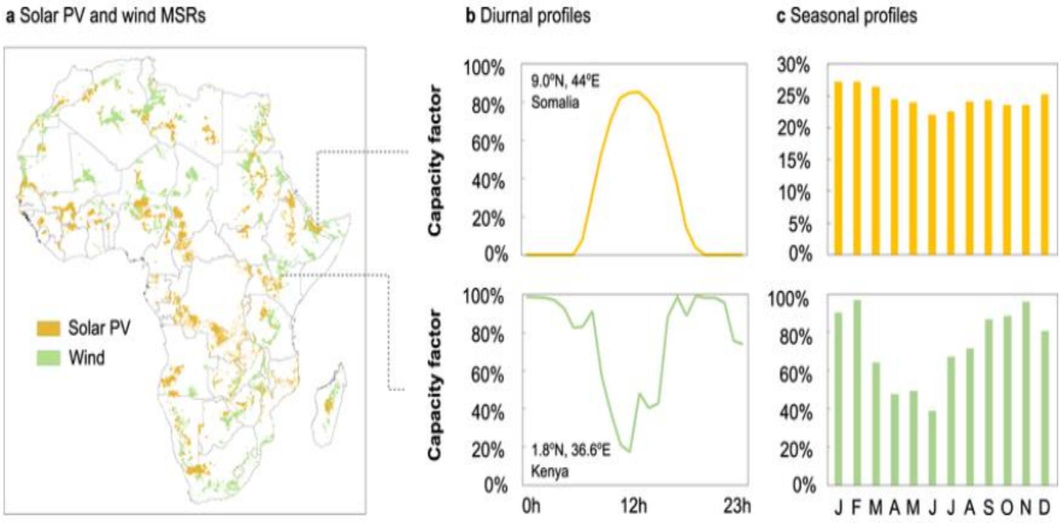


Fig. 14. illustrates regions suitable for solar photovoltaic and onshore wind power modeling

Quantum-Classical Hybrid Computing: Emerging technologies in quantum computing are being integrated with classical computing systems to tackle complex problems more efficiently. IBM's Qiskit and Google's Quantum AI platforms provide tools for hybrid quantum-classical algorithms, where quantum computers handle specific tasks, and classical systems manage the overall process [69-71]. This hybrid approach leverages the strengths of both types of computing to solve problems in areas like cryptography, material science, and optimization.

4.8 Healthcare and Biomedical Systems

Hybrid Imaging Systems: Advances in medical imaging technologies, such as PET-CT and PET-MRI scanners, combine positron emission tomography (PET) with computed tomography (CT) or magnetic resonance imaging (MRI). These hybrid systems provide more accurate diagnostic information by combining the functional imaging capabilities of PET with the anatomical details of CT or MRI, improving the diagnosis and treatment planning for conditions like cancer and neurological disorders.

Hybrid Artificial Organs: Researchers are developing hybrid artificial organs that combine biological tissues with synthetic materials to create more effective and longer-lasting implants. For instance, hybrid heart valves, which integrate animal tissue with synthetic materials, offer better durability and biocompatibility compared to traditional mechanical or purely biological valves.

4.9 Policy Uncertainties and Their Impact on Hybrid Energy Systems

Policy uncertainties play a critical role in the development and deployment of hybrid energy systems, which integrate multiple forms of renewable energy sources (RES) with traditional power systems to enhance reliability, efficiency, and sustainability. These uncertainties can arise from changes in regulatory frameworks, subsidies, tax incentives, tariffs, and environmental regulations, impacting investment decisions, technological advancements, and operational strategies. Below is a detailed analysis of these uncertainties and their impacts, along with examples of successful and unsuccessful policies from different regions [72,73].

4.10 Impact of Policy Uncertainties

Investment Risks: Policy changes or lack of clear long-term regulatory frameworks can deter investors due to the unpredictability of returns. For example, sudden cuts in subsidies or incentives can halt ongoing projects and dissuade future investments.

Technological Advancements: Uncertain policies can hinder technological progress by creating an unstable environment for research and development (R&D). Consistent support is crucial for the advancement of hybrid systems, which require significant innovation.

Operational Strategies: Hybrid systems rely on integrated planning and operations. Policy uncertainties can disrupt these plans, especially when policies regarding grid integration, energy storage, and distribution are unclear or change frequently.

Market Dynamics: Policies influence market conditions and competition. Uncertain policies can create an uneven playing field, affecting the competitiveness of hybrid energy solutions compared to conventional energy sources.

Environmental Goals: Achieving environmental and sustainability targets requires stable and supportive policies. Uncertainty can delay the adoption of hybrid systems, jeopardizing these goals.

4.11 Successful Policies

Germany's Energiewende: Germany’s energy transition policy, Energiewende, has been relatively successful in promoting hybrid energy systems. The policy provides a clear roadmap with long-term goals, stable subsidies, and incentives for renewable energy projects. The combination of feed-in tariffs (FiTs) and auctions for renewable energy projects has encouraged investments in hybrid systems, integrating wind, solar, and biomass with the existing grid.

California's Renewable Portfolio Standards (RPS): California's RPS mandates that 60% of electricity must come from renewable sources by 2030. This clear and ambitious policy has driven investments in hybrid systems, integrating solar and wind with energy storage solutions. The state’s policies on net metering and incentives for energy storage have also been pivotal in supporting hybrid energy projects.

4.12 Unsuccessful Policies

Spain’s Solar Subsidy Cuts: Spain’s abrupt reduction of solar subsidies in 2010 is an example of how policy uncertainty can negatively impact hybrid energy systems. The retroactive cuts led to a loss of investor confidence, project cancellations, and financial losses for ongoing projects. This policy shift caused a significant slowdown in the adoption of hybrid systems that relied on solar energy.

Australia’s Mixed Signals on Renewable Energy Targets: Australia has experienced policy inconsistencies with its renewable energy targets. Changes in government and fluctuating commitments to renewable energy targets have created uncertainty, impacting investments in hybrid systems. While some states have been proactive, the lack of a cohesive national policy has hindered the overall growth of hybrid energy systems.

Impact of Policies and Incentives on the Adoption and Development of Renewable Energy in African Countries.

Renewable energy adoption in African countries is influenced significantly by various policies and incentives. These measures are essential for overcoming economic, technological, and infrastructural barriers, promoting sustainable energy solutions, and addressing the continent’s growing energy demands. Below is a detailed discussion of the impact of specific policies and incentives on the development and adoption of renewable energy across Africa.

4.13 Policy Frameworks

National Renewable Energy Action Plans (NREAPs)

Example: South Africa’s Integrated Resource Plan (IRP) 2019.

Impact: The IRP outlines the country's energy mix, with a significant focus on renewable energy sources. It sets clear targets for solar, wind, and hydroelectric power, providing a roadmap for energy diversification and reducing reliance on coal. The plan has led to increased investments in renewable projects, such as the successful Renewable Energy Independent Power Producer Procurement Programme (REIPPPP).

Feed-in Tariffs (FiTs)

Example: Uganda's Renewable Energy Feed-in Tariff (REFiT) program.

Impact: FiTs guarantee a fixed price for electricity generated from renewable sources, providing financial certainty to investors. Uganda's REFiT has attracted significant private sector investments in small-scale hydro and solar projects, enhancing the country's renewable energy capacity and rural electrification efforts.

4.14 Regulatory Frameworks

Example: Kenya’s Energy Act 2019

Impact: The Energy Act establishes a comprehensive regulatory framework for energy production, distribution, and consumption. It includes provisions for renewable energy development, grid integration, and licensing. The Act has facilitated the growth of Kenya’s geothermal and wind energy sectors, positioning the country as a leader in renewable energy in East Africa.

Incentive Programs

Tax Incentives

Example: Rwanda’s tax exemptions for renewable energy equipment.

Impact: By offering exemptions on import duties and value-added tax (VAT) for renewable energy equipment, Rwanda has reduced the cost of deploying solar and other renewable technologies. This policy has led to increased adoption of solar home systems and mini-grids, particularly in off-grid rural areas.

Subsidies and Grants

Example: Morocco’s subsidies for solar water heaters under the PROMASOL program.

Impact: The PROMASOL program provides subsidies for households and businesses to install solar water heaters. This initiative has significantly increased the adoption of solar thermal technology, reducing reliance on traditional energy sources and lowering greenhouse gas emissions [74-77].

Public-Private Partnerships (PPPs)

Example: Ethiopia’s Reppie Waste-to-Energy Project.

Impact: The Reppie project, a collaboration between the Ethiopian government and private investors, converts waste into electricity. PPPs like this leverage private sector expertise and capital, accelerating the deployment of large-scale renewable energy projects and enhancing energy security.
Case Studies of Success and Challenges

Success: South Africa’s REIPPPP

Impact: Since its inception, the REIPPPP has attracted over $15 billion in investments and added 6,422 MW of renewable energy capacity. The program's transparent bidding process and government guarantees have built investor confidence, resulting in significant job creation and local economic development.

Challenges: Nigeria’s Renewable Energy Policy Implementation

Impact: Despite having a robust renewable energy policy framework, Nigeria faces challenges in implementation due to bureaucratic hurdles, inconsistent policies, and inadequate infrastructure. These issues have hindered the full realization of the country’s renewable energy potential.

5. CONCLUSION

Research on wind and PV solar hybrid renewable energy systems has advanced but gaps remain. Improving models to capture the variability of wind and solar resources accurately with high-resolution data and advanced statistical methods is crucial. Integrating energy storage into simulations can enhance system stability and flexibility. Understanding the relationship between wind and solar resources in specific areas can optimize system design. Developing dynamic control algorithms for real-time adjustments based on weather and grid conditions is essential. Using probabilistic forecasting can improve predictions amid uncertainties. Assessing long-term impacts on grid stability, markets, and regulations is vital for sustainable integration. Wind-solar hybrid systems offer benefits like enhanced energy production, reliability, reduced emissions, and alignment with climate goals.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of manuscripts.

ACKNOWLEDGEMENTS

This work was supported by Special guiding funds for building energy conservation and green building in Zhenjiang City (zk20220001; JSU10SK2024ZX003)

COMPETING INTERESTS

The authors have declared that no competing interests exist.

REFERENCES

1. Badwawi RA, Abusara M, Mallick T. A review of hybrid solar PV and wind energy system. Smart Science. 2015;3(3):127-138.
2. Dehariya MTSS, Kori AK. A Review Article of Control and Performance Evolution of Fopid Based Single Stage Grid Connected PV System; 2022.
3. Silverman M, Worthman S. The future of renewable energy industries. The Electricity Journal. 1995;8(2):12-31.
4. Russo M. et al., Future perspectives for wind and solar electricity production under high-resolution climate change scenarios. Journal of Cleaner Production. 2023;404: 136997.
5. Bansal RC. Automatic reactive-power control of isolated wind-diesel hybrid power systems. IEEE Transactions on Industrial Electronics. 2006;53(4):1116-1126.
6. Bakos GC. Feasibility study of a hybrid wind/hydro power-system for low-cost electricity production. Applied Energy. 2002;72(3-4):599-608.
7. Karki R, Billinton R. Reliability/cost implications of PV and wind energy utilization in small isolated power systems. IEEE Transactions on Energy Conversion. 2001;16(4):368-373.
8. Agarkar B, Barve DS. A Review on Hybrid solar/wind/ hydro power generation system. International Journal of Current Engineering and Technology. 2016;188.
9. Harmsen R. et al., The unrecognized contribution of renewable energy to Europe's energy savings target. Energy Policy. 2011;39(6):3425-3433.
10. Sinha S, Chandel S. Review of recent trends in optimization techniques for solar photovoltaic–wind-based hybrid energy systems. Renewable and sustainable energy reviews. 2015;50:755-769.
11. Nema P. A current and future state of art development of hybrid energy system using wind and PV- solar: A review. Renewable and Sustainable Energy Reviews; 2009.
12. Artigao E. et al., Wind turbine reliability: A comprehensive review towards effective condition monitoring development. Applied Energy. 2018;228:1569-1583.
13. Alemzero D, Acheampong T, Huaping S. Prospects of wind energy deployment in Africa: technical and economic analysis. Renewable Energy. 2021;179:652-666.
14. Helsen J. et al., Multibody modelling of varying complexity for modal behaviour analysis of wind turbine gearboxes. Renewable energy. 2011;36(11):3098-3113.
15. Bastankhah M, Porté-Agel F. A new analytical model for wind-turbine wakes. Renewable energy. 2014;70:116-123.
16. Zhou S. et al., A novel multi-objective scheduling model for grid-connected hydro-wind-PV-battery complementary system under extreme weather: A case study of Sichuan, China. Renewable Energy. 2023;212:818-833.
17. Bokde N, et al., A review on hybrid empirical mode decomposition models for wind speed and wind power prediction. Energies. 2019;12(2):254.
18. Jackson D, et al., Investigation of three-dimensional wind flow behaviour over coastal dune morphology under offshore winds using computational fluid dynamics (CFD) and ultrasonic anemometry. Earth Surface Processes and Landforms. 2011;36(8):1113-1124.
19. Dabiri JO. et al., A new approach to wind energy: opportunities and challenges. Physics of Sustainable Energy III (PSE III): Using Energy Efficiently and Producing it renewably. 2015;1652(1): 51-57.
20. Ku ML. et al., Advances in energy harvesting communications: Past, present, and future challenges. IEEE Communications Surveys & Tutorials. 2015;18(2):1384-1412.
21. Ahmad S, Abdul Mujeebu M, MA. Farooqi, Energy harvesting from pavements and roadways: A comprehensive review of technologies, materials, and challenges. International Journal of Energy Research. 2019;43(6):1974-2015.
22. Soares-Ramos EP, et al., Current status and future trends of offshore wind power in Europe. Energy. 2020;202:117787.
23. Chen J. Development of offshore wind power in China. Renewable and Sustainable Energy Reviews. 2011; 15(9):5013-5020.

24. Fayram AH, De Risi A. The potential compatibility of offshore wind power and fisheries: an example using bluefin tuna in the Adriatic Sea. Ocean & Coastal Management. 2007;50(8):597-605.
25. Ajayi OO. Assessment of utilization of wind energy resources in Nigeria. Energy policy. 2009;37(2):750-753.
26. Ren Z. et al., Offshore wind turbine operations and maintenance: A state-of-the-art review. Renewable and Sustainable Energy Reviews. 2021;144:110886.
27. Duran C. Bifacial solar cells: high efficiency design, characterization, modules and applications; 2012.
28. Guerrero-Lemus R, et al., Bifacial solar photovoltaics–A technology review. Renewable and sustainable energy reviews. 2016;60:1533-1549.
29. Strong S. Building integrated photovoltaics (BIPV). Whole building design guide. 2010;9.
30. Ludwig D, et al. Evaluation of an onsite integrated hybrid PV-Wind power plant. AIMS Energy. 2020;8(5):988-1006.
31. Molina MG, dos Santos EC, Pacas M. Improved power conditioning system for grid integration of photovoltaic solar energy conversion systems. in 2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA); 2010.
32. Xu Y, Singh C. Power system reliability impact of energy storage integration with intelligent operation strategy. IEEE Transactions on smart grid. 2013;5 (2):1129-1137.
33. Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renewable and sustainable energy reviews. 2009;13(5):1082-1088.
34. Borch K, Clausen NE, Ellis G. Environmental and social impacts of wind energy. DTU International energy report. 2014:86-90.
35. Devine-Wright P. Public engagement with large-scale renewable energy technologies: breaking the cycle of NIMBYism. Wiley Interdisciplinary Reviews: Climate Change. 2011;2(1):19-26.
36. Cameron L, Van Der Zwaan B. Employment factors for wind and solar energy technologies: A literature review. Renewable and Sustainable Energy Reviews. 2015;45:160-172.
37. Bezdek RH. The environmental, health, and safety implications of solar energy in central station power production. Energy. 1993;18(6):681-685.
38. Lackner KS, J. Sachs, A robust strategy for sustainable energy. Brookings Papers on Economic Activity. 2005;(2):215-284.
39. Ngan MS, Tan CW. Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia. Renewable and Sustainable energy reviews. 2012;16(1):634-647.
40. Campos-Guzmán V, et al., Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies. Renewable and Sustainable Energy Reviews. 2019;104: 343-366.
41. Li C, et al., Techno-economic performance study of stand-alone wind/diesel/battery hybrid system with different battery technologies in the cold region of China. Energy. 2020;192:116702.
42. Huang Q, et al., Multi-turbine wind-solar hybrid system. Renewable Energy. 2015; 76:401-407.
43. Jedou E. et al., A cartographic approach coupled with optimized sizing and management of an on-grid hybrid PV-solar-battery-group based on the state of the sky: An african case study. Solar Energy. 2021;227:101-115.
44. Enegy R. Highly renewable energies in Africa
45. Gbadamosi SL, Nwulu NI. Optimal power dispatch and reliability analysis of hybrid CHP-PV-wind systems in farming applications. Sustainability. 2020;12(19): 8199.
46. Kiplagat JK, Wang RZ, Li TX. Renewable energy in Kenya: Resource potential and status of exploitation. Renewable and Sustainable Energy Reviews. 2011;15(6): 2960-2973.
47. Mbungu NT, Bansal RC, Naidoo R. Smart energy coordination of a hybrid wind/PV with battery storage connected to the grid. The Journal of Engineering. 2019;(18): 5109-5113.
48. Muchiri K. et al., Wind and solar resource complementarity and its viability in wind/PV hybrid energy systems in Machakos, Kenya. Scientific African. 2023;20:e01599.
49. Maatallah T, Ghodhbane N, Nasrallah SB. Assessment viability for hybrid energy system (PV/wind/diesel) with storage in the

northernmost city in Africa, Bizerte, Tunisia. Renewable and Sustainable Energy Reviews. 2016;59:1639-1652.

50. Wazed SM, et al., A review of sustainable solar irrigation systems for Sub-Saharan Africa. Renewable and Sustainable Energy Reviews. 2018;81:1206-1225.
51. Nyemba WR. et al., Optimization of the design and manufacture of a solar-wind hybrid street light. Procedia Manufacturing. 2019;35:285-290.
52. Groba F, Cao J. Chinese renewable energy technology exports: the role of policy, innovation and markets. Environmental and Resource Economics. 2015;60:243-283.
53. Ndiritu SW, Engola MK. The effectiveness of feed-in-tariff policy in promoting power generation from renewable energy in Kenya. Renewable Energy. 2020;161:593-605.
54. Peidong Z. et al., Opportunities and challenges for renewable energy policy in China. Renewable Energy. 2018;4_486-4_503.
55. Sterl S, et al., An all-Africa dataset of energy model “supply regions” for solar photovoltaic and wind power. Scientific Data. 2022;9(1):664.
56. Haji MN, et al., A symbiotic approach to the design of offshore wind turbines with other energy harvesting systems. Ocean Engineering. 2018;169:673-681.
57. Green MA, Ho-Baillie A, Snaith HJ. The emergence of perovskite solar cells. Nature Photonics. 2014;8(7):506-514.
58. Gueymard CA. Spectral circumsolar radiation contribution to CPV. in AIP Conference Proceedings. American Institute of Physics; 2010.
59. Hansen UE, Pedersen MB, Nygaard I. Review of solar PV policies, interventions and diffusion in East Africa. Renewable and Sustainable Energy Reviews. 2015; 46:236-248.
60. Muftah AF, et al., Factors affecting basin type solar still productivity: A detailed review. Renewable and Sustainable Energy Reviews. 2014;32:430-447.
61. Shamshir SW, et al., Factors affecting solar stills productivity and improvement techniques: a detailed review. Applied Thermal Engineering. 2016;100:267-284.
62. Kazimierczuk AH. Wind energy in Kenya: A status and policy framework review. Renewable and Sustainable Energy Reviews. 2019;107:434-445.
63. Sichilalu S, Tazvinga H, Xia X. Optimal control of a fuel cell/wind/PV/grid hybrid system with thermal heat pump load. Solar energy. 2016;135:59-69.
64. Nema P, Nema R, Rangnekar S. PV-solar/wind hybrid energy system for GSM/CDMA type mobile telephony base station. international journal of energy and environment. 2010;1(2):359-366.
65. Kaldellis J, Vlachos GT. Optimum sizing of an autonomous wind–diesel hybrid system for various representative wind-potential cases. Applied energy. 2006;83(2):113-132.
66. Ehnberg SJ, Bollen MH. Reliability of a small power system using solar power and hydro. Electric power systems research. 2005;74(1):119-127.
67. Chachuat BI. Mixed-integer linear programming (MILP): Model formulation. McMaster Univ. Dep. Chem. Eng. 2019;17:1-26.
68. Gupta R, Kumar R, Bansal AK. Economic analysis and design of stand-alone wind/photovoltaic hybrid energy system using Genetic algorithm. in 2012 International Conference on Computing, Communication and Applications; 2012.
69. Bansal AK, Gupta R, Kumar R. Optimization of hybrid PV/wind energy system using Meta Particle Swarm Optimization (MPSO). in India International Conference on Power Electronics 2010 (IICPE2010); 2011.
70. Suhane P, et al., Sizing and performance analysis of standalone wind-photovoltaic based hybrid energy system using ant colony optimisation. IET Renewable Power Generation. 2016;10(7):964-972.
71. Wüstenhagen R, Wolsink M, Bürer MJ. Social acceptance of renewable energy innovation: An introduction to the concept. Energy policy. 2007;35(5):2683-2691.
72. Aliyu AK, Modu B, Tan CW. A review of renewable energy development in Africa: A focus in South Africa, Egypt and Nigeria. Renewable and Sustainable Energy Reviews. 2018;81:2502-2518.
73. Bashmakov I. et al., Climate Change Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 11. 2022, Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States); 2022.

74. Lai LL, Zhang HT. Smart Grids to Revolutionize Chinese Cities: Challenges and Opportunities. IEEE Power and Energy Magazine. 2022;20(5):26-38.
75. Lima YA. Renewable energy in Africa: Kenya's success and its possible implementation in Angola. Payne Institute Student Commentary Series: Commentary; 2023.
76. El-Houari H, et al., Energy, Economic, Environment (3E) analysis of WT-PV-Battery autonomous hybrid power plants in climatically varying regions. Sustainable Energy Technologies and Assessments. 2021;43:100961.
77. Yu C. et al., Impact of non-renewable energy and natural resources on economic recovery: Empirical evidence from selected developing economies. Resources Policy. 2023;80:103221.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/120675