

# Generation and Integration of Renewable Energy Resources into Power Grid: A review



T. A. Ayorinde<sup>1,2,3\*</sup>, T. Jamiru<sup>1</sup> and P. F. L. Roux<sup>4</sup>

<sup>1</sup>Department of Mechanical and Mechatronics Engineering, Tshwane University of Technology, South Africa

<sup>2</sup>National Biotechnology Research and Development Agency, Abuja, Nigeria

<sup>3</sup>Department of Agricultural and Environmental Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria.

<sup>4</sup>Department of Electrical Engineering, Tshwane University of Technology, South Africa



**ABSTRACT:** The integration of renewable energy resources (RERs) into power grids (PG) is crucial for sustainable energy development, owing to the increasing demand for clean energy and the need to reduce greenhouse gas (GHG) emissions. This review examines a range of RERs, including solar, wind, hydropower, geothermal, marine, and bioenergy. It highlights the challenges posed by their intermittent energy output owing to weather variations to grid stability, including low system inertia and fluctuations in voltage and frequency. These technical limitations hinder real-time power balance and grid stability. This review identifies improved power electronic systems, smart grid infrastructure, and efficient energy storage technologies that can effectively manage this intermittency and perfectly integrate these RERs into PG by improving control, dynamic load balancing, and dependability, allowing RERs to be seamlessly integrated into current power grids and contributing to a more sustainable and resilient energy future. This review identifies recent innovations, such as ad power electronics, smart grid infrastructure, and efficient energy storage systems, as critical facilitators of smooth RER integration. These technologies improve control, permit dynamic load balancing, and increase the reliability of the system. Recent innovations in renewable energy generation, grid integration, and energy management were also investigated, with case studies from South Africa, Turkey, India, Taiwan, the Democratic Republic of Congo, and California demonstrating successful microgrid and storage solutions. These examples demonstrate a global movement towards renewable-based power systems and the vital role that ongoing technical breakthroughs play in supporting a robust and sustainable energy future.

**KEYWORDS:** Renewable Energy Resources, Power Grid, Power Generation, Energy Integration, Sustainable Development.

[Received Jun. 8, 2025; Revised July 29, 2025; Accepted July 30, 2025]

Print ISSN: 0189-9546 | Online ISSN: 2437-2110

## I. INTRODUCTION

The global demand for renewable energy resources (RERs) is rapidly increasing, as they play a crucial role in driving sustainable ecosystems that support global economic development (Moriarty and Honnery, 2019). The global economy remains heavily dependent on energy consumption, particularly from conventional fossil fuels and petrochemical-based polymers. This reliance on fossil fuels has led to significant environmental degradation, including soil contamination, air pollution, ozone layer depletion, and sea level rise, all driven by greenhouse gas (GHG) (Ayorinde and Olasebikan, 2020a).

GHG emissions contribute significantly to global warming and have several public health implications. For instance, high temperatures increase the frequency of heat-related illnesses (mild heat cramps to life-threatening conditions that lead to heatstroke), and air pollution contributes to an increase in respiratory and cardiovascular ailments due to increased levels of pollutants, such as ground-level ozone and particulate matter (Kan, 2022). GHG-induced climate

variability intensifies the spread of vector-borne diseases, such as malaria and dengue (Morton *et al.*, 2019), while increasing the risk of hunger, waterborne infections, and mental health issues, particularly among vulnerable populations (Pörtner *et al.*, 2022). These health and environmental implications highlight the critical need to reduce GHG emissions.

In this context, RERs offer a competitive solution for producing fuel, power, and heat, propelling economic growth while emitting little or no GHG (Mauk *et al.*, 2017). These energy sources are clean, inexhaustible, and sustainable, making them crucial for addressing environmental concerns associated with the use of conventional energy resources (Moriarty and Honnery, 2019). Harnessing RERs and leveraging innovative conversion technologies will pave the way for sustainable and renewable energy development, reduce environmental degradation, and enhance energy security for the future (Leonard *et al.*, 2020). This global transition is further accelerated by fluctuating oil prices, ozone layer depletion, and increasing unsustainability of conventional energy resources (Leonard *et al.*, 2020). Consequently, fossil fuels can be gradually replaced by clean, limitless, and eco-friendly resources including solar, wind, biomass, hydro, and geothermal energy (Mauk *et al.*, 2017).

\*Corresponding author: [ayorindeadedayo@gmail.com](mailto:ayorindeadedayo@gmail.com)

doi: <https://doi.org/10.63746/njtd.v22i4.3743>

Utilising these resources to increase long-term energy security, lower carbon emissions, and promote environmental sustainability requires cutting-edge conversion technologies and grid-integration techniques.

Realising the full potential of RERs requires the integration of their variable energy outputs through advanced smart grid integration techniques. However, this integration introduces significant technical complexities, primarily because RERs are completely dependent on weather and climatic conditions (Bloomfield *et al.*, 2022). A comprehensive understanding of the meteorological factors that influence the frequency of renewable energy output is necessary to ensure a stable and dependable power generation system (White *et al.*, 2017). These factors operate across multiple timescales, with short-term variations, such as hourly wind ramping events, sudden declines in solar intensity for PV output, intermittent ocean currents, and localised river flow variation due to topography, which are typically driven by local weather conditions. In contrast, long-term seasonal fluctuations, such as those affecting hydropower output due to water demand during the planting season or changes in river morphology, are generally influenced by broader patterns of climatic variability. Understanding these parameters is critical for forecasting the total annual energy requirements and peak residual loads (Bloomfield *et al.*, 2018). For instance, in Europe, colder winters lead to higher energy consumption and lower wind energy output, which are influenced by the phase of the North Atlantic Oscillation. Similarly, regional climatic variations in Africa have a significant impact on renewable energy generation. In East Africa, solar photovoltaic output can be reduced during the long rainy season owing to persistent cloud cover, whereas dry seasons offer more favourable conditions (Conway *et al.*, 2017). In Southern Africa, hydropower generation is susceptible to rainfall variability and seasonal river flows, which are influenced by the El Niño Southern Oscillation. Therefore, integrating climate-aware planning and forecasting into renewable energy strategies is essential for achieving sustainable energy solutions (Mathivha *et al.*, 2024). These insights are crucial for developing energy systems that can effectively manage weather-related uncertainties and unpredictability in renewable-energy generation.

Meteorology-driven factors in RERs can result in grid instability, frequency variations, and mismatches between supply and demand (Ohba *et al.*, 2023). Existing grid systems, which are primarily designed for centralised generation and transmission, lack the flexibility, real-time monitoring, and advanced control technology needed to manage the dispersed energy flows. Compounding these are obstacles such as inadequate energy storage, limited monitoring capabilities, and weak regulatory frameworks, especially in developing nations (Ejuh Che *et al.*, 2025). To overcome these barriers, innovative integration strategies such as smart grids integration, distributed generation, digital control technologies, and large-scale energy storage have been deployed to enhance grid stability, resilience, and operational efficiency (Makola *et al.*, 2023). Countries with abundant renewable energy potential, particularly Africa, Asia, and the Middle East, stand to benefit significantly from these advancements (Aliyu *et al.*, 2018). The

successful implementation of such systems not only reduces greenhouse gas emissions and enhances energy access but also accelerates progress toward the United Nations Sustainable Development Goals (SDGs).

Global energy consumption trends also underscore the urgency of this clean and renewable energy transition. Worldwide energy use rose from 524 quadrillion British thermal units (Btu) in 2010 to 630 quadrillion Btu in 2020, with projections indicating a further rise to 820 quadrillion Btu by 2040. The most significant growth in consumption is expected in Asia and the Americas, with peak usage projected to occur between 2025 and 2040. While Europe's energy demand remains relatively stable, the Middle East and Africa show consistent growth, while Central and South America maintain steady consumption. These global patterns highlight the urgent need for scalable, secure, and sustainable energy alternatives, especially across Africa (Bilgen, 2014).

Conventional grids used in Africa were designed for a centralised, predictable power supply, making them less capable of handling decentralised and variable RERs. As nations strive to achieve climate objectives and enhance energy accessibility, the implementation of renewable energy technologies has intensified. Successful integration of renewable energy resources into existing power systems faces several technological and infrastructure obstacles. Challenges such as grid stability, fluctuating energy supply, and limited storage capacity must be addressed to ensure dependable and efficient power transmission. The incorporation of localised RERs into power grids is an area ripe for further exploration. Although individual RERs have been widely used for electricity generation in both PG and centralised power systems, the coordinated integration of multiple RERs into MGs is relatively sparse and not fully developed. This review offers a comprehensive examination of studies on RER generation and its integration into PG, with the aim to explore new integration strategies that facilitate the development of a robust and decentralised grid. It provides a holistic knowledge base that integrates findings and perspectives, vital to establishing a theoretical framework and huge literature from various research articles, while highlighting fields where more research is required.

This review examines the latest developments in renewable energy generation and integration, emphasising current technical innovations, advanced grid management techniques, and the progression of PG systems. It analyses the distribution methods and operational difficulties related to the integration of renewable energy resources into both centralised and decentralised energy systems. Furthermore, it showcases case studies that exemplify successful integration models and the best practices for expanding renewable energy solutions, thereby supporting the need for energy transitions and providing valuable insights for policymakers, academics, and stakeholders committed to sustainable global energy systems.

This paper is structured as follows: Section 2 presents an overview of the RERs available for conversion into a PG. Section 3 discusses technological advancements, and Section 4 discusses integration and grid management. Sections 5 and 6 discuss the power grid distribution and potential challenges in power integration, respectively. This paper concludes with

case studies of RERs integrated into PG across different continents.

## II. OVERVIEW OF RENEWABLE ENERGY RESOURCES

The uniqueness of RER is derived from its chronic and continuous flow in nature, as illustrated in Figure 1. Renewable resources, such as solar energy, are reliable because the sun shines daily and can be stored in plants and released through metabolic activities, decay, and combustion (Twidell, 2021). Other resources, including wind, hydropower, geothermal energy, waves, tides, ocean thermal energy, and biomass, continue to flow through the ecosystem, regardless of the harvesting systems implemented (Ayorinde and Olasebikan, 2020b).

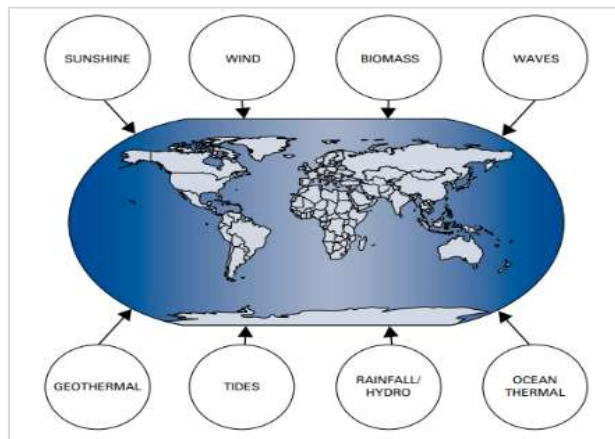
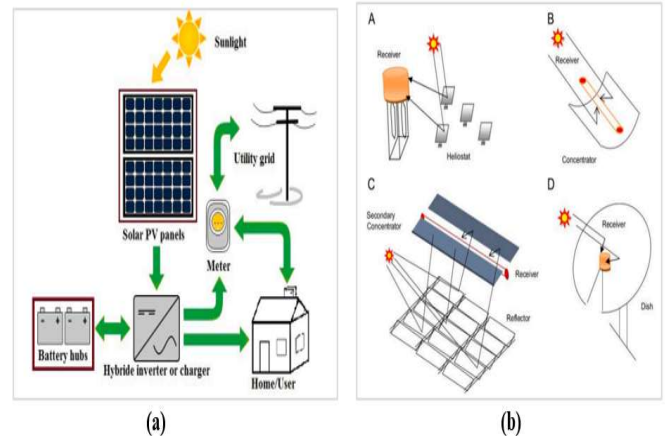


Figure 1: Renewable energy resources (Twidell, 2021)

### A. Solar Energy

Solar energy is one of the most readily available and promising RERs, with significant potential for exploration. It is clean, sustainable, and facilitates low-carbon use. Solar energy is generated using two primary technologies: photovoltaic (PV) systems, which capture solar radiation and convert it into electricity using silicon-based panels (Figure 2a); and concentrated solar power systems, which use mirrors or lenses to magnify sunlight intensity and generate heat that fires conventional steam turbines to provide electricity (Figure 2b) (Behura *et al.*, 2021). These technologies enable electricity generation for residential, transportation, and industrial applications without contributing to GHG emissions (Ayorinde and Olasebikan, 2020a). Despite the vast potential of solar energy, its integration into PG presents several technical and operational challenges (Pegels, 2010). The inherent variable and non-dispatchable nature of solar energy leads to fluctuations in energy output owing to the daily diurnal cycle and changing weather conditions. This variability complicates integration into conventional grids which are traditionally designed for steady, centralised power generation. Solar systems lack the ability to ramp up or scale down energy outputs in real time, limiting their responsiveness to sudden changes in load conditions. This necessitates the implementation of advanced energy storage and smart grid

integration systems to provide a balanced and stable energy supply (Shahzad and Jasińska, 2024).



Legend (A) heliostat reflector with a central receiver, (B) parabolic trough, (C) linear Fresnel, and (D) dish

Figure 2: (a) Schematic of a typical solar photovoltaic system; (b) basic components of a concentrated solar power system (Shahabuddin *et al.*, 2021)

### B. Wind Energy

Wind power is a rapidly growing RER that converts the kinetic energy of wind into electrical energy using wind turbines. Both onshore and offshore wind farms utilise turbines capable of generating and transmitting hundreds of megawatts of clean energy (Ellabban *et al.*, 2014). The most widely adopted wind turbine configuration, shown in Figure 3, is favoured because of its high efficiency and reliability (Diaz and Soares, 2020).

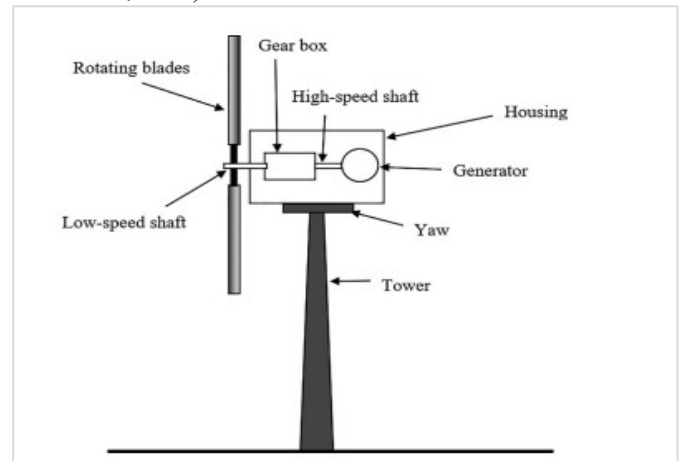


Figure 3: Modern wind turbine system (Bhattacharjee, 2021; Blaabjerg and Ma, 2017)

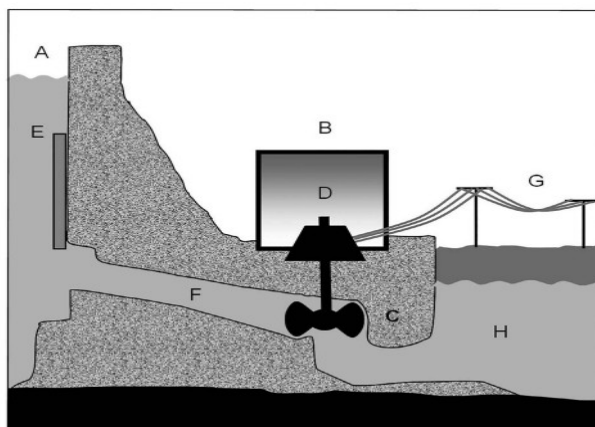
Turbine blades fabricated from fibreglass-reinforced polyester offer superior mechanical properties, fatigue resistance, and environmental durability. Their aerodynamic design maximises exposure to wind, thereby enhancing kinetic energy capture for power generation. The yaw mechanism amplifies the energy frequency while its gearbox drives the generator, converting mechanical energy into an electrical

output. (Bhattacharjee, 2021). The control system maintains system safety and efficiency by regulating power generation during extreme wind conditions (Blaabjerg and Ma, 2017).

Despite significant technological advancements, the integration of wind energy into existing power grids presents numerous challenges. The inherent variability and intermittency of wind, driven by the unpredictability of climatic conditions, leads to fluctuations in power output, which can compromise grid stability and reliability. Traditional power grids, originally designed for centralised and predictable generation, encounter difficulties in accommodating the decentralised and non-dispatchable nature of wind energy, necessitating the development of advanced weather forecasting methods, smart energy storage systems, and grid integration and protection strategies to balance the energy frequency within the PG. Sophisticated auxiliary control systems, such as frequency regulation, voltage support, and reactive power compensation systems, are needed to control inertia and ensure stable, secure, and resilient energy systems (Blaabjerg and Ma, 2017; UpWind, 2011).

### C. Hydro Power

Hydropower is the oldest and most significant renewable power source, accounting for 16% of the world's total electricity generation and 72% of all renewable energy production (Ellabban et al., 2014). It uses the kinetic energy of moving water to rotate turbines and produce electricity. Water from rivers, streams, and canals is typically stored in large reservoirs. The stored water was released as needed, with the flow rates and water heads carefully regulated to match the electrical demand. This allows for a stable and flexible power supply, particularly during peak-load periods (Ellabban et al., 2014; Sathaye et al., 1995). The primary energy components driving the turbine are the water head and kinetic energy from turbulent flows. As shown in Figure 4, some hydropower plants utilise large natural waterfalls or steep river terrains, whereas others are built on rivers with flat profiles (Ruin and Sidén, 2019).



Legend: A = reservoir, B = powerhouse, C = turbine, D = generator, E = intake with grid and gate, F = penstock, G = power line, H = receiving river or lake

Figure 4: Geometry of a hydroelectric plant (Ruin and Sidén, 2019)

Seasonal fluctuations in water availability, climate change, and conflicting demands for water use are challenges

for hydropower generation. Expansion initiatives are hampered by environmental and social issues such as community displacement, silt accumulation, and ecological degradation. However, when integrated with variable renewable energy sources, such as solar and wind, hydropower continues to be an essential dispatchable energy source that may aid in grid instability (Ohunakin et al., 2014).

### D. Geothermal Energy

Geothermal energy, utilised in over 70 countries, has a generating capacity of 200 petajoules (PJ) equivalent to 57 terawatt-hours (TWh) and an installed capacity of 10 gigawatts (GW). It also contributes approximately 270 PJ to space heating (Bhatia and Bhatia, 2014). This unique form of renewable energy originates from the internal heat of Earth, which is stored during its formation and generated by nuclear reactions, as shown in Figure 5. Energy is stored in rocks and water retained within pores and fractures beneath the Earth's crust. Naturally, a small amount of energy escapes to the surface through hot springs and geysers. Geothermal energy is extracted through deep boreholes as hot water or steam and channelled to generate power (Ruin and Sidén, 2019).

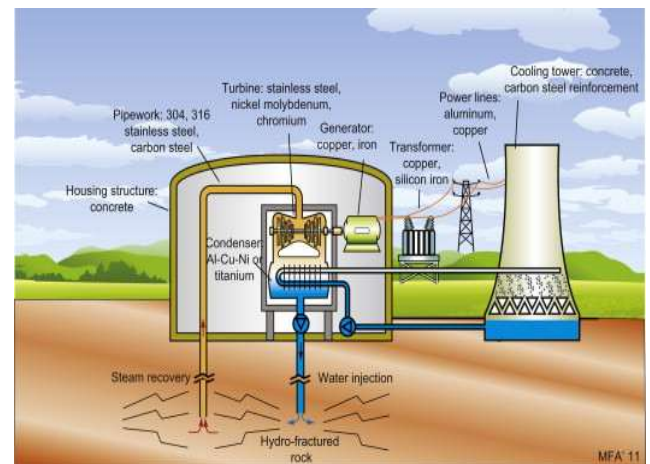


Figure 5: Geothermal power plant (Ruin and Sidén, 2019)

However, significant technological, financial, and environmental obstacles have hindered the widespread integration of geothermal energy. Among the most critical are the substantial initial costs related to deep drilling and reservoir development. Large-scale deployment is hampered by restricted fluid flow rates across different locations and uncertainties related to subsurface geological conditions. Environmental concerns, such as land subsidence, groundwater contamination, and induced seismicity, also pose risks to geothermal operations. Additionally, the long-term sustainability of geothermal reservoirs remains uncertain owing to the potential for gradual heat depletion. Addressing these challenges requires intentional research and development, site-specific geological modelling, and the implementation of strong regulatory frameworks to ensure the safe and efficient integration of geothermal energy into PG (Wilberforce et al., 2019).



### E. Marine Energy

Marine resources, including ocean waves, tidal ranges, currents, and salinity gradients, have the potential to produce 7,400 exajoules (EJ) of renewable energy annually, which is more than the world's current energy consumption and is expected to meet future demands (Ayorinde and Olasebikan, 2021). Conversion technologies, such as buoyancy-driven systems, overtopping devices, and oscillating water columns, offer promising techniques for harvesting ocean waves. As shown in Figure 6, buoyancy systems convert vertical wave motion into mechanical or hydraulic energy, overtopping devices capture wave overflow to drive turbines, and oscillating water columns generate power from air pressure variations caused by wave-induced water movement. These technologies are particularly promising for countries with extensive coastlines because they offer modularity, scalability, and low maintenance (Santos-Mugica *et al.*, 2014).

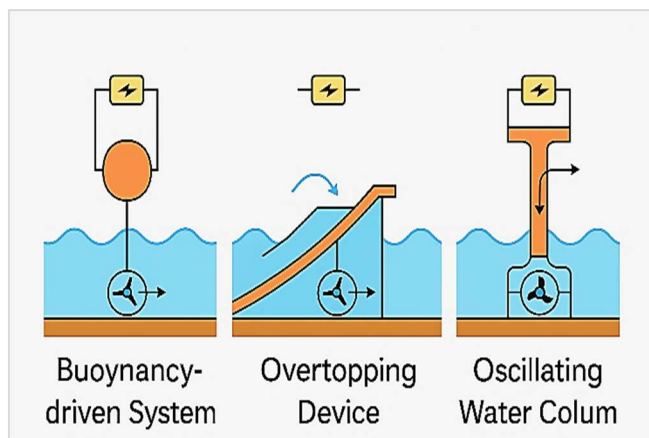


Figure 6: Schematic of marine energy conversion (Güney, 2015)

However, the intermittent and unpredictable nature of marine energy presents significant integration challenges for microgrids, which typically lack system inertia and have a limited backup capacity. This variability can cause voltage and frequency instabilities, necessitating advanced control systems, reliable energy storage, smart inverters, and accurate forecasting tools. Despite harsh marine environments and high initial costs, marine energy technologies hold significant promise for powering coastal and island microgrids, contributing to sustainable and decentralised energy systems (Kumar and Zare, 2019).

### F. Bioenergy

Bioenergy is refined from lignocellulose of edible and non-edible crops, livestock residues, food industry waste, municipal solid waste, organic waste, herbaceous and woody materials, and industrial crops (Ayorinde, 2024). As shown in Figure 7, solar energy captured by photosynthesis and stored in plant cells is converted into bioethanol, biodiesel, or biogas through thermochemical methods and biochemical processes (Akintunde *et al.*, 2025). It ranks second only to hydropower among renewable energy sources, contributing to global energy resources, lowering production costs, and providing a

sustainable and clean energy option for transportation, heating, and electricity generation. Bioenergy systems emit lower levels of sulfur oxides than conventional fossil fuels, thus promoting cleaner air. They also improve waste management and contribute to affordable, reliable, and sustainable energy solutions, thereby advancing sustainable cities and communities (Lundqvist, 2020).

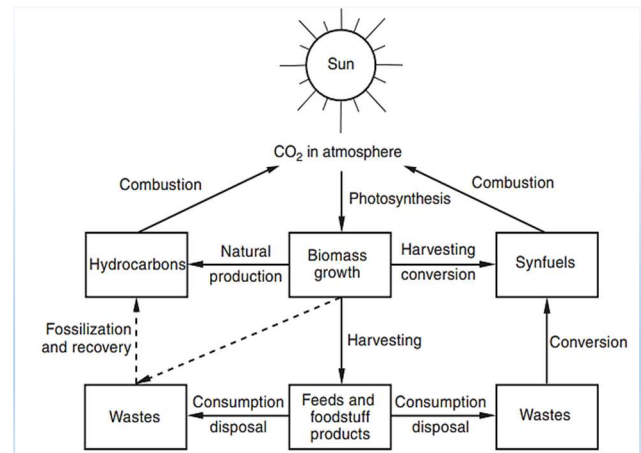


Figure 7: Bioenergy feedstock derived from sunlight (Ellabban *et al.*, 2014; Klass, 2004)

Key obstacles to integrating bioenergy into current PG include the unpredictability of biomass supply, slow reaction times of bioenergy conversion processes, and a lack of flexibility in comparison to other RES. Further constraints include regulatory concerns, inadequate energy storage, limited rural grid access, and insufficient smart grid infrastructure. To fully achieve the promise of bioenergy, these obstacles must be overcome through focused legislative changes, infrastructural spending, and cutting-edge grid technologies (Singh *et al.*, 2025).

## III. REVIEW PROCESS AND METHODOLOGY

Relevant and recent research and review articles were selected for this study using targeted keyword searches across major scientific databases, including Web of Science, ScienceDirect, Springer, and MDPI. In total, 150 articles were downloaded. To ensure relevance, the authors screened the publications based on their titles, abstracts, and keywords, focusing primarily on articles published within the last ten years. However, some older publications were included to provide a foundational context for the evolution of renewable energy technologies from conventional systems to modern innovations. After eliminating irrelevant materials, 103 journal articles, research papers, and reviews were retained for in-depth analysis. This paper provides a comprehensive review of the generation and integration of RERs into PG.

## IV. TECHNOLOGICAL ADVANCEMENT FOR RENEWABLE ENERGY GENERATION

Technological innovation is pivotal for promoting renewable energy sources, with advancements in solar and

wind systems enhancing efficiency, lowering costs, and improving electricity network interactions.

#### A. Advances in Solar Panels

Bifacial perovskite solar cells (PSC) represent a cutting-edge photovoltaic (PV) technology that harnesses the unique properties of halide perovskites for light absorption and energy conversion. Among the most prominent halide perovskite materials are methylammonium lead iodide (MAPbI<sub>3</sub>) and caesium lead bromide (CsPbBr<sub>3</sub>). They offer a high power output per unit area that captures radiation from both the front and rear surfaces, utilising albedo to increase the energy yield (Mahapatra *et al.*, 2022). As shown in Figure 8, the cells have exceptional optoelectronic properties, enhanced stability, and efficient charge transport layers that minimise the recombination of energy losses (Nowsherwan *et al.*, 2025). Perovskite solar cells are becoming more efficient and versatile energy-generating alternatives, delivering higher outputs than monofacial systems in fixed-tilt systems. They increased the energy yield through albedo reflection by capturing light from both the front and back surfaces using translucent and semi-transparent rear contact electrodes. Despite obstacles, including electrode deterioration and rear-side carrier recombination, ongoing innovation continues to seek improvements in efficiency and cost reduction, particularly for applications such as agrivoltaics (Ogundipe *et al.*, 2024).

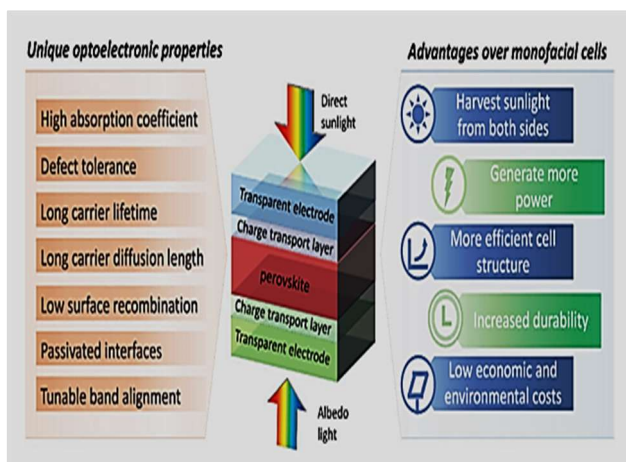


Figure 8: Schematic structure of a bifacial perovskite solar cell (Song *et al.*, 2022)

#### B. Advances in Wind turbines

Wind turbine technologies are optimised by increasing the aerodynamic characteristics of blades using smart power electronics, such as direct-drive turbines (DDTs), allowing effective power conversion in low-wind-speed regions (Rodriguez and Xydis, 2021). As shown in Figure 9, DDTs utilise a low-speed permanent magnet generator with three-phase armature windings; however, their reliance on rare earth elements raises concerns regarding sustainability and material supply (Gong and Qiao, 2013). Research on different magnet compositions and novel generator types, such as doubly fed induction generators (DFIGs) and high-temperature superconducting generators, continues to increase performance, reliability, and environmental effects (Blewett,

2023). The advent of renewable energy sources has necessitated effective integration and energy storage solutions to ensure grid stability and reliable electricity supply.

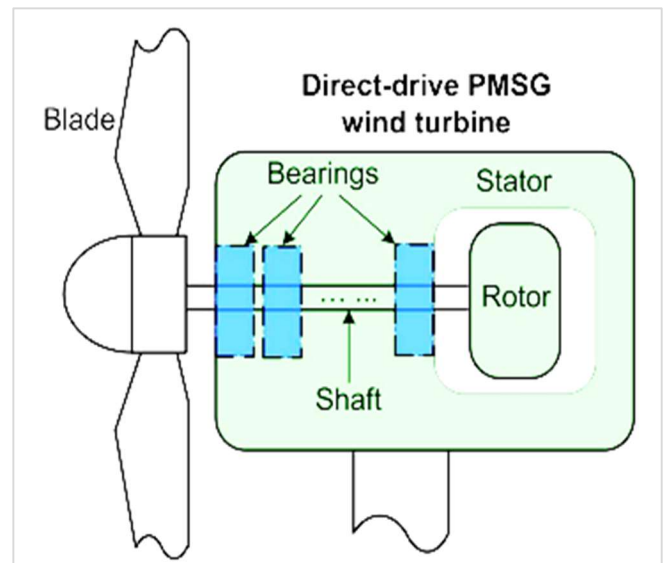


Figure 9: shows the configuration of a direct-drive wind turbine (Blewett, 2023)

#### V. RENEWABLE ENERGY RESOURCES INTEGRATION

The integration of RERs into PG improves energy generation efficiency and reliability. It reduces the intermittency of the energy frequency by standardising the electrical characteristics of energy resources for seamless integration. This section explores the technology required for the efficient integration of RERs into PG.

##### A. Power Electronics for Renewable Energy Resources

###### Conversion

Power electronics (PE) are essential to the integration of RERs into PG because they are designed to accommodate variable energy inputs with different output frequencies in an efficient and dependable manner. A typical PE system comprises a power converter, load or power generator source, and a smart control unit made of advanced semiconductors and power drives. As shown in Figure 10, renewable sources first pass through a load interface, followed by a power converter, which conditions and transforms the output from DC to AC or vice versa to ensure compliance with grid frequency standards. The control system manages voltage, frequency, and power flow, often using real-time local or centralised references to enable energy exchange, optimize performance, and implement maximum power point tracking (MPPT). For instance, in a wind energy system, PE provides frequency synchronisation and variable-speed operation, whereas in PV systems, it enables voltage regulation, MPPT, and DC-AC conversion. By adapting the system to fluctuating electrical outputs, matching grid characteristics, and facilitating the seamless integration of distributed generating systems, PE offer dynamic control of both active and reactive power. This guarantees smooth conversion of energy, grid compliance to energy thresholds, and enhanced power quality for

environmentally friendly energy systems (Souza Junior and Freitas, 2022).

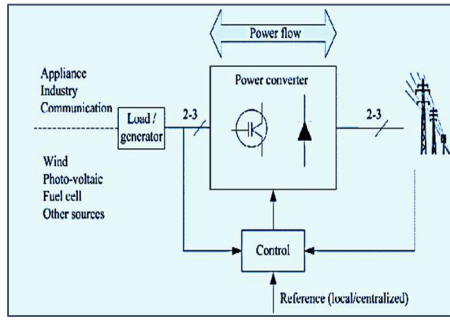


Figure 10: Typical power electronic system (Souza Junior and Freitas, 2022)

The development of sophisticated semiconductors and high-performance power drives has significantly enhanced the performance of PE systems used in renewable energy integration. These semiconductors exhibit enhanced energy conversion along varying ranges of power, reduced harmonic distortion, and improved overall efficiency and reliability of RER generation, integration, and transmission. The basic configuration of PE systems has evolved to accommodate the frequency variation peculiar to various RERs. One significant change is the move away from traditional silicon (Si) and towards wide-bandgap materials such as silicon carbide (SiC) (Rasul *et al.*, 2025). The semiconductors provides better power density, thermal performance, and switching speed (Sahu *et al.*, 2025). SiC technology is also revolutionising battery energy storage systems, EV charging infrastructure, and PG inverters, making it foundational for decentralised renewable energy integration (Amirpour, 2025). Sophisticated semiconductor devices, such as Gate Turn-Off Thyristors (GTOs), integrated-gate commutated thyristors (IGCTs), and Insulated-Gate Bipolar Transistors (IGBTs), have become indispensable in contemporary power conversion systems. These components are essential for the dynamic and effective regulation of renewable energy systems inside smart grids because they offer quick switching, strong operation, and high current handling capabilities (Vodovozov and Raud, 2025).

Tables 1 and 2 highlight the significance of semiconductor technologies in improving power electronics for effective integration of RER into PG. Table 1 compares the power ratings of Si and SiC semiconductor devices, highlighting the superior thermal performance and higher voltage tolerance of SiC components, which makes them more suitable for high-power applications. Table 2 presents the key performance characteristics, including switching speed, efficiency, and current output, of high-power semiconductor devices such as IGBTs, IGCTs, and GTOs. These devices are pivotal for managing energy flow and maintaining power quality in modern grid infrastructure. Collectively, the data presented in the tables demonstrate how advancements in semiconductor technology enhance the ability of power electronics to handle variable renewable inputs, ensures grid stability, and supports efficient, reliable, and scalable integration of distributed

energy resources into both centralised and decentralised networks (Balkas, 2024).

Table 1: Power ratings of semiconductors for high-power applications (Woo *et al.*, 2024)

Semiconductor Type	Semiconductor	Power Rating (kV)
Si	MOSFET	0.10 - 0.50
	IGBT	0.50 - 6.50
	GTO	4.00 - 9.00
	Thyristor	5.00 - 11.00
SiC	MOSFET	1.00 - 2.00
	BJT	1.00 - 5.00
	IGBT	3.00 - 10.00
	GTO	10.00 - 25.00
	Thyristor	10.00 - 40.00

Table 2: High-power semiconductors for power integration (Chakraborty *et al.*, 2025)

Semiconductor	Speed	Gain	Efficiency	Control	Current Output (kA)
IGBT	Fast	High	Low	Voltage	2
IGCT	Very fast	Medium	High	Current	4
GTO	Medium	Medium	High	Current	10

**B. Electrical Energy Storage Technologies**

Electrical Energy Storage (EES) technologies play a vital role in mitigating the intermittency of RERs by ensuring grid stability, load balancing, energy storage during peak load, and energy availability during peak demand. EES are broadly classified into mechanical, chemical, electrical, electrochemical, and thermal storage technologies, each offering distinct advantages and limitations depending on the system capacity, response time, loading, and storage duration, as shown in Figure 11 (Rana *et al.*, 2023), and discuss as follows;

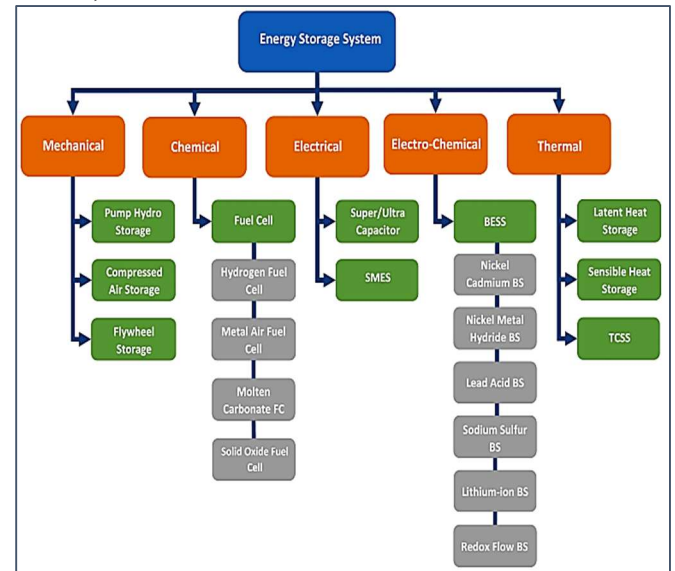


Figure 11: Electrical energy storage technologies based on storage forms (Nikolaidis and Poullikkas, 2017; Rana *et al.*, 2023)

1. Mechanical energy storage systems are devices that transform potential energy into kinetic energy or vice versa for subsequent conversion into electrical energy.



This technology includes flywheel storage, compressed air, and pumped hydro, as discussed below.

- Flywheel energy storage system (FESS) illustrated in Figure 12 uses a high-speed rotor supported by magnetic bearings inside a low-friction vacuum chamber to store rotational kinetic energy. It is perfect for balancing load, controlling frequency, stabilising the power grid, and facilitating the integration of intermittent renewable energy sources because it allows for quick charge and discharge when combined with power electronic systems. It is a dependable and sustainable option for contemporary grid applications owing to its high efficiency, extended cycle life, and quick response.

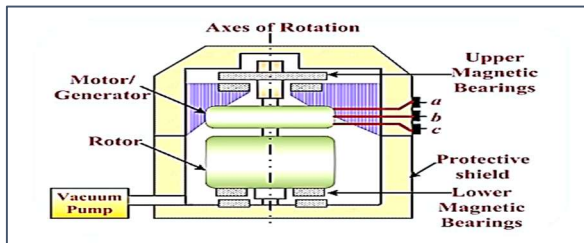


Figure 12: Functional diagram of a flywheel (Tan *et al.*, 2021)

- Pumped hydro storage (PHS) system shown in Figure 13 uses a pump to move water from a lower reservoir to an upper reservoir to store water during excess renewable energy electricity supply. The stored water is released again through the turbine to produce power during periods of high demand. PHS is managed by a power conditioning system, and perfect for grid applications, including load balancing, frequency control, and renewable energy integration, because it provides high efficiency, long-duration storage, and quick response. Power electronics are essential for controlling energy flow and guaranteeing smooth communication between the grid and storage system (Tan *et al.*, 2021).

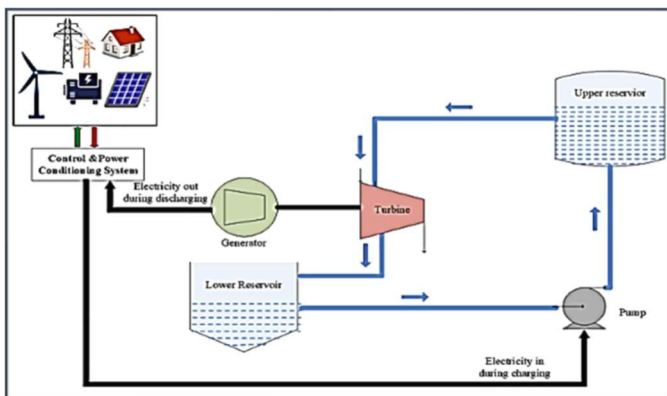


Figure 13: Pumped-hydro energy storage system (Krishan and Suhag, 2019)

- Compressed air energy storage (CAES) system, which stores energy in the form of compressed air, is

shown in Figure 14. This system facilitates PG integration using low- and high-pressure compressors to compress ambient air, which is then stored in an underground tank when there is a surplus of power, usually from renewable sources such as solar or wind. Compressed air is released, heated (either with natural gas or stored heat), and expanded through turbines to power a motor-generator and generate electricity when the demand for electricity increases. The charging and discharging processes are controlled by a central controller and a power conditioning unit. Large-scale, long-duration storage is one way in which CAES improves the grid dependability. When combined with power electronics, it also makes it possible for effective energy conversion, frequency control, and the steady integration of intermittent renewable energy sources into both centralised and decentralised systems (Krishan and Suhag, 2019).

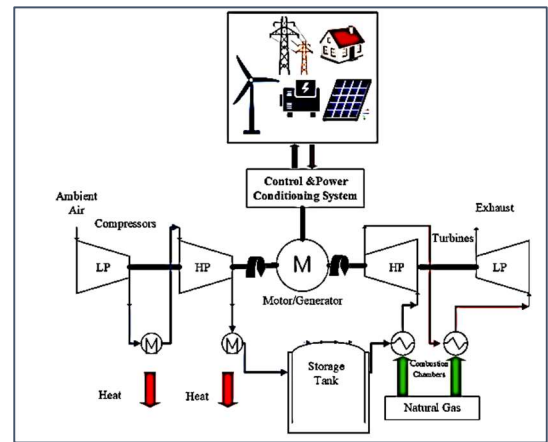


Figure 14: Pumped-hydro energy storage system; (b) Compressed air energy storage system (Krishan and Suhag, 2019)

2. Chemical energy storage systems play an important role in integrating RERs into PG by allowing long-term storage and flexibility. These systems use fuel cells and reversible electrochemical reactions to convert electricity into chemical energy, which can then be dispatch as required. Hydrogen fuel cells (HFCs), for example, generate energy by mixing hydrogen and oxygen, leaving only water as a byproduct. Metal-air fuel cells use metals and ambient oxygen to provide high energy densities, but they have efficiency and lifespan issues. High-temperature technologies such as solid oxide fuel cells and molten carbonate are better suited for industrial application because of their strength and capacity, while microbial fuel cells are also a sustainable alternative, producing power from organic waste under anaerobic conditions, making them useful for decentralised energy systems and wastewater treatment. With suitable power electronics interfaces, these chemical storage technologies may efficiently stabilise voltage and frequency, assist peak shaving, and assure a dependable power supply from intermittent energy sources. They are also suitable for both



ecologically beneficial and ideal grid supports (Revankar, 2019).

3. Electrical energy storage systems use supercapacitors and superconducting magnetic energy storage devices to integrate RERs into PG. The system stores energy in the magnetic fields generated by the superconducting coils, allowing ultrafast energy delivery with minimal losses. It is characterised by a high-power density and the ability to transfer energy instantly while managing intermittent output, improving grid stability, and providing a quick reaction to supply and demand changes. This system is ideal for short-term grid support applications such as voltage control, frequency stabilisation, and regenerative braking. It also has an extended life cycle and a rapid charge/discharge rate. However, the system requires a cryogenic cooling system, which creates complexity in the design and increases the cost, limiting its scalability. Combined with modern power electronic systems, these technologies provide significant assistance in dynamic grid operations and dependable RER integration (Muttaqi *et al.*, 2019).
4. Electrochemical energy storage systems offer flexible, dependable, and scalable solutions to handle the variability and intermittency associated with integrating RERs into the PG. Lithium-ion batteries are among the most widely adopted technology due to their high energy density, rapid response, and modular architecture. However, their application is constrained by safety concerns and high initial costs (Stadler and Sterner, 2018). Sodium-sulphur batteries provide high-capacity, long-duration storage that is ideal for large-scale grid applications, particularly for balancing peak demands. Vanadium redox flow batteries are characterized by their independent scaling of energy and power, extended cycle life, and deep discharge capability, especially valuable for grid stabilization, renewable energy time-shifting, and load management (Rana *et al.*, 2023). As summarised in Table 3, these energy storage technologies work together to make the power grid more robust and efficient by allowing for the smooth integration of variable RERs.
5. Thermal Energy Storage (TES) systems supplement electrical energy storage in RER integration by allowing excess electricity to be converted into heat or cold for later use, particularly in residential, commercial, and industrial environments. Sensible heat storage, which uses materials such as water or rocks, is less expensive but has a poor energy density. Latent heat storage uses phase-change materials to achieve a higher energy density and stable thermal output during transitions, whereas thermochemical storage systems provide the highest energy capacity and long-duration storage via reversible chemical reactions, making them suitable for large-scale applications. Although TES does not directly store electricity, its strategic integration with other

electrical storage systems (such as batteries and supercapacitors) improves grid flexibility, aids demand-side management and enables sector coupling during PG operations. As part of a diverse energy storage portfolio, TES helps boost RER utilisation, reduce peak load, and improve overall grid efficiency in the transition to a low-carbon, resilient energy system (Sarbu and Sebarchievici, 2018).

## VI. POWER GRID DISTRIBUTION

Power grid distribution plays a crucial role in managing and delivering energy from integrated RERs to end users. While energy storage systems help balance generation variability, the distribution networks ensure the seamless flow and coordinated flow of energy across the grid. An effective and smart distribution network is crucial for maximising the use of renewable energy, ensuring grid stability, reducing transmission losses, and supporting a flexible and sustainable energy system. This section delves into the primary functions and innovations that improve grid distribution as the integration of RER increases.

### A. Frequency Regulation

Variations in the electrical power output of the RER cause fluctuations in the frequency of the power generated in the system (Morren *et al.*, 2006). The system must have area control, which is the ability of grid-connected utilities to prevent unplanned transfers of power between themselves and neighbouring utilities, and frequency-responsive reserve denotes the ability of isolated utilities to conform continuously to the frequency standard (Parker, 2009). Frequency regulators are installed in electrical storage systems to supply active power to offending utilities and drop the control loop in the system (Guerrero *et al.*, 2010). Primary, secondary, and tertiary frequency regulation strategies have been developed using centralised, decentralised, and distributed control systems for renewable energy-integrated PG (Guerrero *et al.*, 2012).

### B. Voltage Control

Sustaining the voltage within standardised grid limits is crucial for the stability of power grid distribution in RER integration. Regulatory agencies require that the voltages at the generation and load centres along the transmission and distribution networks remain within a specific range. High voltages are rarely a concern because suitable voltages are maintained at the generation facilities through voltage regulation. Low voltages are prevalent on long distribution lines and typically occur at large distances from generation facilities. To overcome these difficulties, power generation is frequently expanded using the nearest resources (Parker, 2009). The system must have localised reactive power support, functioning as distributed resources because voltage control over long distances is impractical (Rebours *et al.*, 2007). Therefore, Weighted Consensus Control (WCC) and Dynamic Consensus Control (DCC) are used alongside distributed and coordinated control systems to minimise voltage deviations.

Table 3: Types of Electrochemical energy storage systems (Rana *et al.*, 2023; Rana *et al.*, 2022)

Battery	Capacity (MWh)	Lifespan (Years)	Efficiency (%)	Uses	Limitations
Lead-acid battery	0.25 - 50	≤ 20	85-90	Load levelling, peak shaving, and spinning reserve	Poor weight-to-energy ratio. Non-environmentally friendly. Thermal instability due to overcharging.
Nickel-cadmium battery	Nil	Around 10	70-90	Single grid operation, and frequency regulation.	Relatively lower specific storage. Toxic element
Nickel metal hydride battery	Nil	Around 5	65-85	Peak shaving, and isolated grid operation	Complex discharge algorithm. Exothermic Charging
Lithium-ion battery	0.25 - 25	≤ 15	87-92	Peak Shaving, enhanced Power rating, frequency control, and large-storage implementation	High initial cost. Long time to full charging
Sodium sulfur battery	≤ 300	≤ 15	75-85.	Peak shaving, improved power rating, and grid integration	High temperature operation.
Vanadium redox flow battery	≤ 250	≤ 20	75-80	Time shifting, peak shaving, frequency regulation, and improvement power rating	Lower weight-to-energy ratio. Complex battery design

### C. Spinning Reserve

The spinning reserve is a redundant energy source synchronized with the grid system to compensate for energy shortfalls. The spinning generator was designed to generate power at the same frequency as the grid power, enabling a quick switch-on to handle additional loads or compensate for unexpected generator losses owing to machine failures, thereby preventing system instability and potential trip-offs (Parker, 2009).

### D. Power Quality Improvement

Imbalances and fluctuations in energy generation and distribution can degrade power quality. Power quality can be maintained by isolating power surge-sensitive loads from voltage disturbances and power outages. This can be mitigated by smoothing the variations and reducing harmonic distortions. Methods such as unit commitment simulations, discrete Kalman filtering, and various control techniques have been used to maintain the optimal power quality and protect system components (Parker, 2009).

## VII. POTENTIAL CHALLENGES IN RERs INTEGRATION

The integration of RER into PG presents significant challenges, necessitating changes in power system planning and operation that consider both reliability and economic constraints. Large-scale storage must also be incorporated to satisfy peak load demands. Weather conditions, seasonal variations, and geographical variables can cause fluctuations in renewable energy generation. Advanced forecasting models, AI-driven analytics, and grid-balancing approaches are required for improved integration (Bloomfield et al., 2022; Mohd et al., 2008).

### A. Variability and Forecasting Limitations

The integration of RERs into smart grids presents considerable challenges owing to the variability in renewable energy generation, such as fluctuations in solar and wind power, which affect forecasting and system planning (Bloomfield et al., 2022). Owing to the unpredictable nature of these resources, comprehensive forecasting models are required to accurately predict the energy output and provide reliable power delivery data. However, these models are frequently limited by data discrepancies, environmental uncertainty, and the necessity for specialised management strategies for various storage and generation components (Jarmuda and Putz, 2011; Nakamoto and Eguchi, 2024). Furthermore, integrating large-scale storage systems, optimising power flow, and addressing concerns such as voltage fluctuations, harmonic distortion, and system stability pose additional challenges. Despite continued research into adaptive techniques, tackling these problems remains vital to enable efficient and cost-effective RER integration into the grid while ensuring system stability and security (Qu et al., 2025).

### B. Grid Stability and Power Quality Issues

Incorporating RERs into power systems poses considerable challenges due to issues related to grid stability and power quality (S. S. Kumar et al., 2025; Xing et al., 2013). Voltage and frequency fluctuations undermine grid stability, leading to power quality issues such as voltage dips, harmonic distortion, and frequency imbalances, all of which negatively impact the reliability and efficiency of power transmission (Krishan and Suhag, 2019). To address these challenges, advanced control technologies like energy storage systems, flexible PE, and MPPT are essential for optimising the output of renewable power and minimizing fluctuations (Nusrat et al., 2024).

MPPT algorithms assist in extracting the maximum power from RERs, thereby enhancing energy consistency. Effective coordination among generation, storage, and distribution systems is vital for maintaining grid quality and ensuring a stable and reliable energy supply (Hassan *et al.*, 2024; Zafar *et al.*, 2013).

### C. Energy Storage and Management Constraints

Technological constraints in energy storage systems hinder the widespread adoption of RERs. The intermittent nature of these resources complicates energy storage during resource integration, requiring adaptable and responsive systems that can adjust to load fluctuations. Hence the need for sophisticated algorithms to manage charge-discharge scheduling, load balancing, and real-time dispatch to ensure grid stability and efficient energy management. These advanced controls are essential to address technical challenges related to efficiency, lifespan, and response time. Additional barriers to adoption include physical and environmental limitations, especially in densely populated areas or regions with insufficient infrastructure (Kumi, 2023; Raza *et al.*, 2024).

### D. Economic and Regulatory Barriers

The integration of RERs into smart grids is impeded by economic and regulatory constraints. The high initial costs of renewable energy technologies and energy storage devices can limit investment, particularly in developing nations with limited financial resources (Dawn *et al.*, 2024). This financial burden is further compounded by the cost of maintaining and modernising the grid infrastructure to accommodate the peculiarity of RERs (ur Rehman *et al.*, 2024). Regulatory challenges include obsolete policies and regulations that fail to account for the unique characteristics of renewable energy, such as intermittency of the resources, and peculiar requirement for flexible grid management. In many regions, established methods for connecting distributed energy resources to the grid are lacking, and grid operators may encounter difficulties in delivering incentives for renewable energy generation and storage (Mishra *et al.*, 2024; Raza *et al.*, 2024). Furthermore, subsidies and established investments in fossil fuel-based energy sources may create a financial imbalance, making it difficult for RERs to compete equally. To overcome these impediments, extensive policy reforms, financial incentives, and investment in grid modernisation are necessary to encourage a more sustainable and economically feasible energy transition (Aslam *et al.*, 2024; Chandak and Rout, 2021; ur Rehman *et al.*, 2024).

### E. Cybersecurity and Digital Infrastructure Risks

Cybersecurity and digital infrastructure risks are becoming concerns, as RERs are increasingly integrated into smart grids. The reliance on digital technologies, including communication networks, smart meters, and control systems, exposes power grids to potential cyber threats, such as hacking, data intrusion, and system manipulation (Yaacoub *et al.*, 2024). These vulnerabilities can compromise grid stability, disrupt energy distribution, and cause financial or physical damage to critical infrastructure. In addition, the complexity of managing

decentralised energy resources, along with the increasing use of automation and remote monitoring, creates potential entry sites for cyber-attacks. The need for comprehensive cybersecurity measures is amplified by the need to ensure secure communication between distributed energy sources, storage systems, and grid operators (Ohanu *et al.*, 2024). As smart grids evolve, protecting the digital infrastructure against evolving cyber threats requires continuous monitoring, strong encryption protocols, and the development of resilient systems that can rapidly detect and respond to cyberattacks. Securing digital infrastructure is essential for maintaining the integrity, reliability, and safety of power grids in the face of increasing cyber risks (Kumar *et al.*, 2020).

### F. Impact on Fossil Fuel-Based Power Plants

The incorporation of renewable energy sources into the electrical grid has a considerable effect on fossil fuel power plants (Azzi *et al.*, 2015; Timpe *et al.*, 2010). As RERs increase, the need for fossil fuel-based electricity diminishes, and the use of unreliable RER may result in inefficiency within the system. The transition to renewable energy may also affect the profitability of fossil fuel plants, making them less competitive in a market where renewables offer environmental benefits and lower operational costs (Babatunde *et al.*, 2019). This may lead to plant shutdowns or costly changes that improve production and reduce emissions. Despite these pressures, fossil fuel facilities continue to play a critical role in maintaining grid stability by supplying backup power when renewable energy is uncertain. The energy market is evolving, and fossil fuel businesses must adapt by providing complementary services, such as grid balancing and storage, to support renewable energy systems. This development raises concerns about job losses and economic ramifications in areas that are heavily reliant on fossil fuel sectors, underscoring the need for legislative support to facilitate worker transition and retraining (Azzi *et al.*, 2015; Babatunde *et al.*, 2019).

## VIII. Case Studies on Integrated RERs into PG

The prospects of integrating RERs into power networks demonstrate the benefits and challenges of shifting to cleaner energy systems. This is a promising solution for energy inefficiency and carbon emissions. It integrates distributed generation, energy storage, and modern control systems to enhance reliability, reduce transmission losses, and promote sustainability. These case studies have demonstrated their practical applications, highlighting their benefits and drawbacks, promoting energy resilience and environmental sustainability (Kataray *et al.*, 2023).

### A. Smart PG System in South Africa

South Africa is developing smart PG technology to enhance energy sustainability, particularly in regions that experience power outages or lack grid connectivity (Nkambule *et al.*, 2025). Notable projects include the Johannesburg Solar PG Pilot, which provides electricity to 500 residences in Alexandra Township; the hybrid photovoltaic-diesel PG at the University of the Free State's QwaQwa campus; and a 900 kW solar plant in Orania, equipped with a 4.8 MWh battery storage system. Likewise, the Durban International Convention Centre

is exploring PG technology through the integration of renewable energy and storage solutions to improve sustainability and energy efficiency. In KwaZulu-Natal and the Eastern Cape, initiatives aimed at rural electrification that harnesses RERs, such as solar, wind, and biogas, to enhance electricity access (Ayamolowo *et al.*, 2022). These technologies aim to reduce reliance on national utilities and mitigate the effects of regional rolling blackouts (Adefarati and Bansal, 2019). The microgrid projects are financially and environmentally feasible, with a strong internal rate of return of 23.1%, a competitive blended cost of energy of \$0.073/kWh, and a levelised cost of energy of \$0.186/kWh, which are significantly lower than the current Eskom grid prices. With a low payback period of 5.5 years, these systems can save up to 1,135,950 tonnes of CO<sub>2</sub> emissions over a 30-year lifespan, thereby meeting national and global economic and climate energy objectives (Nkambule *et al.*, 2025).

#### B. Smart Dust Module for Sustainable Energy Harvesting in Taiwan

A self-sustaining smart dust module with embedded flexible triple-junction III-V solar cells was developed in Taiwan to boost energy efficiency. This study showed that the dust module could support continuous-wave operation for data collection and wireless transmission, even when the incident angle of sunlight exceeded 75°. This emphasises the feasibility of incorporating advanced solar technologies into PG systems to generate sustainable electricity (Kataray *et al.*, 2023). This module reduces reliance on fossil fuel-powered electricity, lowers operational costs, and increases energy autonomy. The small design, which takes up 40% less space than silicon-based alternatives, saves materials and allows for scalable deployment. Environmentally, these modules offer continuous monitoring and data transfer for grid optimisation, boosting energy efficiency, minimising waste, and assisting with the transition to low-carbon, intelligent energy systems (Liu *et al.*, 2022).

#### C. Rooftop Solar PV System in Puducherry, India

The Government of India invested in the development and installation of a rooftop solar PV system in Puducherry, India, as part of its policy on renewable energy resource generation and integration into smart grids. A total of 400 rooftop PV systems were installed, collectively generating approximately 2 MW of power, which significantly reduced energy expenses for consumers. Depending on the usage patterns and system size, electricity savings range from 20% to 40%. In addition, the decentralised setup minimised the transmission and distribution losses and enhanced the reliability of electricity in the region. The Puducherry project also offered notable environmental benefits; the systems cut CO<sub>2</sub> emissions by more than 2,700 metric tons annually, equivalent to removing nearly 600 cars from roads (Rathore *et al.*, 2019). This research demonstrates both economic and environmental advantages while enhancing sustainable energy access in the urban and semi-urban areas of India (Kataray *et al.*, 2023).

#### D. Frequency and Power Balancing in Isolated PG in Turkey

Coban *et al.* (2022) examined the frequency and power balance of an isolated PG with battery and pump-hydro storage in Turkey, incorporating both battery and pumped-hydro energy storage systems. Their study emphasised the critical role of energy storage in mitigating the variability of wind and solar generation, ensuring that supply consistently meets demand, and supporting frequency regulation to maintain grid stability. Researchers have optimised a proportional-integral controller using real-time wind and solar data. The integration of hydroelectric storage over 24 hours cycle showed improved system performance and reliability. During peak evening hours, the stored renewable energy met the entire demand until 23:00, thereby eliminating the need for diesel generators. This not only reduced operational costs but also significantly cut carbon emissions. Additionally, energy storage is charged during periods of low-cost excess generation and discharged during peak demand, ensuring cost-effective and environmentally sustainable energy delivery. Optimised PI control further minimises losses and reinforces the resilience and efficiency of the smart grid (Kataray *et al.*, 2023).

#### E. Solar PV Integration with Utility Grids in Kinshasa, DR Congo

A study on the solar power potential of suitable sites for photovoltaic (PV) power plant development in Kinshasa, Democratic Republic of the Congo, revealed that integrating PV panels with a 5° tilt angle, combined with battery banks connected to the utility grid, significantly enhanced power stability. The tilt angle was found to optimise the solar exposure, thereby improving the annual energy generation. However, as the PV penetration exceeds 30%, concerns regarding grid stability become more prominent. Advanced technologies, such as battery energy storage systems and static synchronous compensators, are essential to mitigate these challenges and ensure reliable power delivery (Kataray *et al.*, 2023). At 20% PV penetration, active power losses are minimised by up to 25%, resulting in operational cost savings and possible reductions in electricity rates of 12-18%. This integration has the potential to reduce CO<sub>2</sub> emissions by 0.92 million tonnes per year, contributing to climate goals. The findings highlight the economic and environmental benefits of solar integration in vulnerable power systems, as well as the need for poor countries to transition to cleaner, more affordable energy (Kiangebeni Lusimbakio *et al.*, 2025).

#### F. PV-Plus-Storage PG for Public Buildings in California

The economic and environmental advantages of replacing diesel backup generators with PV-plus-storage PG in public buildings in California have been explored. They used an energy integration and optimisation model to build a marginal resilience curve which assesses the cost and environmental impacts of extended outages. The analysis concluded that replacing diesel backup generators in a single building may save \$3 million in public expenditure and reduce CO<sub>2</sub> emissions over 20 years. Applying this concept across California's 22 air districts may result in annual savings of \$31 million to \$385 million. The study also found that increasing the energy storage capacity delivers larger resilience benefits



than adding PV or generator capacity, while reducing costs and emissions (Hwang *et al.*, 2023; Kataray *et al.*, 2023).

### G. Case Study of Reducing Carbon Emissions during COVID

Transitioning to renewable-based PG is crucial for achieving a carbon-neutral society and reducing the effects of climate change. During the COVID-19 pandemic in 2020-2021, global carbon emissions recorded a temporary decline due to widespread lockdowns and reduced industrial activity. However, emissions have been increasing as economies have recovered. Achieving the target of limiting the temperature increase below 2°C involves continued investment and technological advancements in renewable energy sources. Governments must prioritise financial and regulatory support to introduce PG systems into non-residential sectors, which account for almost 65% of global emissions. Enhancing the efficiency and scalability of PG systems will accelerate the shift to clean energy, boost economic sustainability, and contribute to long-term emission reductions (Kataray *et al.*, 2023).

### IX. CONCLUSION

The growing global demand for sustainable energy solutions necessitates the integration of RERs into the current PG infrastructure. This review emphasises the critical importance of solar, wind, hydro, geothermal, bioenergy, and marine energy, while also addressing the challenges posed by the intermittent and weather-dependent nature of RERs, such as variations in solar radiation, wind speed changes, and seasonal hydropower availability, which complicate the maintenance of a stable power supply. The integration of RERs into PG has been significantly advanced by the development of PE converters and energy storage systems EES, which enable the efficient management, conditioning, and distribution of variable power outputs. This progress is facilitated by the development of wide-bandgap semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), which are known for their thermal efficiency and high-frequency operation, resulting in improved performance in PG integration.

Case studies demonstrated the advantages of incorporating RERs into PG. For example, in South Africa, the integration of solar and battery storage in microgrid projects has reduced the risk of power outages, provided competitive energy pricing, and decreased CO<sub>2</sub> emissions by over a million tons. Taiwan's smart dust module, using III-V solar cells, represents a compact solar innovation for low-carbon power generation systems. In India, the adoption of rooftop solar PV in Puducherry has significantly reduced both emissions and electricity costs. Turkey has shown that battery and hydro storage systems, optimized through proportional-integral (PI) control, can maintain frequency stability in isolated grids. The Democratic Republic of the Congo's integration of solar PV with grid-connected batteries has increased energy production while reducing emissions by nearly one million tonnes annually. In California, PV-plus storage systems for public buildings have demonstrated economic and environmental benefits over diesel backup solutions. These examples

collectively highlight the essential role of enhanced PE in expanding smart, efficient, and resilient renewable energy systems worldwide.

To fully harness the potential of RERs, it is crucial to consistently invest in PE research and the development of smart grid infrastructure. Aligning policies, enhancing skills, and adapting technology to specific regions is vital for accelerating deployment, lowering energy costs, and creating inclusive low-carbon energy systems. Through ongoing interdisciplinary collaboration, RERs supported by advanced power electronics can drive a future that is both environmentally sustainable and economically robust.

### AUTHOR CONTRIBUTIONS

**T.A. Ayorinde:** Conceptualization, Methodology, Writing – original draft, Writing – review and editing. **T. Jamiru:** Supervision, Funding acquisition, Writing – review and editing. **P.F. Le Roux:** Supervision, Funding acquisition, Writing – review and editing.

### DECLARATION OF COMPETING INTEREST

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.

### ACKNOWLEDGEMENT

We appreciate the support of Tshwane University of Technology, South Africa,

### REFERENCES

- Adefarati, T. and Bansal, R. C. (2019).** Application of renewable energy resources in a microgrid power system. *The Journal of Engineering*, 2019(18), 5308-5313.
- Akintunde, S. B., Adio, S. A., Daniyan, A. A., Muritala, A. O., Oladejo, K. A., Azeez, S. O., . . . Aladesanmi, T. Ayorinde, T.A. (2025).** Numerical and experimental studies on combustion of Hura crepitans biodiesel-diesel blends in a compression ignition (CI) engine. *Thermal Advances*, 2, 100012.
- Aliyu, A. K., Modu, B. and Tan, C. W. (2018).** A review of renewable energy development in Africa: A focus in South Africa, Egypt and Nigeria. *Renewable and Sustainable Energy Reviews*, 81, 2502-2518.
- Amirpour, S. M. (2025).** Refining Electric Powertrain Efficiency: SiC vs. Si Semiconductor, Thermal Solutions, and Optimal Power Conversion Strategies.
- Aslam, M. M., Lateef, U., Khalid, Z., Saleem, U., Liu, W. and Li, W. (2024).** *Energy Management in Smart Grids: Innovative Solutions for Demand-Side Optimization Considering Control Constraints*. Paper presented at the 2024 3rd International Conference on Emerging Trends in Electrical, Control, and Telecommunication Engineering (EETECTE).
- Amamolowo, O. J., Manditereza, P. and Kusakana, K. (2022).** South Africa power reforms: The Path to a dominant renewable energy-sourced grid. *Energy Reports*, 8, 1208-1215.

- Ayorinde, A. T. (2024).** Mathematical modelling of a kenaf harvester. *Agricultural Engineering International: CIGR Journal*, 26(2).
- Ayorinde, T. A. and Olasebikan, Y. O. (2020a).** Renewable Energy Source Adoption. In S. N. S. A. 2020 (Ed.), *Affordable and Clean Energy*: Springer, Cham.
- Ayorinde, T. A. and Olasebikan, Y. O. (2020b).** Renewable Energy Source Adoption. 1-11. doi:10.1007/978-3-319-71057-0\_33-1
- Ayorinde, T. A. and Olasebikan, Y. O. (2021).** Renewable Energy Source Adoption. In *Affordable and Clean Energy* (pp. 1075-1085): Springer.
- Azzi, M., Duc, H. and Ha, Q. (2015).** Toward sustainable energy usage in the power generation and construction sectors—a case study of Australia. *Automation in Construction*, 59, 122-127.
- Babatunde, O., Munda, J. and Hamam, Y. (2019).** Decarbonisation of electricity generation: Efforts and challenges. *Carbon Footprints: Case Studies from the Energy and Transport Sectors*, 47-77.
- Balkas, E. (2024).** *Revolutionizing Power Electronics with Silicon Carbide to Pioneer Sustainable Solutions*. Paper presented at the 2024 IEEE International Electron Devices Meeting (IEDM).
- Behura, A. K., Kumar, A., Rajak, D. K., Pruncu, C. I. and Lamberti, L. (2021).** Towards better performances for a novel rooftop solar PV system. *Solar Energy*, 216, 518-529.
- Bhatia, S. and Bhatia, S. (2014).** Geothermal power generation. *Advanced renewable energy systems*, edited by: Bathia, S.C, Woodhead Publishing India, 334-388.
- Bhattacharjee, S. (2021).** Wind power technology. In *Sustainable Fuel Technologies Handbook* (pp. 123-170): Elsevier.
- Bilgen, S. (2014).** Structure and environmental impact of global energy consumption. *Renewable and Sustainable Energy Reviews*, 38, 890-902.
- Blaabjerg, F. and Ma, K. (2017).** Wind energy systems. *Proceedings of the IEEE*, 105(11), 2116-2131.
- Blewett, D. (2023).** Wind turbine cost: How much? Are they worth it in 2022? *Weather Guard Lightning Tech*.
- Bloomfield, H., Brayshaw, D. J., Shaffrey, L., Coker, P. J. and Thornton, H. E. (2018).** The changing sensitivity of power systems to meteorological drivers: a case study of Great Britain. *Environmental Research Letters*, 13(5), 054028.
- Bloomfield, H. C., Wainwright, C. M. and Mitchell, N. (2022).** Characterizing the variability and meteorological drivers of wind power and solar power generation over Africa. *Meteorological Applications*, 29(5), e2093.
- Chakraborty, A., Ganguly, R. and Mitra, M. (2025).** *Non-Invasive Junction Temperature Measurement Using Forward Voltage Drop of High-Power pLED Under Tropical Conditions*. Paper presented at the 2025 8th International Conference on Electronics, Materials Engineering and Nano-Technology (IEMENTech).
- Chandak, S. and Rout, P. K. (2021).** The implementation framework of a microgrid: A review. *International journal of energy research*, 45(3), 3523-3547.
- Coban, H. H., Rehman, A. and Mousa, M. (2022).** Load frequency control of microgrid system by battery and pumped-hydro energy storage. *Water*, 14(11), 1818.
- Conway, D., Dalin, C., Landman, W. A. and Osborn, T. J. (2017).** Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption. *Nature Energy*, 2(12), 946-953.
- Dawn, S., Ramakrishna, A., Ramesh, M., Das, S. S., Rao, K. D., Islam, M. M. and Selim Ustun, T. (2024).** Integration of renewable energy in microgrids and smart grids in deregulated power systems: a comparative exploration. *Advanced Energy and Sustainability Research*, 5(10), 2400088.
- Díaz, H. and Soares, C. G. (2020).** Review of the current status, technology and future trends of offshore wind farms. *Ocean Engineering*, 209, 107381.
- Ejuh Che, E., Roland Abeng, K., Iweh, C. D., Tsekouras, G. J. and Fopah-Lele, A. (2025).** The Impact of Integrating Variable Renewable Energy Sources into Grid-Connected Power Systems: Challenges, Mitigation Strategies, and Prospects. *Energies*, 18(3), 689.
- Ellabban, O., Abu-Rub, H. and Blaabjerg, F. (2014).** Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, 39, 748-764. doi:10.1016/j.rser.2014.07.113
- Gong, X. and Qiao, W. (2013).** Bearing fault diagnosis for direct-drive wind turbines via current-demodulated signals. *IEEE transactions on industrial electronics*, 60(8), 3419-3428.
- Guerrero, J. M., Loh, P. C., Lee, T.-L. and Chandorkar, M. (2012).** Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids. *IEEE transactions on industrial electronics*, 60(4), 1263-1270.
- Guerrero, J. M., Vasquez, J. C., Matas, J., De Vicuña, L. G. and Castilla, M. (2010).** Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. *IEEE transactions on industrial electronics*, 58(1), 158-172.
- Güney, M. (2015).** Wave energy conversion systems. *Journal of Naval Sciences and Engineering*, 11(2), 25-51.
- Hassan, M. A., Adel, M. M., Saleh, A. A., Eteiba, M. B. and Farhan, A. (2024).** Maximum Power Point Tracking Based on Finite Voltage-Set MPC for Grid-Connected Photovoltaic Systems Under Environmental Variations. *Sustainability*, 16(23), 10317.
- Hwang, S., Tongsopit, S. and Kittner, N. (2023).** Transitioning from diesel backup generators to PV-plus-storage microgrids in California public buildings. *Sustainable Production and Consumption*, 38, 252-265.
- Jarmuda, T. and Putz, L. (2011).** Intelligent building and smart grid integration of renewable energy sources on the basis of computer simulations. *Poznan University of Technology Academic Journals. Electrical Engineering*, 171-184.

- Kan, H. (2022).** World Health Organization air quality guidelines 2021: implication for air pollution control and climate goal in China. *Chinese Medical Journal*, 135(5), 513-515.
- Kataray, T., Nitesh, B., Yarram, B., Sinha, S., Cuce, E., Shaik, S., . . . Roy, A. (2023).** Integration of smart grid with renewable energy sources: Opportunities and challenges—A comprehensive review. *Sustainable Energy Technologies and Assessments*, 58, 103363.
- Kiangebeni Lusimbakio, K., Boketsu Lokanga, T., Sedi Nzakuna, P., Paciello, V., Nzuru Nsekere, J.-P. and Tshimanga Tshipata, O. (2025).** Evaluation of the Impact of Photovoltaic Solar Power Plant Integration into the Grid: A Case Study of the Western Transmission Network in the Democratic Republic of Congo. *Energies*, 18(3), 639.
- Klass, D. L. (2004).** Biomass for renewable energy and fuels. *Encyclopedia of energy*, 1(1), 193-212.
- Krishan, O. and Suhag, S. (2019).** An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources. *International Journal of Energy Research*, 43(12), 6171-6210.
- Kumar, D. and Zare, F. (2019).** A comprehensive review of maritime microgrids: System architectures, energy efficiency, power quality, and regulations. *Ieee Access*, 7, 67249-67277.
- Kumar, N. M., Chand, A. A., Malvoni, M., Prasad, K. A., Mamun, K. A., Islam, F. and Chopra, S. S. (2020).** Distributed energy resources and the application of AI, IoT, and blockchain in smart grids. *Energies*, 13(21), 5739.
- Kumar, S. S., Srinivasan, C. and Balavignesh, S. (2025).** Enhancing Grid Integration of Renewable Energy Sources for Micro grid Stability using Forecasting and Optimal Dispatch Strategies. *Energy*, 135572.
- Kumi, E. N. (2023).** Energy storage technologies. In *Pumped hydro energy storage for hybrid systems* (pp. 1-21): Elsevier.
- Leonard, M. D., Michaelides, E. E. and Michaelides, D. N. (2020).** Energy storage needs for the substitution of fossil fuel power plants with renewables. *Renewable Energy*, 145, 951-962.
- Liu, C.-Y., Huang, C.-K., Huang, Y.-Y., Chang, K.-C., Yu, K.-L., Chiang, C.-H., . . . Sheu, J.-K. (2022).** Flexible multijunction solar cells embedded inside smart dust modules for outdoor applications to Smart Grids. *Applied Energy*, 306, 117970.
- Lundqvist, A. (2020).** Future development of bioenergy in South Africa: a study of increased use of available biomass for the future development of renewable energy in South Africa. In.
- Mahapatra, A., Kumar, S., Kumar, P. and Pradhan, B. (2022).** Recent progress in perovskite solar cells: challenges from efficiency to stability. *Materials Today Chemistry*, 23, 100686.
- Makola, C. S., Le Roux, P. F. and Jordaan, J. A. (2023).** Comparative analysis of lithium-ion and lead–acid as electrical energy storage systems in a grid-tied microgrid application. *Applied Sciences*, 13(5), 3137.
- Mathivha, F. I., Mabala, L., Matimolane, S. and Mbatha, N. (2024).** El Niño-induced drought impacts on reservoir water resources in South Africa. *Atmosphere*, 15(3), 249.
- Mauk, M., Chiou, R., Narkeviciute, I. and Head, G. (2017).** Sustainable energy education: biofuels from solar-powered algae cultures. *Association for Engineering Education-Engineering Library Division Papers*.
- Mishra, D. P., Gaur, A. P., Rai, Y. K. and Salkuti, S. R. (2024).** Smart Grid and Energy Management Systems: A Global Perspective. In *Energy and Environmental Aspects of Emerging Technologies for Smart Grid* (pp. 629-649): Springer.
- Mohd, A., Ortjohann, E., Schmelter, A., Hamsic, N. and Morton, D. (2008).** *Challenges in integrating distributed energy storage systems into future smart grid*. Paper presented at the 2008 IEEE international symposium on industrial electronics.
- Moriarty, P. and Honnery, D. (2019).** Global renewable energy resources and use in 2050. In *Managing global warming* (pp. 221-235): Elsevier.
- Morren, J., De Haan, S. W., Kling, W. L. and Ferreira, J. (2006).** Wind turbines emulating inertia and supporting primary frequency control. *IEEE Transactions on power systems*, 21(1), 433-434.
- Morton, S., Pencheon, D. and Bickler, G. (2019).** The sustainable development goals provide an important framework for addressing dangerous climate change and achieving wider public health benefits. *Public Health*, 174, 65-68.
- Muttaqi, K. M., Islam, M. R. and Sutanto, D. (2019).** Future power distribution grids: Integration of renewable energy, energy storage, electric vehicles, superconductor, and magnetic bus. *IEEE Transactions on Applied Superconductivity*, 29(2), 1-5.
- Nakamoto, Y. and Eguchi, S. (2024).** How do seasonal and technical factors affect generation efficiency of photovoltaic power plants? *Renewable and Sustainable Energy Reviews*, 199, 114441.
- Nikolaidis, P., and Poullikkas, A. (2017).** A comparative review of electrical energy storage systems for better sustainability. *Journal of power technologies*, 97(3).
- Nkambule, M. S., Hasan, A. N. and Shongwe, T. (2025).** Analyzing the Economic Viability of Microgrid Solutions in the South African Market. *Ieee Access*.
- Nowsherwan, G. A., Ali, Q., Nowsherwan, N., Ali, U. F. and Hussain, S. S. (2025).** Performance and stability improvements in MAPbI<sub>3</sub> perovskite photovoltaics with CsPbI<sub>3</sub> quantum dots. *Multiscale and Multidisciplinary Modeling, Experiments and Design*, 8(1), 10.
- Nusrat, M., Mekhilef, S., Mubin, M., Ahmed, S., Seyedmahmoudian, M., Stojcevski, A. and Alshammari, O. (2024).** Advancements in flexible power point tracking and power control strategies for photovoltaic power plants: A comprehensive review. *Energy Reports*, 12, 237-250.
- Ogundipe, O. B., Okwandu, A. C. and Abdulwaheed, S. A. (2024).** Recent advances in solar photovoltaic technologies: Efficiency, materials, and

applications. *GSC Advanced Research and Reviews*, 20(1), 159-175.

**Ohanu, C. P., Rufai, S. A. and Oluchi, U. C. (2024).** A comprehensive review of recent developments in smart grid through renewable energy resources integration. *Heliyon*, 10(3).

**Ohba, M., Kanno, Y. and Bando, S. (2023).** Effects of meteorological and climatological factors on extremely high residual load and possible future changes. *Renewable and Sustainable Energy Reviews*, 175, 113188.

**Ohunakin, O. S., Adaramola, M. S., Oyewola, O. M. and Fagbenle, R. O. (2014).** Solar energy applications and development in Nigeria: Drivers and barriers. *Renewable and Sustainable Energy Reviews*, 32, 294-301.

**Parker, C. D. (2009).** APPLICATIONS – STATIONARY | Energy Storage Systems: Batteries. In Jürgen Garche (Ed.), *Encyclopedia of Electrochemical Power Sources* (pp. Pages 53-64): Elsevier.

**Pegels, A. (2010).** Renewable energy in South Africa: Potentials, barriers and options for support. *Energy policy*, 38(9), 4945-4954.

**Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., . . . Möller, V. (2022).** IPCC 2022: Climate Change 2022: impacts, adaptation and vulnerability: working group II contribution to the sixth assessment report of the intergovernmental panel on climate change.

**Qu, R., Kou, R. and Zhang, T. (2025).** The Impact of Weather Variability on Renewable Energy Consumption: Insights from Explainable Machine Learning Models. *Sustainability*, 17(1), 87.

**Rana, M. M., Uddin, M., Sarkar, M. R., Meraj, S. T., Shafiullah, G., Muyeen, S., . . . Jamal, T. (2023).** Applications of energy storage systems in power grids with and without renewable energy integration—A comprehensive review. *Journal of energy storage*, 68, 107811.

**Rana, M. M., Uddin, M., Sarkar, M. R., Shafiullah, G., Mo, H. and Atef, M. (2022).** A review on hybrid photovoltaic–Battery energy storage system: Current status, challenges, and future directions. *Journal of energy storage*, 51, 104597.

**Rasul, A., Teixeira, R. and Baptista, J. (2025).** Silicon Carbide Converter Design: A Review. *Energies*, 18(8), 2140.

**Rathore, P. K. S., Chauhan, D. S. and Singh, R. P. (2019).** Decentralized solar rooftop photovoltaic in India: On the path of sustainable energy security. *Renewable energy*, 131, 297-307.

**Raza, A., Liaqat, M., Adnan, M., Iqbal, M. S., Jingzhao, L. and Ahmad, I. (2024).** SAARC super smart grid: Navigating the future—unleashing the power of an energy-efficient integration of renewable energy resources in the saarc region. *Computers and Electrical Engineering*, 118, 109405.

**Rebours, Y. G., Kirschen, D. S., Trotignon, M. and Rossignol, S. (2007).** A survey of frequency and voltage control ancillary services—Part I: Technical features. *IEEE Transactions on power systems*, 22(1), 350-357.

**Revankar, S. T. (2019).** Chemical energy storage. In *Storage and Hybridization of Nuclear Energy* (pp. 177-227): Elsevier.

**Rodriguez, B. and Xydis, G. (2021).** A five-target innovation discussion on low-speed wind turbine system optimization. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1-15.

**Ruin, S. and Sidén, G. (2019).** *Small-Scale Renewable Energy Systems: Independent Electricity for Community, Business and Home*: CRC Press.

**Sahu, S. K., Chacko, S. T., Parmar, O. and Rajput, A. S. (2025).** Wide bandgap Materials: Revitalizing Power Electronics with Advances in Power Semiconductor Devices. *Journal of The Institution of Engineers (India): Series B*, 1-17.

**Santos-Mugica, M., Robles, E., Endegnanew, A. G., Tedeschi, E. and Giehardt, J. (2014).** *Grid integration and power quality testing of Marine Energy Converters: Research Activities in the MARINET project*. Paper presented at the 2014 Ninth international conference on ecological vehicles and renewable energies (EVER).

**Sarbu, I. and Sebarchievici, C. (2018).** A comprehensive review of thermal energy storage. *Sustainability*, 10(1), 191.

**Sathaye, J., Meyers, S., Sathaye, J. and Meyers, S. (1995).** Rangelands and grasslands. *Greenhouse gas mitigation assessment: a guidebook*, 211-226.

**Shahabuddin, M., Alim, M. A., Alam, T., Mofijur, M., Ahmed, S. F. and Perkins, G. (2021).** A critical review on the development and challenges of concentrated solar power technologies. *Sustainable Energy Technologies and Assessments*, 47, 101434.

**Shahzad, S. and Jasińska, E. (2024).** Renewable revolution: A review of strategic flexibility in future power systems. *Sustainability*, 16(13), 5454.

**Singh, R., Gaur, A., Soni, P., Jain, R., Pant, G., Kumar, D., . . . Dehghani, M. H. (2025).** A review of biofuels and bioenergy production as a sustainable alternative: opportunities, challenges and future perspectives. *Journal of Environmental Health Science and Engineering*, 23(2), 23.

**Song, Z., Li, C., Chen, L. and Yan, Y. (2022).** Perovskite solar cells go bifacial—mutual benefits for efficiency and durability. *Advanced materials*, 34(4), 2106805.

**Souza Junior, M. and Freitas, L. (2022).** Power Electronics for Modern Sustainable Power Systems: Distributed Generation, Microgrids and Smart Grids—A Review. *Sustainability* 2022, 14, 3597. In: s Note: MDPI stays neutral with regard to jurisdictional claims in published . . .

**Souza Junior, M. E. T. and Freitas, L. C. G. (2022).** Power electronics for modern sustainable power systems: Distributed generation, microgrids and smart grids—A review. *Sustainability*, 14(6), 3597.

**Stadler, I. and Sterner, M. (2018).** Urban energy storage and sector coupling. In *Urban Energy Transition* (pp. 225-244): Elsevier.

**Tan, K. M., Babu, T. S., Ramachandaramurthy, V. K., Kasinathan, P., Solanki, S. G. and Raveendran, S. K. (2021).** Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. *Journal of energy storage*, 39, 102591.



**Timpe, C., Bauknecht, D., Koch, M. and Lynch, C. (2010).** Integration of electricity from renewable energy sources into European electricity grids. *ETC/ACC Technical Paper, 18*, 2010.

**Twidell, J. (2021).** *Renewable energy resources*: Routledge.

**UpWind, N. (2011).** Design limits and solutions for very large wind turbines. *EWEA, Brussels, Belgium*.

**ur Rehman, A., Iqbal, S., Shafiq, A., Alshammari, N. F., Dar, S. H. and Iqbal, R. T. (2024).** Multifaceted impacts of widespread renewable energy integration on socio-economic, ecological, and regional development. *Sustainable Futures, 8*, 100241.

**Vodovozov, V. and Raud, Z. (2025).** Review of the Present State, Development Trends, and Advancements of Power Electronic Converters Used in Robotics. *Energies, 18*(10), 2638.

**White, C. J., Carlsen, H., Robertson, A. W., Klein, R. J., Lazo, J. K., Kumar, A., . . . Murray, V. (2017).** Potential applications of subseasonal-to-seasonal (S2S) predictions. *Meteorological Applications, 24*(3), 315-325.

enhanced geothermal energy technologies. *Science of The Total Environment, 659*, 851-861.

**Woo, K., Bian, Z., Noshin, M., Martinez, R. P., Malakoutian, M., Shankar, B. and Chowdhury, S. (2024).** From wide to ultrawide-bandgap semiconductors for high power and high frequency electronic devices. *Journal of Physics: Materials, 7*(2), 022003.

**Xing, T. W., Shen, H., Ding, J., Dong, L., Han, J. H. and Song, Y. T. (2013).** Survey of wind power and integration smart grid technologies. *Advanced Materials Research, 614*, 1771-1777.

**Yaacoub, J. P., Noura, H., Azar, J., Salman, O. and Chahine, K. (2024).** *Cybersecurity in Smart Renewable Energy Systems*. Paper presented at the 2024 International Wireless Communications and Mobile Computing (IWCMC).

**Zafar, S., Nawaz, K., Naqvi, S. and Malik, T. (2013).** Integration of renewable energy sources in smart grid: A review. *the Nucleus, 50*(4), 311-327.

**Wilberforce, T., Baroutaji, A., El Hassan, Z., Thompson, J., Soudan, B. and Olabi, A. G. (2019).** Prospects and challenges of concentrated solar photovoltaics and