

Utilization of Existing Electrical Infrastructure for Renewable Energy Deployment

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Abstract—Electricity underpins the functioning of modern societies, driving residential, commercial, industrial, and transportation sectors. Historically, the predominant reliance on fossil fuels—coal, oil, and natural gas—has ensured reliable power generation but at the cost of finite resource depletion and significant greenhouse gas emissions, thereby exacerbating global climate change. The imperative to mitigate these environmental impacts, supported by advances in technology and decreasing costs, has accelerated the adoption of renewable energy sources (RES), including solar, wind, hydropower, biomass, and geothermal energy. Despite their environmental and sustainability advantages, the inherent intermittency and variability of RES introduce substantial challenges to their seamless integration into conventional power grids. Addressing these challenges necessitates the deployment of advanced enabling technologies such as large-scale energy storage systems, smart grid infrastructure, hybrid generation models, and demand-response mechanisms. This study systematically examines the characteristics and grid-integration challenges of major RES, evaluates their socio-economic and environmental benefits, and analyzes global policy frameworks and case studies from leading nations. The findings aim to inform strategic approaches for enhancing grid reliability, optimizing resource utilization, and facilitating an equitable transition toward low-carbon, resilient energy systems.

Index Terms—Electrical infrastructure; Power grid system; renewable energy.

I. INTRODUCTION

Electricity is the backbone of modern society. Every home, business, and industry depends on it for lighting, communication, transportation, and production. Traditionally, electricity has been generated primarily from fossil fuels, such as coal, oil, and natural gas. While these sources provide

consistent and reliable power, they are finite and release large amounts of greenhouse gases, contributing to global climate change. In recent decades, the urgency to combat climate change, coupled with technological advances and falling costs, has driven the adoption of renewable energy sources (RES) such as solar, wind, hydropower, biomass, and geothermal energy. Unlike fossil fuels, renewable sources are naturally replenished and produce minimal environmental pollution [1]. However, integrating renewable energy into existing electric grids poses significant challenges. Unlike conventional power plants that can provide continuous, controllable electricity, solar and wind power are intermittent and variable [9]. This variability requires innovative grid management strategies, including energy storage, smart grids, and demand-response mechanisms.

Globally, governments and industries are pursuing large-scale integration of renewable energy to meet sustainability goals. For example, the International Energy Agency (IEA) reports that renewable energy accounted for nearly 30% of global electricity generation in 2023, with projections to exceed 50% by 2040 [2]. The study aims to understand different renewable energy sources and their characteristics, assess the advantages and challenges of integrating them into power grids, examine supporting technologies like storage, smart grids, and hybrid systems, review international case studies and policies, and offer recommendations to improve future renewable energy integration.

II. RENEWABLE ENERGY SOURCES

Renewable energy sources (RES) are derived from natural processes that are continuously replenished.

Unlike fossil fuels, they do not deplete over human timescales and produce minimal environmental pollution. Understanding the types, characteristics, and limitations of these sources is critical for their integration into the electric grid.

The study reviews various renewable energy sources and their characteristics. Solar energy, using photovoltaic panels or solar thermal systems, is abundant, low-cost after installation, and scalable, but depends on sunlight, land, and weather conditions [11]. Wind energy captures kinetic energy via onshore or offshore turbines, offering significant generation in windy regions, though it is variable and may impact wildlife and cause noise concerns [3]. Hydropower provides reliable and continuous electricity with storage potential and flood-control benefits, but large dams can disrupt ecosystems and require high initial costs [1]. Biomass and biogas convert organic waste into electricity or fuel, offering on-demand power and waste reduction, yet they compete for land, may emit pollutants, and require sustainable feedstock [2]. Geothermal energy delivers stable, low-emission baseload power but is geographically limited and costly. Ocean energy, including tidal, wave, and thermal systems, offers high-density, predictable output but remains emerging, expensive, and environmentally sensitive [12]. Finally, small-scale distributed energy such as rooftop solar, mini-wind turbines, and small biomass plants improves local energy access and reduces grid stress, though it often requires storage, technical support, and has limited capacity. Together, these sources highlight the potential and challenges of integrating renewable energy into modern electricity systems [13]. Renewable energy sources each have unique characteristics, advantages, and limitations. Successful integration into the electric grid requires a combination of these sources, along with energy storage, grid modernization, and supportive policies [1]. Understanding the basics of each source lays the foundation for analyzing grid integration challenges and solutions.

III. ELECTRIC GRID

The electric grid is a complex system that delivers electricity from power generation sources to homes, businesses, and industries [4]. It is often referred to as the backbone of modern society because nearly every aspect of daily life depends on a reliable supply of

electricity. Understanding the grid's components, functions, and limitations is critical for integrating renewable energy sources.

A. Components of the Electric Grid

The electric grid consists of three main components: generation, transmission, and distribution.

➤ Generation

Electricity is produced at power plants using various energy sources, such as fossil fuels, nuclear power, or renewables like solar, wind, and hydropower. Generation units convert mechanical, thermal, or chemical energy into electrical energy.

- Conventional Power Plants: Coal, natural gas, and nuclear plants provide continuous, controllable electricity, often called "baseload power."
- Renewable Sources: Solar and wind are intermittent and require specialized integration methods to ensure stable electricity supply.

➤ Transmission

Once electricity is generated, it is transmitted over high-voltage lines to reduce energy loss over long distances. Transmission lines connect power plants to substations and regional distribution networks.

- High Voltage: Using voltages of 110 kV or higher reduces losses.
- Interconnectivity: Transmission networks are interconnected to allow electricity sharing across regions, improving reliability.
- Power from remote wind or solar farms must travel long distances, requiring upgraded transmission lines.
- Variable generation can cause fluctuations in voltage and frequency.

➤ Distribution

Distribution systems deliver electricity from substations to end users, such as homes, offices, and factories.

- Medium and Low Voltage Lines: Electricity is stepped down from high-voltage transmission lines for safe use.
- Smart Meters and Sensors: Modern grids increasingly use digital tools to monitor consumption and detect faults.

B. Grid stability and reliability

Maintaining grid stability is essential to prevent blackouts and equipment damage. Grid operators must balance electricity supply and demand in real time.

➤ **Key Challenges:**

Maintaining grid stability requires constant frequency (50/60 Hz), proper voltage regulation, and adequate reserve power to handle sudden demand shifts or fluctuations from renewables. To address these challenges, energy storage systems (e.g., batteries, pumped hydro) stabilize supply, smart grids manage power flows in real time, and forecasting tools predict solar and wind output for proactive grid adjustments.

C. Modern Grid Innovations

To accommodate increasing renewable penetration, the electric grid is evolving into a smart grid, which uses digital communication, sensors, and automated controls.

➤ **Features of Smart Grids:**

The electric grid is the central infrastructure that delivers electricity from generation to consumption. Integrating renewable energy requires understanding the grid's components, one-way vs. two-way power flows, and stability challenges [2]. Modern innovations like smart grids, energy storage, and microgrids are essential for ensuring a reliable, flexible, and renewable-friendly electricity network.

IV. ENVIRONMENTAL SUSTAINABILITY

The most compelling reason to incorporate renewable energy is the urgent need to reduce greenhouse gas (GHG) emissions. Fossil fuel-based electricity generation is a major contributor to global CO₂ emissions, which drive climate change and environmental degradation.

➤ **Climate Change Mitigation:**

Replacing coal, oil, and gas plants with solar, wind, hydro, and other renewable sources reduces CO₂ and other pollutants. For example, Germany's Energiewende policy has helped reduce emissions while increasing renewable electricity production.

- **Air Quality Improvement:** Burning fossil fuels releases particulates and nitrogen oxides that degrade air quality, causing respiratory illnesses and other health problems. Renewable energy reduces these pollutants.
- **Water Conservation:** Thermal power plants consume significant water for cooling, whereas solar and wind plants require minimal water, conserving valuable resources.

A. Energy Security and Independence

Countries dependent on imported fossil fuels face economic and geopolitical risks. Renewable energy strengthens energy security by lowering import dependence, diversifying the energy mix to reduce price and supply vulnerabilities, and enabling localized generation like rooftop solar for greater resilience against outages [3].

B. Economic Benefits

Renewable energy adoption drives substantial economic benefits by creating jobs in manufacturing, installation, and maintenance, lowering long-term energy costs despite high initial investments, and attracting significant public and private funding that spurs innovation and industrial growth. For example, global renewable energy investments surpassed \$400 billion in 2023, highlighting its strong economic potential [5].

Renewable energy integration is critical for environmental protection, energy security, economic growth, social development, and long-term sustainability. Countries adopting renewables not only reduce emissions but also improve energy independence, create jobs, and provide electricity to underserved regions. This establishes a strong rationale for prioritizing renewable energy incorporation into national grids worldwide.

V. CHALLENGES IN INCORPORATING RENEWABLES

While renewable energy sources offer significant benefits, integrating them into the electric grid is complex. Various technical, economic, and regulatory challenges must be addressed to ensure a reliable, stable, and cost-effective electricity supply. This section explores the main challenges in detail.

A. Intermittency and Variability

A major challenge of renewable energy is its intermittency, especially in solar and wind power, where output varies with weather, time of day, and seasonal changes. These fluctuations can disrupt grid stability, causing frequency and voltage variations that may lead to blackouts if not effectively managed.

B. Energy Storage Limitations

Reliable integration of renewable energy into the grid depends on effective storage solutions that can retain

excess electricity for periods of low generation. Battery storage, including lithium-ion and flow batteries, offers flexible and rapid response capabilities but is constrained by high costs and limited lifespan [10]. Pumped-hydro storage is a mature and efficient option, though it requires favorable geographic conditions and substantial capital investment. Emerging technologies, such as green hydrogen and thermal storage, hold significant promise but remain in the early stages of development. Despite their potential, large-scale energy storage faces several challenges, including high upfront costs, technical complexity of deployment, and environmental concerns related to battery production and disposal.

C. Grid Stability and Reliability

Incorporating a high share of intermittent renewable energy sources presents significant challenges to grid stability. Maintaining a consistent frequency of 50/60 Hz becomes more complex as variable generation from solar and wind disrupts the balance between supply and demand [14]. Likewise, voltage regulation is critical to prevent fluctuations that can damage appliances and industrial equipment. To address sudden drops in renewable output, spinning reserves from conventional power plants are often required, which lowers overall efficiency and increases operational costs. Potential solutions include the deployment of smart grids equipped with sensors and real-time control systems, the use of advanced inverter technologies in renewable generators to support grid functions, and the integration of hybrid systems that combine renewable and conventional power sources to enhance flexibility and reliability [11].

D. Transmission and Distribution Challenges

Renewable energy generation is frequently situated in remote locations, such as large solar and wind farms, far from major urban load centers [6]. Delivering electricity over these long distances often requires extensive transmission infrastructure, yet many existing grids lack the capacity to handle high-voltage transfers or bidirectional power flows. This mismatch can lead to congestion in transmission corridors and energy losses during long-distance delivery, ultimately restricting the effective utilization of renewable resources. Addressing these challenges requires upgrading transmission networks, deploying

high-voltage direct current (HVDC) lines for efficient long-distance power transfer, and promoting distributed generation closer to demand centers to reduce transmission burdens and improve overall grid reliability [7].

E. Economic and Financial Barriers

Although renewable energy technologies are generally cost-effective over the long term, their deployment often involves substantial upfront capital investments. The installation of solar panels, wind turbines, energy storage systems, and necessary grid upgrades requires significant initial funding [8]. Many developing countries or smaller energy markets face additional financing challenges due to limited access to affordable capital. Furthermore, existing electricity market structures often fail to adequately compensate intermittent or distributed generation, creating barriers to investment [9].

F. Policy and Regulatory Challenges

Effective integration requires supportive policy frameworks:

- **Inconsistent Regulations:** Policies may differ across regions, creating barriers for cross-border electricity trading.
- **Lack of Incentives:** Some markets fail to reward renewable generation or storage adequately.
- **Grid Codes and Standards:** Technical standards may not accommodate high shares of intermittent sources.

The integration of renewable energy into the electric grid faces technical, economic, regulatory, and social challenges. Intermittency, storage limitations, grid stability, transmission constraints, financing barriers, and policy gaps must be addressed. With appropriate technological, financial, and regulatory measures, these challenges can be overcome, paving the way for large-scale renewable adoption.

VI. SOLUTIONS AND STRATEGIES FOR INTEGRATING RENEWABLE ENERGY

However, a combination of technical innovations, policy measures, and strategic planning can enable large-scale integration. This section explores the solutions and strategies in detail.

A. Energy Storage Solutions

Energy storage plays a critical role in balancing the intermittent nature of renewable generation with electricity demand. Among storage technologies, battery storage is widely adopted for grid-scale applications. Lithium-ion batteries are favored for their high efficiency and fast response times, while flow batteries provide longer-duration storage suitable for smoothing renewable output [20]. However, these batteries face challenges such as high initial costs, limited lifespan, and environmental concerns related to disposal [15]. They are commonly applied in solar farms to store excess daytime energy for evening use and in wind farms to balance night-time generation [13]. Pumped hydro storage is another key solution, using excess electricity to pump water to elevated reservoirs, which is then released to generate electricity during peak demand [1]. This method provides large-scale storage and helps stabilize grid frequency, though it is geographically constrained and requires significant upfront investment. Emerging technologies are also gaining attention, including green hydrogen, which converts surplus renewable electricity into hydrogen for storage or industrial applications, and thermal storage, which stores heat from solar plants for electricity generation when sunlight is unavailable [4].

B. Smart Grid Technologies

Smart grids leverage digital communication and automation to optimize electricity flow and enable efficient integration of renewables.

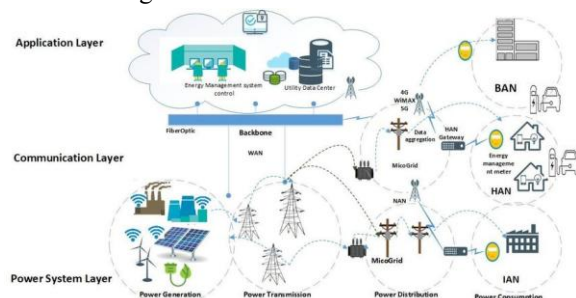


Fig 1 Smart grid architecture diagram

Key features include real-time monitoring through sensors that track generation and consumption, allowing rapid responses to imbalances, and automated control systems that maintain voltage and frequency stability. Demand response programs encourage consumers to shift electricity usage to periods of high renewable generation, while

distributed energy management integrates rooftop solar, small wind turbines, and local storage into the grid. For example, smart grid deployments in the United States and Europe have successfully reduced renewable energy curtailment and improved overall efficiency.

C. Hybrid Power Systems

Hybrid power systems, which combine multiple energy sources, enhance reliability and reduce dependence on any single type of generation [15]. Solar-wind hybrid systems, for instance, compensate for intermittent sunlight with wind energy and vice versa. Similarly, renewable-conventional hybrids integrate solar or wind with gas or hydropower to maintain baseload electricity [7]. These systems offer significant advantages, including increased reliability and reduced storage requirements, while optimizing the use of resources across diverse geographical regions. In India, hybrid renewable parks combine solar and wind projects with battery storage to ensure a stable power supply to the grid [1].

D. Microgrids and Decentralized Systems

Microgrids are localized grids capable of operating independently or in coordination with the main grid. They enhance reliability for remote communities, reduce transmission losses, and support renewable integration without overloading the central grid. Applications range from rural electrification projects in Africa and Southeast Asia to university campuses, industrial zones, and military bases that utilize on-site solar generation and storage. By enabling localized control and flexibility, microgrids strengthen resilience and contribute to efficient renewable deployment.

E. Advanced Forecasting and Predictive Tools

Modernizing grid infrastructure is essential to accommodate distributed and intermittent renewable generation. High-voltage direct current (HVDC) lines enable efficient long-distance transmission from remote renewable sites, while flexible AC transmission systems (FACTS) improve voltage control and reduce losses [14]. Digital sensors and automated control systems enhance monitoring and fault detection across the network. China, for instance, has invested heavily in ultra-high-voltage (UHV) lines that connect remote wind and solar farms to major

urban centers, demonstrating how infrastructure upgrades can support large-scale renewable integration [5]. Integrating renewable energy into the grid requires a multi-faceted strategy combining storage, smart grids, hybrid systems, microgrids, forecasting tools, policy incentives, and infrastructure upgrades. These solutions address intermittency, reliability, and economic challenges while enabling a sustainable, low-carbon energy future.

VI. POLICY AND REGULATORY SUPPORT

Effective integration of renewable energy into the electric grid is not only a technical challenge but also a policy and regulatory challenge. Supportive frameworks, incentives, and regulations are essential to promote investment, ensure grid stability, and encourage sustainable energy practices. This section explores key policies and regulatory mechanisms that enable renewable energy adoption worldwide.

VII. FUTURE OF RENEWABLE INTEGRATION

The future of electricity grids lies in the widespread integration of renewable energy sources (RES), supported by technological innovation, policy frameworks, and evolving market structures. As countries aim for net-zero emissions, renewable integration will play a central role in ensuring sustainable, reliable, and affordable electricity.

A. Increasing Renewable Penetration

Global renewable electricity generation is projected to exceed 50% by 2040, with solar and wind leading the growth. Countries around the world are setting ambitious targets to accelerate this transition [1]. The European Union aims to achieve 75% renewable electricity by 2050, India targets 500 GW of renewable capacity by 2030, and China plans for 50% of its electricity to come from non-fossil sources by 2030 [16]. Achieving high penetration of renewables will require advanced grid planning, energy storage, and robust interconnections to maintain stability.

B. Advanced Energy Storage and Flexibility

Energy storage is becoming increasingly critical to integrate variable renewable energy sources effectively [18]. Long-duration storage technologies, such as flow batteries, green hydrogen, and thermal storage, will complement conventional lithium-ion

batteries. Flexible grid operations—including demand response, vehicle-to-grid (V2G) systems, and hybrid generation—will provide necessary adaptability. Additionally, microgrids are expected to become key building blocks, offering resilience and efficiency for communities and industrial clusters [11]. For example, California and Japan are investing in large-scale lithium-ion and hydrogen storage systems to reliably integrate solar and wind energy [18].

C. Digitalization and Smart Grids

The digitalization of energy systems through AI, blockchain, and IoT is transforming grid management. Artificial intelligence and machine learning improve forecasting, optimize grid operations, and enable predictive maintenance. Blockchain technology facilitates peer-to-peer renewable energy trading, while IoT devices allow real-time monitoring of distributed energy resources and overall grid performance. European smart grid pilots, for instance, use AI to optimize wind and solar dispatch, minimizing curtailment and enhancing reliability [6].

D. Sector Coupling and Electrification

Electrification of transport and industry is expected to significantly increase electricity demand. Sector coupling—the integration of electricity, heat, and gas—allows renewable electricity to be stored or converted into other energy forms, enhancing system flexibility [7]. Surplus renewable electricity can also be used to produce green hydrogen for industrial applications, transportation, and long-term storage. Germany, for example, is developing hydrogen hubs to utilize excess wind and solar power for industrial hydrogen production [16].

E. Global Grid Interconnections

Regional supergrids and transcontinental initiatives are key to sharing renewable electricity across large areas, smoothing out variability, and enhancing reliability. Projects like the “Desertec” initiative envision transmitting solar power from desert regions to distant markets using high-voltage direct current (HVDC) lines. These interconnections reduce curtailment, optimize resource use, and support global energy security [10].

F. Policy and Market Evolution

Evolving policy and market mechanisms are crucial to accelerate renewable energy adoption. Dynamic tariffs and flexibility markets encourage electricity consumption during periods of high renewable generation. Carbon pricing and net-zero policies drive investment in low-carbon technologies, while coordinated international policy frameworks enable cross-border electricity trading and renewable deployment.

G. Challenges for the Future

Despite these opportunities, several challenges must be addressed. Increasing digitalization raises cybersecurity risks for grids, and massive infrastructure upgrades are required for transmission, storage, and smart grid deployment. Large-scale projects may also face social resistance due to land use and environmental concerns. Overcoming these challenges will require strategic planning, stakeholder engagement, and international cooperation [11]. The future of renewable energy integration relies on high renewable penetration, advanced storage, smart grids, sector coupling, global interconnections, and emerging technologies [17]. With proper policies, infrastructure, and international collaboration, electricity grids can become cleaner, more flexible, and resilient, paving the way for a sustainable energy future.

VIII. SUMMARY & RECOMMENDATIONS

The integration of renewable energy sources (RES) into electric grids is an environmental, economic, and social necessity [17].

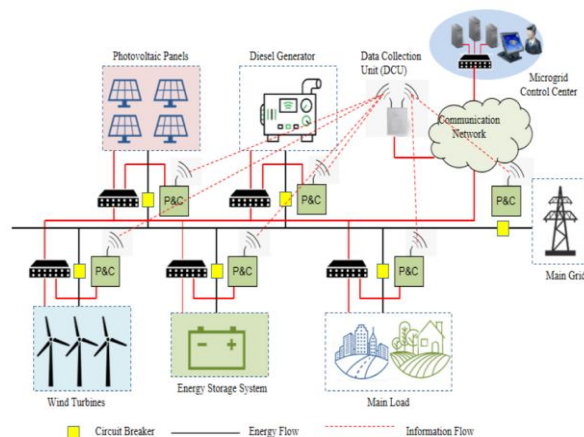


Fig 2 Future-ready renewable energy grid schematic

The study highlights that RES significantly reduce greenhouse gas emissions, improve air quality, conserve resources, and drive job creation, innovation, and energy independence. However, technical barriers—including the intermittency of solar and wind power, storage constraints, grid stability issues, and outdated transmission infrastructure—remain key challenges. Policy instruments such as feed-in tariffs, carbon pricing, and renewable portfolio standards, combined with international cooperation, have proven essential in advancing large-scale adoption. Successful integration strategies include the use of hybrid systems, microgrids, smart grids, and advanced forecasting tools, alongside large-scale storage technologies such as batteries, pumped hydro, and emerging solutions like green hydrogen. Global experiences from countries such as Germany, Denmark, China, India, and the United States demonstrate that strong policy support, robust infrastructure investment, and continued innovation are critical for achieving high renewable penetration [19].

To accelerate progress, the report recommends:

- Modernizing grid infrastructure with HVDC lines, FACTS, and digital smart grid technologies.
- Expanding storage capacity to ensure system flexibility and resilience.
- Strengthening policy frameworks with stable incentives, carbon pricing, and updated interconnection standards.
- Investing in R&D and workforce training to drive innovation and operational expertise.
- Enhancing international collaboration through cross-border power trading, shared best practices, and climate-finance initiatives for developing nations.

The energy transition will be defined by higher renewable penetration, digitalized smart grids, localized microgrids, and integrated low-carbon systems linking electricity, transport, and industry. With coordinated policy action, advanced technologies, and global partnerships, renewable energy can become the cornerstone of a reliable, flexible, and sustainable power grid of the future.

IX. CONCLUSION

Incorporating renewable energy into the electric grid is a complex but achievable goal. The combination of technical solutions, policy frameworks, economic incentives, and global cooperation will enable the world to transition to a low-carbon, sustainable energy future. Policymakers, utilities, researchers, and the public must collaborate to overcome challenges, seize opportunities, and ensure that renewable energy delivers reliable, affordable, and clean electricity for generations to come.

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