



REVIEW ARTICLE

Overview of the evolution and impact of renewable energy sources on modern electrical grids

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Abstract

The economic growth and development of nations worldwide hinge significantly on the electrical power sector. Across both developed and developing economies, there is a notable increase in the global demand for electric energy. The commitment to decarbonize economies, involving substituting fossil fuels with renewable energy sources (RES), alongside the growing adoption of electric power for transportation and heating to combat climate change, is anticipated to drive a substantial upswing in global electricity consumption. Consequently, it is logical to promote for integrating sustainable development principles into the operational framework of the electric power sector. This review seeks to evaluate the role of renewable energy in fostering the sustainable development of the electrical power sector. It specifically examines its impact on energy providers and consumers, encompassing businesses and households transitioning into prosumers. Additionally, the review scrutinizes the effects of renewables on the utility side and highlights their benefits for the grid.

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1. Introduction

The mandate for the energy sector's sustainable modernization has necessitated deregulation in the power industry. Among the various innovative proposals, microgrids are the most promising solution [1]. Microgrids (MG) are compact electrical distribution networks comprising distributed generators (renewable and non-renewable generators), diverse loads, and energy storage devices. They operate in grid-connected or islanded modes facilitated by suitable interfacial power electronic devices [2]. Autonomic grids, in the form of MGs, are particularly relevant in remote communities where connecting to utility networks is technologically and economically unfeasible. Initially, the contribution of renewable energy sources (RES) to the power network was negligible compared to conventional generators, making their

impact inherently inconspicuous. However, recent commitments to renewable and sustainable power generation have elevated RES, such as solar photovoltaics, wind, hydropower, and hydrogen technologies, to the forefront of integrations into the electrical power network. Microgrids provide flexibility for implementing suitable control schemes and power management algorithms to uphold the power quality delivered by transient RES through power electronic interventions [3]. Power electronic devices play a crucial role in integrating various forms of RES, energy storage devices, and diverse loads, offering flexibility in MGs. Additionally, multiple conceptualized topologies of power electronic converters/inverters have been proposed [4–6] to establish a point of common coupling (PCC). This PCC is pivotal in forming DC, AC, and hybrid AC-DC microgrids for different voltage and frequency levels. Consequently, numerous power

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electronic interfacing configurations and topologies have been suggested to create a diversified power generation framework, allowing MGs to manage power and energy flow [7,8] efficiently. Renewable energy sources, sourced from elements like wind, solar power, hydropower, geothermal energy, biomass, and hydropower, play a pivotal role in addressing the contemporary energy landscape [9, 10] As the 21st century unfolds, the world faces a depletion of usable energy derived from finite fossil fuels, including oil, gas, coal, natural gas, and nuclear power. Despite advances, renewable energies like wind and solar have yet to replace conventional sources on a comprehensive and flexible scale. The increasing dependence on renewable energy stems from recognizing that fossil fuels are exhaustible resources, with estimates indicating insufficient proven oil reserves to meet global demand by the mid-21st century [11, 12]. This situation presents a paradox, considering that two centuries ago, all energy sources were inherently renewable and sustainable. Wind-propelled sea vessels transported people and goods, while water-powered machines such as water mills. In the United States, developers and power plant owners are strategically planning for over 70% of new electricity generating capacity in 2021 to come from renewable energy sources, with solar energy constituting the largest share at 39%, followed by wind at 31%. Most of this electricity is derived from large hydroelectric plants, contributing approximately 6% to total electricity generation. Some analysts categorize nuclear power as renewable energy due to its low carbon emissions, accounting for around 10% of global electricity generation. In 2015, the largest hydropower plant generated 16.3% of the world's total electricity, amounting to approximately 16 billion kilowatt-hours (kWh), representing the second-largest share of global electricity generation at 4.2 billion kWh [13]. The feasibility of decarbonizing the energy sector has led to the gradual replacement of fossil fuels with renewable energy sources. Renewable energy from replenish able natural resources provides a sustainable alternative without depleting the Earth's resources. The World Bank asserts that generating electricity from renewable sources is achievable without emitting greenhouse gases, the primary contributors to global warming and climate change [14]. In Europe (EU—27 countries), renewables constitute around 20% of gross final energy consumption, while in Asia, renewables account for 24%, with hydropower making up 18% of that figure [15]. Wind energy encompasses electricity generated from small wind turbines on commercial properties, with the National Renewable Energy Laboratory (NREL) noting that wind power contributes over 1.3 million megawatts (MW) of electricity generation capacity across 41 U.S. states and two territories.

2. Electric power and sustainable development

To address forthcoming energy challenges, pivotal renewable energy sources with significant potential include solar, wind, hydro, and biomass. Adopting renewable energy sources becomes imperative for ensuring a country's sustainable development, given the depleting reserves of fossil fuels,

escalating global fossil fuel prices, and the imperative to minimize environmental impacts. Integrating nuclear energy into electricity generation is a strategy to curtail resource demands to a more sustainable threshold. The level of industrialization and commercialization achieved by these technologies is a critical consideration. The number of materials employed in electricity production, gauged by the consumption of fossil fuel-producing technology and the degree of industrialization attained, is unavoidable. It is especially pertinent as the industrial scale and pace of technological development are typically more advanced in developed countries compared to developing nations. Sustainable development in the electric power sector involves balancing meeting current energy needs and ensuring the well-being of future generations and the planet. This paradigm emphasizes the integration of renewable energy sources, such as solar, wind, hydro, and biomass, to mitigate reliance on finite fossil fuels and curb environmental degradation. The commitment to decarbonization, coupled with the electrification of transport and heating, is pivotal in addressing global warming and climate change [16].

Strategies for sustainable development in electric power encompass embedding principles of environmental responsibility, social equity, and economic viability into the sector's functioning. This includes promoting energy efficiency, minimizing environmental impact, and engaging in responsible resource management.

Moreover, sustainable development considerations extend to the resilience and adaptability of power infrastructure, ensuring it can withstand the challenges posed by climate change and other disruptions. Balancing the energy needs of developed and developing economies is crucial to achieving inclusive and equitable progress.

3. Influencing factor of Renewable energy generation

Renewable energy generation is influenced by several critical factors that collectively shape the trajectory of sustainable power development. Firstly, resource availability is paramount, with geographical locations possessing abundant sunlight, wind, water, or biomass being more conducive to efficient energy generation [17]. Technological advancements are pivotal, continuously improving the efficiency and cost-effectiveness of renewable energy technologies like solar panels and wind turbines. Moreover, the regulatory landscape significantly impacts renewable energy projects, with supportive policies, incentives, and regulations fostering investment and deployment [18].

The availability of financial resources and supportive funding mechanisms is another crucial factor in determining the scale and pace of renewable energy initiatives. Seamless integration into existing power grids and developing essential infrastructure like energy storage systems is critical for ensuring a reliable and stable energy supply. Public awareness and acceptance are influential; garnering community support helps overcome challenges related to land use and environmental concerns. Additionally, the economic

competitiveness of renewable energy relative to conventional sources is pivotal for widespread adoption. In essence, successful renewable energy generation requires a harmonious interplay of resource availability, technological innovation, supportive policies, financial backing, infrastructure development, and community engagement [19, 20].

4. Pricing Mechanisms in Smart Grids

Pricing mechanisms in intelligent grids are pivotal components of advanced energy management systems that integrate modern technology into traditional power grids. These mechanisms aim to optimize electricity consumption, enhance grid reliability, and promote sustainable energy practices. One notable pricing strategy is Time-of-Use (TOU) pricing, where electricity rates vary based on the time of day. This encourages consumers to shift their energy-intensive activities to periods of lower demand, promoting load balancing and grid stability. Real-Time Pricing (RTP) takes this a step further by reflecting the actual cost of electricity at any given moment, encouraging consumers to adjust their usage based on prevailing market conditions. Critical Peak Pricing (CPP) involves higher prices during peak demand or stress periods on the grid, incentivizing consumers to reduce usage during essential times and contributing to grid reliability. Demand Response Programs offer financial incentives for consumers to adjust their electricity consumption in response to grid conditions, enhancing overall system flexibility. Dynamic Pricing continuously adjusts rates based on changing electricity market conditions, empowering consumers to make real-time decisions about their energy usage [21].

Incentive-based pricing encourages the adoption of energy-efficient technologies or practices by providing financial rewards. Capacity pricing charges consumers based on their peak electricity usage, motivating them to manage and reduce peak demand and contributing to grid efficiency. Feed-in Tariffs (FIT) guarantee fixed payment rates for renewable energy producers, promoting the integration of renewable sources into the grid. These pricing mechanisms collectively contribute to optimizing electricity distribution in smart grids. They foster a resilient, sustainable, and responsive energy infrastructure by aligning consumer behavior with grid conditions, promoting efficiency, and encouraging the adoption of cleaner energy sources. As intelligent grids evolve, pricing mechanisms are crucial in shaping a more adaptive and sustainable energy landscape.

The global transition towards sustainable energy solutions is driven by escalating energy demands and the pressing need to address environmental concerns [22]. Traditional energy sources, primarily fossil fuels, have long been the backbone of our energy infrastructure. However, their environmental repercussions, coupled with their finite nature, have necessitated a shift towards renewable energy sources [23]. Renewable energy, derived from natural processes that are continually replenished, offers a promising alternative. Harnessing power from sources such as solar, wind, and hydro, renewable energy not only provides a sustainable means of

energy production but also represents a significant shift towards an eco-friendlier future [24]. However, the integration of these sources into modern electrical grids presents challenges. These grids, designed around the consistent and predictable output of fossil fuel power plants, grapple with the variable and intermittent nature of renewable energy [25]. The imperative for this integration is clear: to maximize the benefits of renewable energy, it must be seamlessly woven into our energy infrastructure. This review seeks to provide a comprehensive overview of the evolution of renewable energy sources, their integration challenges, and the subsequent ramifications for grid management. Through this exploration, we aim to shed light on the path forward—a path towards a cleaner, more sustainable energy landscape.

5. Evolution of renewable energy sources

5.1 Historical Perspective

The journey of renewable energy sources is a testament to humanity's quest for sustainable and environmentally friendly power solutions. Historically, before the Industrial Revolution, humans primarily relied on renewable sources like windmills, water wheels, and biomass for their energy needs [22]. However, the discovery of coal and other fossil fuels shifted the focus towards these non-renewable sources, given their abundance and energy density. It wasn't until the late 20th century, with the growing awareness of environmental degradation and the looming energy crisis, that there was a renewed interest in renewables. The early adoption of modern renewable technologies, such as solar panels and wind turbines, marked the beginning of a new era in energy production [23].

5.2 Major Renewable Energy Sources

Several renewable energy sources have emerged as frontrunners in the race towards a sustainable future:

- **Solar Energy:** Harnessing the power of the sun, solar energy has seen exponential growth, especially with the advent of photovoltaic cells. Solar farms and rooftop installations have become commonplace, providing a clean and abundant source of energy [24].
- **Wind Energy:** Wind turbines, dotting landscapes and offshore areas, capture the kinetic energy of the wind, converting it into electricity. Wind energy's potential, especially in regions with consistent wind patterns, has made it a significant player in the renewable sector [25].
- **Hydro Energy:** Utilizing the gravitational force of flowing or falling water, hydroelectric power has been a longstanding renewable source. From large-scale dams to small run-of-the-river installations, hydro-energy remains a vital component of the renewable mix [26].

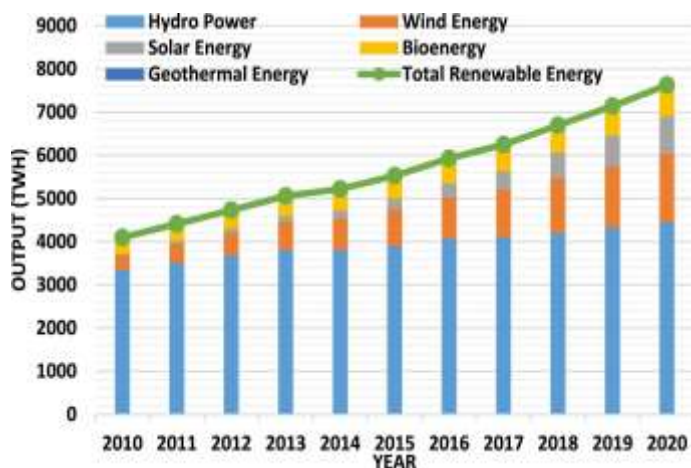


Figure 1. Total renewable energy usage (2010–2020) [27]

5.3 Technological Advancements

The trajectory of renewable energy has been steeped in technological innovation. Enhanced materials and engineering techniques have led to solar panels that can convert more sunlight into electricity than ever before. Wind turbines have grown larger, more efficient, and more durable, capturing more wind energy per unit. Battery storage technologies have seen dramatic improvements, addressing one of the most significant hurdles of renewable energy: variability and intermittency [24]. These advancements, alongside digitalization and smart technologies, have smoothed the integration of renewables into electrical grids. They have also made renewable energy more cost-competitive, challenging the long-held economic advantage of fossil fuels. As we venture further into the 21st century, continuous innovation, research, and development in renewable energy technologies remain paramount for a sustainable energy future (Lu & Li, 2022).

6. Integration into modern electrical grids

6.1 Benefits of Integration

Integrating renewable energy sources into modern electrical grids isn't just an environmental imperative; it's also increasingly seen as a sound economic strategy. Renewable energy sources contribute to the diversification and resilience of energy grids, protecting them from fluctuations in the price or supply of any one source. Moreover, they help nations and entities meet international climate targets and are increasingly attractive to investors and consumers alike (Imtiaz, Khan, Yamin, et al., 2020). However, the benefits extend beyond economics and sustainability. Renewable energy sources are also driving a wave of innovation in energy grid management, leading to the development of smarter, more efficient grids. These modern grids are better equipped to handle the demands of contemporary society, including the need for rapid, real-time adjustments to supply and demand (Lu & Li, 2022).

6.2 Challenges of Integration

Despite these benefits, integrating renewable energy sources into existing grids isn't without its challenges. These sources often generate power intermittently - solar panels only work during the day, and wind turbines only when it's windy. This variability means that grids need to be able to quickly and efficiently switch between energy sources as conditions change (Salkuti, Pagidipala, & Kim, 2021). Additionally, many renewable energy sources generate direct current (DC) electricity, while most electrical grids are designed to handle alternating current (AC). Converting DC to AC can lead to energy losses, reducing the overall efficiency of the energy transfer process. There's also the issue of energy storage. To truly rely on renewable energy, we need efficient ways to store excess energy generated when conditions are favorable (Agajie, Fopah-Lele, Amoussou, et al., 2023).

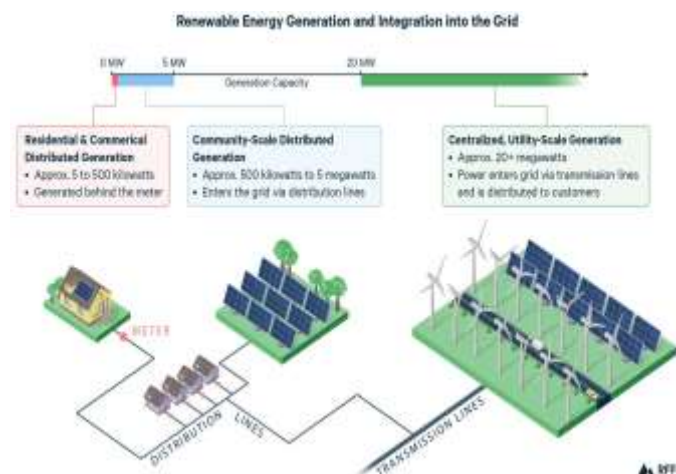


Figure 2. Renewable Energy Generation and Integration into the Grid. (Kathryne Cleary & Karen Palmer, 2022)

6.3 Case Studies

Several regions worldwide have showcased the successful integration of renewables into their electrical grids

- Germany: Known for its "Energiewende" or energy transition, Germany has successfully integrated a significant amount of wind and solar energy into its grid, often meeting more than half of its electricity demand from renewables (Salkuti, Pagidipala, & Kim, 2021).
- California, USA: With its ambitious renewable energy targets, California has made strides in integrating solar and wind energy, backed by battery storage solutions, ensuring grid reliability (Imtiaz, Khan, Yamin, et al., 2020).
- Denmark: Often hailed as a pioneer in wind energy, Denmark's grid frequently operates with wind energy meeting or even exceeding its electricity demand, showcasing the potential of renewables when backed by robust grid management strategies (Agajie, Fopah-Lele, Amoussou, et al., 2023).

7. Impact on grid management

7.1 New Era of Grid Management

The rise of renewable energy sources is driving a revolution in grid management. In the past, grids were relatively straightforward systems that delivered electricity from a few large, centralized power plants to consumers. However, the intermittent nature of renewable energy requires a more flexible, intelligent approach to grid management (Lu & Li, 2022). Smart grids, equipped with sensors, communication tools, and advanced analytics, can monitor and adjust the flow of electricity in real-time, responding rapidly to changes in supply and demand. These technologies also support distributed energy resources, like rooftop solar panels, allowing consumers to not only consume power but also to generate it and feed it back into the grid (Hernández Mayoral, Dueñas Reyes, et al., 2021).

7.2 Grid Adaptability

Modern electrical grids must be incredibly adaptable, capable of quickly responding to fluctuations in energy supply and demand. Renewable energy sources, like solar and wind power, can be highly variable, generating lots of electricity under ideal conditions and very little when conditions are less favorable (Salkuti, Pagidipala, & Kim, 2021). To manage this variability, grids are increasingly turning to advanced data analytics and machine learning. These tools can predict changes in energy supply and demand and make near-instantaneous adjustments to keep the grid stable. They're also essential for efficient energy trading, allowing entities with excess energy to sell it to those in need (Imtiaz, Khan, Yamin, et al., 2020).

7.3 Energy Storage Solutions

Energy storage is a critical component of modern electrical grids, helping them manage the variability of renewable energy sources. There are several promising energy storage technologies currently in use or in development, including lithium-ion batteries, redox flow batteries, and pumped hydro storage systems. These technologies can store excess energy when supply exceeds demand and release it when the opposite is true (Agajie, Fopah-Lele, Amoussou, et al., 2023).

8. Future perspective

8.1 Emerging Technologies

Looking ahead, several emerging technologies have the potential to further streamline the integration of renewable energy sources into electrical grids. For instance, microgrids - small, localized energy grids - can operate independently of the main grid, providing resilience and efficiency. They're particularly useful in remote or disaster-prone areas, where maintaining a connection to the main grid can be challenging

(Lu & Li, 2022). There's also significant potential in the realm of energy storage, with researchers exploring new materials and methods to increase the efficiency and capacity of batteries. Furthermore, as the Internet of Things (IoT) continues to expand, we'll likely see more energy devices with built-in connectivity, providing grid operators with a wealth of real-time data (Salkuti, Pagidipala, & Kim, 2021).

8.2 Policy and Regulatory Changes

Governments and regulatory bodies play a pivotal role in the transition to renewables. Policies that incentivize renewable energy adoption, tax breaks for green energy projects, and regulations that mandate a certain percentage of renewable energy in the grid mix can accelerate the shift towards a sustainable energy future (Hernández Mayoral, Dueñas Reyes, et al., 2021). Collaborative efforts between policymakers, industry stakeholders, and the public are essential to navigate the challenges and harness the full potential of renewable energy.

9. Conclusions

The global transition towards sustainable energy sources represents a monumental shift in our approach to energy production and consumption. As we've explored, the evolution of renewables, from their historical roots to modern technological advancements, has been nothing short of transformative. Their integration into modern electrical grids, while fraught with challenges, offers unparalleled benefits in terms of reliability, sustainability, and adaptability. The journey, marked by innovations, policy shifts, and collaborative efforts, underscores the significance of renewables in shaping a sustainable energy future. As we stand at this juncture, the promise of a cleaner, greener energy landscape beckons, emphasizing the pivotal role of renewable energy sources in modern grid management.

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