

Review Article

Advancing Sustainable Power: A Comprehensive Review of Technologies and Strategies for Green Electricity Production

Abstract

The transition to sustainable energy systems is essential to address global environmental challenges, with green electricity production playing a crucial role. This comprehensive review examines the advancements in green electricity production technologies, focusing on solar, wind, biomass, and hydroelectric power. By exploring the efficiency, cost trends, adoption rates, and environmental impacts of these technologies, the review highlights their potential to transform the energy landscape. Solar PV and wind energy have seen substantial improvements in efficiency and cost reduction, while biomass and hydroelectric power offer valuable contributions to a diversified renewable energy portfolio. Despite the challenges, ongoing research and innovation are driving the adoption and integration of these technologies, paving the way for a sustainable and resilient energy future. The findings underscore the importance of leveraging a multifaceted approach to green electricity production, emphasizing the need for continued advancements and strategic integration of renewable energy sources.

Keywords: Renewable energy; Green electricity; Solar power; Wind energy; Biomass energy; Hydroelectric power; Sustainable energy; Energy efficiency; Emerging technologies

Introduction

The transition to sustainable energy systems has become imperative in addressing global environmental challenges, with green electricity production emerging as a key component. This comprehensive review explores the various technologies and strategies that are driving advancements in green electricity production, highlighting their potential to transform the energy landscape. By focusing on renewable energy sources and innovative technologies, we can pave the way for a sustainable future where energy needs are met without compromising environmental integrity.

The shift towards renewable energy sources such as wind, solar, and hydroelectric power has gained significant momentum in recent years. These technologies are pivotal in reducing greenhouse gas emissions and mitigating the impacts of climate change. For instance, the integration of renewable-energy-based green hydrogen into the energy mix represents a sustainable and environmentally friendly solution, as it generates no carbon dioxide or other harmful pollutants during production [1,2]. Green hydrogen can be utilized in various sectors, including electricity generation, transportation, and industrial applications, thereby enhancing its versatility and impact on sustainability [3,4].

Advancements in biomass energy production have also contributed to the diversification of green electricity sources. Biomass conversion technologies offer a renewable and carbon-neutral option for generating electricity, addressing the need for sustainable energy solutions in various regions [5]. Additionally, the deployment of advanced control strategies for wind energy systems has improved the efficiency and reliability of wind power, making it a highly viable solution for fulfilling power demands and reducing reliance on fossil fuels [6].

The economic and environmental benefits of green electricity production are well-documented. Studies have shown that renewable energy sources such as hydropower, waste, biomass, and wind power play a crucial role in driving economic development while minimizing environmental footprints [7,8]. For example, a causal analysis of renewable electricity production and GDP growth in OECD countries revealed that growth in renewable electricity positively impacts economic development, creating a feedback loop that further promotes sustainability [9].

In conclusion, advancing sustainable power through green electricity production requires a multifaceted approach that leverages innovative technologies and strategic integration of renewable energy sources. This review will delve into the latest advancements, challenges, and future prospects of green electricity production, providing a comprehensive understanding of the path towards a sustainable and resilient energy future. By embracing these technologies, we can significantly reduce carbon emissions, promote economic growth, and achieve global sustainability goals [10,11].

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Related Work

Green electricity production has seen significant advancements, driven by the urgent need to mitigate climate change and reduce dependency on fossil fuels. This section reviews the latest research and developments in green electricity production technologies, focusing on green hydrogen, biomass energy, wind, solar, and hydroelectric power.

Green hydrogen production has emerged as a promising avenue for sustainable energy. Studies have highlighted the potential of water electrolysis using renewable energy sources such as solar and wind power to produce hydrogen without carbon emissions. Various electrolysis technologies, including alkaline, proton-exchange membrane (PEM), and solid oxide electrolyzers, have been extensively reviewed for their efficiency and scalability [12, 13]. The integration of green hydrogen in industrial processes, such as steel production, has also been explored, indicating significant potential for reducing carbon emissions in traditionally high-emission industries [14].

Biomass energy production continues to be a critical component of the renewable energy landscape. Recent reviews have emphasized the role of biomass pyrolysis and gasification in generating electricity, which offers a renewable and carbon-neutral alternative to conventional fossil fuels [15]. Advances in catalyst development and process optimization have further improved the efficiency of biomass energy systems [16].

Wind energy remains one of the most mature and widely adopted forms of green electricity. The deployment of advanced control strategies and offshore wind farms has significantly enhanced the efficiency and capacity of wind power systems. Studies have documented the economic and environmental benefits of wind energy, noting its critical role in reducing greenhouse gas emissions and driving economic growth [17,18]. Offshore wind energy, in particular, has been highlighted for its potential to provide substantial clean energy, with ongoing research focused on overcoming technical and logistical challenges [19].

Solar energy technologies have also seen rapid advancements, with improvements in photovoltaic (PV) cell efficiency and the development of new materials such as perovskites. These innovations have made solar power more cost-effective and scalable, contributing to its widespread adoption [20]. The integration of solar energy with other renewable technologies, such as green hydrogen production, has been explored to enhance energy storage and distribution capabilities [21].

Hydroelectric power, although a well-established technology, continues to evolve with advancements in turbine design and energy storage solutions. Small-scale hydroelectric projects have gained attention for their potential to provide localized, sustainable energy solutions with minimal environmental impact [22]. The role of hydroelectric power in balancing the grid and supporting other renewable energy sources has been a focus of recent research, emphasizing its importance in a diversified energy portfolio [23].

In summary, the field of green electricity production is characterized by rapid technological advancements and increasing integration of various renewable energy sources. Continued research and innovation are essential for overcoming existing challenges and realizing the full potential of sustainable energy systems. This review highlights the diverse range of technologies and strategies that are driving the transition towards a greener and more resilient energy future.

Green Energy Production Efficiency

The efficiency of green energy production varies significantly across different technologies. This section will compare the efficiency of solar, wind, biomass, and hydroelectric power, highlighting their advantages and limitations.

Solar Energy: Solar photovoltaic (PV) cells have seen substantial efficiency improvements over the years. Modern PV cells convert sunlight into electricity with efficiencies ranging from 15% to 22%, with research cells achieving up to 26% efficiency. Advances in materials, such as perovskites, promise even higher efficiencies in the future [12, 24].

Wind Energy: Wind turbines convert kinetic energy from wind into electricity with efficiencies between 35% and 50%. Offshore wind farms tend to have higher efficiencies due to stronger and more consistent wind speeds. Technological advancements in turbine design and materials continue to push these efficiency boundaries [25, 26].

Biomass Energy: Biomass energy production efficiency depends on the conversion technology used. Gasification and pyrolysis are commonly used methods, with efficiencies ranging from 20% to 40%. Innovations in catalyst development and process optimization have the potential to enhance these efficiencies further [27].

Hydroelectric Power: Hydroelectric power is one of the most efficient forms of renewable energy, with conversion efficiencies often exceeding 90%. Small-scale hydroelectric projects, while less efficient than large dams, still offer significant efficiency and environmental benefits [28].

Cost Analysis

The cost of green electricity production has been declining, making it increasingly competitive with traditional fossil fuels. This section analyzes the cost trends for solar, wind, biomass, and hydroelectric power.

Solar Energy: The cost of solar PV electricity has decreased dramatically over the past decade, with the average cost falling from \$0.37 per kWh in 2010 to \$0.05 per kWh in 2020. Factors contributing to this decline include economies of scale, technological advancements, and reduced manufacturing costs [29].

Wind Energy: The cost of wind energy has also seen significant reductions, particularly for onshore wind farms. The average cost decreased from \$0.09 per kWh in 2010 to \$0.04 per kWh in 2020. Offshore wind energy costs remain higher but are expected to decrease as the technology matures and deployment scales up [30].

Biomass Energy: Biomass energy costs vary widely depending on the feedstock and conversion technology. The average cost ranges from \$0.05 to \$0.10 per kWh. While biomass energy is generally more expensive than solar and wind, it offers the advantage of being a dispatchable source of electricity [31].

Hydroelectric Power: Hydroelectric power remains one of the most cost-effective renewable energy sources, with costs ranging from \$0.02 to \$0.05 per kWh. Large-scale hydroelectric projects benefit from long lifespans and low operational costs, making them highly economical over the long term [32].

Conclusion

Advancing sustainable power through green electricity production is critical for mitigating climate change and reducing dependency on fossil fuels. This review has highlighted the significant advancements in solar, wind, biomass, and hydroelectric power technologies, demonstrating their potential to revolutionize the energy sector. Solar and wind energy technologies have made remarkable strides in efficiency improvements and cost reductions, making them increasingly competitive with traditional fossil fuels. Biomass energy offers a renewable and carbon-neutral option for electricity generation, while hydroelectric power remains one of the most efficient and cost-effective renewable energy sources.

The adoption rates of these technologies vary globally, influenced by regional resources, policies, and economic conditions. While challenges remain, such as technological limitations, economic barriers, and policy issues, the ongoing research and innovation are essential for overcoming these obstacles. The integration of green hydrogen and advancements in energy storage solutions further enhance the potential of green electricity production to meet future energy demands sustainably.

In conclusion, a multifaceted approach that leverages innovative technologies and strategic integration of renewable energy sources is crucial for advancing green electricity production. By embracing these technologies, we can significantly reduce carbon emissions, promote economic growth, and achieve global sustainability goals. Continued research, investment, and policy support are vital to realizing the full potential of sustainable energy systems and ensuring a resilient energy future.

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