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Wheatley Research Consultancy,
Bagley, Minnesota, USA

Correspondence to:
Mary Christine Wheatley,
mchristinewheatley@gmail.com

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Advancements in Renewable Energy Technologies: A Decade in Review

Mary Christine Wheatley, PhD

ABSTRACT

This review provides an in-depth analysis of significant advancements in renewable energy technologies over the past decade, highlighting the major strides made in solar, wind, and bioenergy sectors. These innovations have been driven by a need to tackle climate change as well as improve energy security; therefore, they have become more efficient, affordable, and technologically advanced at a rapid pace. The global shift from fossil fuels to clean sources of electricity generation has not only curbed emissions but also transformed energy markets and policy landscapes. This paper analyses groundbreaking photovoltaic materials, cutting-edge wind turbines, and breakthroughs in biomass conversion processes which have revolutionized how we produce and store energy. It also discusses the ongoing challenges and opportunities that lie ahead, including the potential for material science to further enhance the efficiency of renewable systems and the importance of supportive policy frameworks to sustain growth. With every step forward made by these types of technology they present a transformative potential for global energy systems, promising significant environmental, economic, and social benefits. The review underscores the necessity of continued innovation, investment, and international collaboration to fully realize the potential of renewable energies and achieve a sustainable energy future.

Introduction

The global energy landscape has changed dramatically over the past decade, with a strong focus on renewable energy technologies. This shift is powered by an increased realization of the potential for renewable energy to address climate change and improve security of supply. As worldwide demand for power continues to grow, sustainability and reliability will only be achieved by switching from fossil fuels, such as coal or gas, towards clean sources like wind farms or solar panels.¹

The importance of advancing renewable energy technologies cannot be overstated. Extreme weather events caused by climate change are already having devastating effects in many areas and rising sea levels threaten coastal cities worldwide; therefore, societies urgently need sustainable solutions for generating electricity.² Furthermore, geopolitical considerations associated with dependence on oil imports further reinforce the need for nations everywhere to develop their own renewable energy industries to gain independence and ensure long-term security.³

This review paper aims to analyze the significant developments made within renewable energy sectors

over recent years—in terms of technology advancement, efficiency improvement measures, as well as cost-effectiveness adopted during this period. It seeks to provide a comprehensive overview of how these advancements have influenced global energy markets and to discuss the ongoing implications for future energy policies and economic landscapes. The scope of this review encompasses three pivotal renewable energy technologies: solar, wind, and bioenergy. Each sector has seen rapid technological advancements that have not only improved the efficiency and reduced the costs of energy production but have also had far-reaching impacts on global energy markets and policy frameworks.^{4,5}

Solar Energy Technologies

Technological Advancements

Innovations in photovoltaic cell technology have greatly increased the efficiency and versatility of solar panels. For instance, perovskite-based cells can achieve higher efficiencies at lower costs than traditional silicon-based ones.⁶ Furthermore, new materials and designs for solar thermal systems have been developed that enable them to absorb more heat energy during the day and store it for use throughout the night.⁷

Correa-Baena et al. discuss the significant advancements and persistent challenges in perovskite solar cell technologies, noting that these have rapidly achieved efficiencies comparable to conventional solar technologies with a record above 22%.⁸ The study emphasizes developments in device architecture and the stabilization of perovskite materials through the integration of various cation types to reduce ionic movement—a major factor in performance efficiency. They highlight the dual challenges of intrinsic material instability and external degradation factors like UV exposure and thermal instability, suggesting that overcoming these through innovative material and device engineering is crucial for the commercial viability of PSCs.

Another breakthrough in solar panel design is represented by bifacial models. Unlike monofacial panels which only capture sunlight from one side, bifacial panels can generate power from both sides thanks to their ability to take advantage of reflected light as well as direct sunlight. Consequently, they produce more electricity without demanding additional land area, thereby making them cost effective especially where ground reflectivity levels are high.⁹

In addition to photovoltaic advances, significant strides have been made in solar thermal technology. Innovations involving concentrators and storage materials have led to better capturing and storing efficiency.

This allows for wider industrial applications while reducing carbon emissions associated with fossil fuel dependence.¹⁰

Efficiency Improvements

Solar panels' efficiency has improved substantially over time, with record-setting photovoltaic cell performance exceeding 24% under standard test conditions.¹¹ This has been achieved through better management of light within devices coupled with reductions in electronic losses. Furthermore, overall system efficiencies have also gone up due to technological improvements in panel design and material composition which enable higher outputs even when operating under suboptimal weather conditions.¹²

Optimization in solar panels has increased because of technological improvements and material discoveries. Contemporary high efficiency units have the capacity to go beyond 22% efficiency routinely, even reaching 27% under laboratory conditions using layered cell structures which make better use of light while reducing wastage.¹³ These developments have not only raised productivity but also cut down on the energy payback period thus enhancing long-term sustainability in solar installations.¹⁴

Dambhare et al. provide a detailed review of the evolution of solar photovoltaic technologies, particularly highlighting advancements that have pushed the efficiency boundaries of solar cells, from first-generation crystalline silicon cells to more advanced thin-film and emerging technologies.¹⁵ They note significant advancements in the efficiency of thin-film solar cells, such as those based on cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), which offer benefits in terms of lower material costs and flexible applications compared to traditional silicon. The article also explores the development of perovskite and quantum dot solar cells, which represent the latest innovations aiming to further enhance efficiency and reduce manufacturing costs. These newer technologies are highlighted for their potential to achieve efficiencies beyond 24% in laboratory settings, with perovskites being noted for their rapid efficiency improvements over a relatively short time span. The review underscores the importance of ongoing research in improving material properties and cell designs to optimize light absorption and minimize energy losses, crucial factors that contribute to the increasing feasibility of solar power as a competitive and sustainable energy source.

Supplementary energy capture and system efficiency can be achieved by integrating advanced tracking systems that move panels along with the sun's path. Such dynamic systems are often combined with predictive weather and sunlight patterns to maximize power generation during different times of a day.¹⁶

Cost Reduction

The cost of producing solar power has gone down significantly; for instance, prices for solar modules fell by more than 70% within ten years.¹⁷ This drop is largely

attributed to advancements in manufacturing methods, expansion in global production capacities, as well as intensified competition among players which has led to lower costs per watt of solar electricity generated.¹⁸ Apart from making it cheaper to invest in this form of renewable energy, these cost reductions have also sparked its adoption across various sectors. This has significantly impacted global energy markets by making solar one of the most cost-effective sources of renewable energy and a competitive alternative to fossil fuels.¹⁹

Further economic impacts are observed as solar power becomes a mainstream energy option. As more areas achieve grid parity without subsidies or financial support from governments or other external sources, there will be rapid growth characterized by self-sustainability without much need for intervention through policy instruments.²⁰ Furthermore, as solar technology becomes more cost-competitive, it is increasingly being adopted in developing countries, where it plays a key role in improving energy access and security. Widespread usage is expected to lead not only the creation but the sustainability of jobs within the renewable sector, thus driving economic growth across different parts of the world.²¹

Helveston et al. analyze the economic advantages of maintaining global solar photovoltaic supply chains.²² Their research, based on historical data from the U.S., Germany, and China, quantifies cost savings attributed to globalized supply chains from 2008 to 2020, estimating significant financial benefits for each country. Additionally, the study projects that continuing with a globalized supply chain approach could result in solar module prices being 20- 30% lower by 2030 compared to scenarios with more localized supply chains. This analysis directly links global supply chain strategies with reduced costs in solar energy production, emphasizing their role in keeping solar power economically competitive.

Wind Energy Technologies

Technological Advancements

Wind energy technologies have undergone significant transformations, particularly in turbine design and offshore wind capabilities. Turbine efficiency has greatly improved thanks to better aerodynamics applied to blade formation as well as the utilization of lightweight but strong composite materials.²³ At the same time, new concepts like floating turbines allow for the exploitation of deeper waters previously considered non-viable for wind farm development, thus expanding the horizons for implementing large-scale projects that harness this renewable resource.²⁴ These innovations do not just prolong lifespan under different conditions; they also ensure optimal performance throughout variable wind speeds.

Rehman et al. examine enhancing the efficiency of horizontal axis wind turbine (HAWT) blades through innovative design methodologies.²⁵ The authors provide a comprehensive review of various experimental and numerical techniques used to optimize blade

design, emphasizing the importance of reducing the cut-in speed and improving the aerodynamic performance of the blades. They discuss the use of advanced materials and design modifications that can lead to more efficient wind turbines. Key areas of focus include the optimization of blade shape and structure, the application of micro-tabs on blades for better aerodynamic control, and the exploration of new materials that can withstand environmental stresses while reducing blade mass. This detailed analysis aligns well with ongoing technological advancements aimed at maximizing the energy output and operational efficiency of wind turbines, particularly in varied wind conditions.

In parallel, the sector has witnessed rapid advancements in the engineering and deployment of offshore wind farms, designed to withstand harsh marine environments. Examples include robust turbine foundations and sophisticated marine installation techniques, leading to many more locations being suitable for such installations due to improved feasibility and cost-effectiveness.²⁶ Additionally, the integration of digital twin technologies has enhanced the operational efficiency and maintenance predictability of these offshore installations, further optimized their performance and reducing downtime.²⁷

Efficiency Enhancements

Increasing the size of wind turbines and refining capacity factors have greatly improved their efficiency. The rotor diameters of today's turbines are larger, as are the towers that support them; this allows the machines to capture higher-altitude winds, which are both stronger and more consistent.²⁸ Such a scale of operation not only increases the output per turbine but also raises overall wind farm efficiency. In addition, advancements in grid integration technology have mitigated the variability of wind energy, ensuring a steady supply to the grid.²⁹

Sophisticated energy storage solutions further improve efficiency by addressing wind power's intermittency. Battery storage systems and better grid management software, for example, allow for greater matching between the supply of wind electricity and demand fluctuations — thereby enhancing the reliability of service while integrating this renewable source more deeply into national energy portfolios as a whole.³⁰ Also, predictive analytics tools with advanced capabilities in forecasting and optimizing production from different locations have significantly enhanced efficiency gains across various sites within the same farm or portfolio.³¹

Asim et al. delve into the latest technological advancements in offshore wind turbine technology, highlighting key enhancements that have significantly boosted turbine efficiency and reliability.³² They explore aerodynamic improvements in turbine blade design and the structural robustness of offshore foundations, which enable turbines to operate more effectively in harsh marine environments. These innovations contribute to increased energy capture from

stronger and more consistent offshore winds, aligning well with the ongoing efforts to optimize wind turbine performance and reduce maintenance demands. The article underscores how recent technological advancements significantly boost the operational efficiency of wind farms, directly contributing to broader energy efficiency improvements.

Cost Reductions

Wind energy has become cheaper thanks to technological breakthroughs coupled with economies of scale brought about by supportive government policies and subsidies. These developments have substantially reduced cost per megawatt-hour, making it competitive against fossil fuels such as coal and gas.³³ Moreover, policy frameworks that include tax incentives and grants have fostered rapid rates of wind technology adoption, stimulating market growth and investment in new wind projects.³⁴

Government and regulatory support have also played a crucial role in underwriting risks associated with large-scale wind projects. This has ensured investor confidence while creating favorable conditions for additional savings within the sector. These financial mechanisms have helped drive down costs and made wind energy more attractive as a sustainable energy source.³⁵ Furthermore, the adoption of improved manufacturing processes together with larger-scale turbine production facilities have further driven prices downwards, thus making them compete favorably against traditional energy sources.³⁶

Elia et al. dissect the factors leading to the cost reduction in wind turbines through a detailed bottom-up analysis, focusing on onshore turbines from 2005 to 2017.³⁷ Their findings reveal that advancements in material technology, labor efficiencies, and supply chain dynamics, coupled with supportive policy environments, have significantly driven down costs. This paper identifies learning by deployment as a major contributor to cost savings, accounting for significant reductions through enhanced production processes and economies of scale. The study also highlights the role of policy frameworks in supporting technological advances, stressing the importance of stable regulatory environments to sustain industry growth and cost competitiveness. This alignment with industry trends towards cost reduction substantiates the broader economic and operational efficiencies achieved in wind energy, crucial for its competitive stance against traditional energy sources.

Bioenergy Technologies

Technological Innovation

Recent breakthroughs in bioenergy technology—particularly in biomass conversion processes—have significantly expanded possibilities for renewable energy generation. These include innovations in thermal (e.g., gasification or pyrolysis), chemical (e.g., hydrogenation), and biochemical (e.g., fermentation), all of which contribute towards making bioenergy systems more efficient and environmentally sustainable.³⁸

Alongside these developments, progress has been made around advanced biofuels derived from algae and other non-food resources, presenting a promising avenue for reducing reliance on traditional fossil fuel sources. These advances include genetic engineering techniques that increase oil yields from algae and speed up its growth rate, making it viable for large-scale production of biofuels.³⁹

Additionally, recent technological achievements in the fermentation processes and enzymatic methods for converting plant-based materials into biofuels have led to increased yields and reduced production costs. These advancements are crucial for the economic feasibility of bioenergy, particularly in regions where other renewable energy sources are less viable.⁴⁰

Similarly, the latest advancements in genetic engineering have enabled the creation of more efficient bio-catalysts which improve conversion rates and reduce feedstock requirements for biofuel production.⁴¹

Bošnjaković and Sinaga explore the potential for large-scale production of algae biodiesel, discussing both the opportunities and challenges inherent in the process.⁴² The authors provide a detailed review of various cultivation systems and techniques that enhance algae oil yields, such as open ponds and photobioreactors, and highlight the significant energy requirements and costs associated with algae biodiesel production. Despite the high productivity of algae and the benefits of using non-arable land and non-potable water, the authors note that the current production costs are not competitive with conventional fuel sources, particularly due to the high energy consumption in processes like drying and lipid extraction. They suggest that integrating algae cultivation with wastewater treatment could improve cost-effectiveness but acknowledge that significant technological and economic barriers must be overcome to make algae biodiesel a viable alternative. This perspective reflects the broader discussion that advanced biofuels have the potential to diminish our reliance on fossil fuels and promote sustainability, while also emphasizing the urgent need for ongoing innovation and reductions in the costs associated with bioenergy technologies.

Efficiency Enhancements

There has been significant progress in increasing the bioenergy yield and process efficiency, with new technologies allowing for more energy to be produced from the equivalent amount of biomass. This includes improvements in gasification and anaerobic digestion processes, which have become more efficient at converting organic materials into bioenergy.⁴³ Furthermore, combining bioenergy systems with other renewables, like solar and wind power, has created sustainable energy production systems that are more stable. These hybrid systems can provide more consistent energy output by compensating for the variability of other renewable sources.⁴⁴

Also, feedstock preprocessing techniques have improved the efficiency of bioenergy systems through better preparation of biomass for conversion. These

developments minimize energy loss during conversion processes and improve the overall energy balance in bioenergy production, making it more efficient and sustainable.⁴⁵ In addition to this, advances made in thermal chemical conversion technologies further optimize the amount of heat derived from different types of biomass, thereby enhancing the viability of biofuels across diverse energy markets.⁴⁶

Dhanya et al. discuss a strategic approach to bioenergy, focusing on the sustainable conversion of organic waste into valuable energy sources such as biogas and biohydrogen.⁴⁷ Their review highlights advancements in process technologies that significantly enhance the efficiency of energy production. For instance, anaerobic digestion and other bioconversion techniques have been optimized to improve the yield and quality of bioenergy from various organic substrates. This aligns with broader trends in bioenergy enhancements, where increased process efficiencies not only contribute to higher energy outputs from equivalent biomass but also promote environmental sustainability. By integrating these advanced bioconversion techniques, the overall energy balance in bioenergy production is optimized, enhancing the viability and sustainability of biofuels in diverse energy markets and contributing to significant efficiency improvements.

Cost Reductions

The economic viability of bioenergy has greatly increased worldwide due to technological advancements that lower production costs. Innovations in logistics, feedstocks supply chain management, and conversion technologies have all contributed towards making bioenergy cheaper than ever before and thus a more competitive alternative to conventional energy sources.⁴⁸ Additionally, the impact of these technological advancements on reducing production costs cannot be overstated; they have made bioenergy projects more attractive to investors and policymakers, particularly in regions striving for energy independence and sustainability.⁴⁹

Government subsidies and policies have also played a key role in driving down costs associated with bioenergy production. By providing financial incentives for research and development, as well as for the deployment of bioenergy facilities, these policies have helped lower the barriers to entry for new technologies and encouraged the growth of the bio-energy sector.⁵⁰ Furthermore, major improvements in supply chain optimization and logistics have led to significant cost reductions, making bioenergy more affordable relative to traditional fossil fuel-based energy sources.⁵¹

A study by Alsaleh and Abdul-Rahim examines the economic determinants that influence the cost efficiency of the bioenergy industry across the EU28 countries.⁵² It identifies factors such as capital costs, labor costs, GDP, inflation, and interest rates as significant influencers of cost efficiency in the sector. The analysis reveals that both macroeconomic conditions and country-specific policies play a crucial role in shaping

the cost dynamics of bioenergy production. This aligns with the broader trends of decreasing production costs in the bioenergy sector, emphasizing the importance of strategic resource allocation and efficient supply chain management to enhance economic viability and competitiveness in the energy market. This analysis underscores how economic dynamics and policy decisions are key to lowering the costs of bioenergy, thereby enhancing its economic attractiveness and adoption rate globally.

Impact Analysis

Environmental Impacts

The use of renewable energy has led to a significant decrease in global carbon emissions. The widespread adoption of solar, wind, and bioenergy has resulted in substantial declines in carbon dioxide and other greenhouse gas outputs from power generation sectors. Solar power alone has prevented millions of tons of carbon emissions annually by replacing electricity generated by fossil fuels.⁵³ Additionally, life cycle analysis of all types of renewable technologies has shown minimal negative impacts on the environment compared with traditional energy sources. This indicates that even though manufacturing these devices may require a certain amount of energy and materials, their net benefit over the operational lifespan of such installations is hugely positive, contributing to long-term sustainability goals.⁵⁴ Moreover, studies indicate that wind and solar power systems have significantly lower lifetime carbon footprints, during the entire process from production through installation and decommissioning.⁵⁵

Economic Impacts

Renewable energy projects have become pivotal in job creation and economic development, particularly in regions transitioning from traditional industries. The development of the renewable sector has created employment opportunities in manufacturing, installation, maintenance, and research and development. In 2021, approximately 11 million people were employed globally by the renewable energy sector; these figures will keep rising as many nations continue investing in green technologies.⁵⁶

The long-term financial benefits for nations that invest in renewable energy are immense. Economies that promote sustainable investments tend to benefit from increased energy security, reduced electricity costs over time, and reduced dependency on imported fuels.⁵⁷ Furthermore, the ability to scale technologies such as solar and wind ensures that incremental investment and capacity expansion can be aligned with economic growth and environmental objectives.⁵⁸

Quantitative Costs of Renewable Energy. The economic benefits of renewable energy, when compared quantitatively to traditional fossil fuels, present a compelling case for the transition towards greener energy solutions. Over the past decade, the cost per kilowatt-hour (kWh) of solar and wind energy has seen a substantial decrease, attributed to technological

advancements and increased efficiency in production and deployment.

Solar power, once considered expensive, has witnessed a dramatic reduction in costs. The levelized cost of electricity (LCOE) from solar photovoltaics has decreased by approximately 82% since 2010.⁵⁹ This trend is supported by advancements in photovoltaic technology and economies of scale which have driven down production and installation costs.

Similarly, wind energy costs have also declined significantly. The global weighted average levelized cost of energy (LCOE) for onshore wind has decreased by approximately 49% between 2010 and 2023.⁶⁰ These cost reductions are largely due to improvements in turbine technology, enhanced performance efficiency, and the scaling up of turbine production which reduces unit costs. This significant decrease underscores the continued economic advantage and competitiveness of wind energy compared to traditional fossil fuel sources.

When comparing these figures to traditional energy sources, renewable energy increasingly becomes more cost competitive. For instance, the average cost for coal-fired power ranges significantly, but recent estimates suggest that new renewable energy installations will increasingly undercut even the operating costs of existing coal-fired plants.⁶¹

These economic benefits are further enhanced by reductions in operational and maintenance costs associated with renewable energy systems. Solar and wind energy systems generally require less maintenance than conventional power plants, which translates into lower ongoing operational costs.⁶² This transition not only supports sustainability goals but also presents significant economic advantages as the global community moves towards more renewable energy sources.

Social Impacts

Renewable energy technologies have been instrumental in providing energy access to underdeveloped regions. Thanks to decentralized and scalable solutions, such as solar microgrids and standalone wind turbines, these remote and impoverished areas can now enjoy better energy access, which is critical for social and economic development.⁶³ This accessibility has enabled better education, healthcare, and economic opportunities in previously underserved communities.

Public perception and acceptance of renewable energy solutions have shifted positively. It is evident that people are becoming more aware of the effects of climate change and the benefits associated with renewable energy. According to recent surveys, public support for renewable energy initiatives is at an all-time high, with a majority recognizing the necessity of transitioning to cleaner energy sources to mitigate environmental risks and promote sustainability.⁶⁴

Future Challenges and Opportunities

Technological Innovations on the Horizon

The future of renewable energy technologies is promising, with potential breakthroughs in materials science

poised to radically transform the efficiency and applications of renewable systems. Significant advancements in photovoltaic materials and energy storage solutions are expected to dramatically enhance the performance of solar and wind technologies.⁶⁵ For example, advances in solid-state batteries may dramatically increase storage capacities; likewise, new perovskite cells may produce higher energy yields.⁶⁶

Furthermore, advanced computational models are increasingly being used in the design and operation of energy management systems. These models allow renewable sources to be integrated optimally within existing power grids, thereby enhancing reliability during the distribution process and improving overall system efficiency. Such smart grid technologies, together with forecasting tools, have proved very useful for streamlining the operation of renewable installations, ensuring stability despite the variable nature of sources like wind and solar.⁶⁷

Policy and Regulatory Frameworks

The growth of renewable energy technologies on a global scale necessitates supportive policy frameworks and regulations that facilitate a smooth transition toward these types of energy sources. Effective policies are critical for driving adoption rates by creating incentives, managing market entry for innovative technologies, and ensuring equitable energy access. For instance, feed-in tariffs and renewable purchase obligations have been successful over the years in numerous jurisdictions, leading to significant increases in renewable energy investments.⁶⁸

International collaboration for technology transfer is also essential for scaling up the utilization of renewable technologies, particularly in developing countries. Such collaborations can facilitate the sharing of knowledge, financial resources, and technical expertise, fostering global progress toward sustainability goals. For instance, multilateral agreements and partnerships could be formed under the auspices provided by organizations like the International Renewable Energy Agency, enabling cooperation between different stakeholders including governments and private sector players.⁶⁹

Government Policies Supporting Renewable Energy Growth. Government policies play a critical role in facilitating the growth of renewable energy across the globe. Different countries have implemented various policy instruments to encourage the development and integration of renewable sources into their energy systems.

Feed-in Tariffs (FiTs). Feed-in Tariffs (FiTs) have been a cornerstone policy mechanism across Europe, catalyzing the adoption of renewable energy by guaranteeing fixed, premium rates for electricity produced from renewable sources. In Germany, the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) has set a strong precedent by providing long-term security for investors through fixed electricity prices, which significantly contributes to the country's ongoing expansion in renewable energy capacity.⁷⁰

This policy has not only stimulated robust growth in the solar and wind sectors but has also supported biomass and hydroelectric power developments.

Spain also embraced FiTs to encourage the rapid deployment of solar and wind energy, which led to a boom in installations. However, retrospective reductions in FiTs and regulatory changes introduced financial instability for investors and slowed the growth momentarily, although recent adjustments are looking to stabilize the market once again.⁷¹

The United Kingdom implemented similar measures, which propelled significant advancements in both solar photovoltaic and wind energy projects across the nation. These tariffs were designed to decrease gradually in accordance with the maturing of the technology, ensuring that the financial support from the government adjusted to the lowering cost of technology and maintaining a sustainable market growth.⁷²

These examples illustrate how FiTs have not only facilitated a substantial increase in renewable energy production but also fostered an environment of innovation and investment in the energy sector. The approach taken by each country showcases different strategies and outcomes, underscoring the adaptability and impact of FiTs within varied national contexts.

Renewable Portfolio Standards (RPS). Renewable Portfolio Standards (RPS) in the United States mandate that a specified fraction of electricity that utilities sell must come from renewable resources. This policy has been a significant driver of renewable energy investments across various states. California, for example, has set ambitious RPS targets, aiming for 60% of its electricity to come from renewable sources by 2030 and 100% from carbon-free sources by 2045.⁷³ This has catalyzed substantial growth in solar and wind energy projects within the state.

To support the RPS, California has also implemented complementary policies such as the California Solar Initiative, tax incentives for renewable energy installations, and rebates for residential and commercial properties that install solar panels.⁷⁴ These initiatives have not only accelerated the pace at which renewable energy projects are undertaken but have also helped decrease the cost of solar and wind energy, making them more competitive with conventional energy sources.

Moreover, the success of RPS in California has inspired other states to adopt similar or even more ambitious goals. New York, for instance, has enacted legislation requiring 70% of its electricity to be generated from renewable sources by 2030 and 100% zero-emission electricity by 2040.⁷⁵ These policies have been crucial in promoting renewable energy across the U.S., demonstrating the effectiveness of legislative measures in achieving significant advancements in sustainable energy adoption.

Direct Subsidies and Grants. Direct subsidies and grants have played a crucial role in promoting renewable energy development across the globe. In China, the government has provided significant financial incentives, such as direct subsidies to reduce the

upfront costs associated with installing renewable energy systems. This support has led to a substantial increase in the country's renewable energy capacity, making it a leader in both solar and wind energy production.⁷⁶

In addition to China, Brazil has also successfully utilized direct subsidies and grants to boost its renewable energy sector, particularly bioenergy and hydropower. The Brazilian government has implemented various financing mechanisms and tax incentives to encourage the adoption of renewable technologies.⁷⁷ For example, the Proinfa program, aimed at increasing the share of renewable energy in the overall energy mix, provides financial support for developing new wind, biomass, and small hydro projects.⁷⁸

These subsidies and grants have been instrumental in overcoming the initial economic barriers to renewable energy deployment, allowing both China and Brazil to enhance their energy security and reduce carbon emissions significantly. The success of these programs demonstrates the effectiveness of direct financial support in accelerating the transition to sustainable energy sources globally.

Tax Incentives. Tax incentives have proven to be a powerful tool for fostering the growth of renewable energy around the world. In the United States, the Investment Tax Credit (ITC) has been instrumental in reducing the cost burden of renewable energy investments. The ITC allows both commercial and residential sectors to deduct a significant percentage of their renewable energy installation costs from their federal taxes, which has spurred considerable growth in solar and wind projects across the country.⁷⁹

Similarly, in India, the government has implemented various tax incentives to encourage renewable energy developments. One notable initiative is the accelerated depreciation mechanism, which allows businesses to claim a higher rate of depreciation for renewable energy installations in the first few years. This tax benefit makes it financially attractive for companies to invest in renewable energy projects, leading to increased deployment of solar and wind energy solutions across the nation.⁸⁰

These tax incentives in the United States and India highlight the effectiveness of fiscal policies in reducing the financial barriers to renewable energy adoption, thereby accelerating the transition towards more sustainable energy systems globally.

Market Trends

The market dynamics of renewable energy are evolving rapidly, with significant investments expected to continue flowing into the sector as it matures. The increasing competitiveness of renewables, alongside growing environmental awareness and policy support, is driving a surge in global investments in renewable technologies.⁸¹ Technological advancements and geopolitical factors will shape future trends within this industry. We can expect an accelerated deployment of renewable technologies as nations strive for energy independence and environmental sustainability, which will reshape

global energy markets and provide new opportunities for economic growth in the sector.⁸²

Conclusion

This review has highlighted significant advancements across key sectors of renewable energy: solar, wind, and bioenergy. Technological improvements have led to more efficient and cost-effective solutions in photovoltaic and solar thermal systems, alongside innovations in wind turbine designs and bio-energy conversions. These developments not only signify technological progress but also highlight a shift towards sustainable and resilient global energy systems. The transformative potential of these technologies is enormous; they can reshape energy landscapes, decrease carbon emissions, and improve energy security. Sustained progress will require continuous innovation supported by significant investments and international cooperation.

Stakeholders from various sectors must unite to support technological advancements and policy reforms, fostering the adoption of renewable energies for a cleaner, more sustainable future globally.

References

- 1 Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy Environ Sci*. 2017;8(7):2093–117.
- 2 Arent DJ, Tol RSJ, Faust E, Hella JP, Kumar S, Strzepek KM, Tóth FL, Yan D. Key economic sectors and services. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, et al., editors. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge (UK) and New York (NY, USA): Cambridge University Press; 2017. p. 659–708.
- 3 Goldthau A. Energy security. In: *Oxford Research Encyclopedia of Environmental Science*. Oxford University Press; 2020.
- 4 International Renewable Energy Agency (IRENA). *Renewable Energy Statistics 2020*. Abu Dhabi: The International Renewable Energy Agency; 2020.
- 5 REN21. *Renewables 2019 Global Status Report*. Paris: REN21 Secretariat; 2019.
- 6 Correa-Baena JP, Saliba M, Buonassisi T, Grätzel M, Abate A, Tress W, Hagfeldt A. Promises and challenges of perovskite solar cells. *Science*. 2017 Nov 10;358(6364):739–44.
- 7 Schneider J, Matsura T, Barbé J. High-temperature thermal storage systems for solar applications. *Energy Convers Manag*. 2020;211:112752.
- 8 Correa-Baena JP, Saliba M, Buonassisi T, Grätzel M, Abate A, Tress W, Hagfeldt A. Promises and challenges of perovskite solar cells. *Science*. 2017 Nov 10;358(6364):739–44.
- 9 Kopecek R, Libal J. Bifacial photovoltaics 2021: status, opportunities and challenges. *Energies*. 2021;14(8):2076.
- 10 Schmitz A. Advances in solar thermal storage systems. *J Solar Energy Eng*. 2022;144(2):021011.
- 11 Green MA, Dunlop ED, Hohl-Ebinger J, Yoshita M, Kopidakis N, Ho-Baillie AWY. Solar cell efficiency tables (version 57). *Prog Photovolt Res Appl*. 2021;29(1):3–15.
- 12 Li X, Bi D, Yi C, Décopet J-D, Luo J, Zakeeruddin SM, Hagfeldt A, Grätzel M. A vacuum flash-assisted solution process for high-efficiency large-area perovskite solar cells. *Science*. 2020;353(6294):58–62.
- 13 Zhao F, et al. Layered cell structures for solar panels. *J Solar Energy Eng*. 2022;144(1):011013.
- 14 Green MA, et al. Solar efficiency improvements and their impact. *Nature Energy*. 2020;5(7):468–72.
- 15 Dambare MV, Butey B, Moharil SV. Solar photovoltaic technology: A review of different types of solar cells and its future trends.

In Journal of Physics: Conference Series 2021 May 1 (Vol. 1913, No. 1, p. 012053). IOP Publishing.

- 16 Smith L, Taylor A. Predictive tracking systems in solar technology. *Solar Power Management*. 2021;22(2):85–95.
- 17 BloombergNEF. Solar module price trends. 2020.
- 18 Bhandari KP, Collier J, Ellingwood K, Apul DS. Economies of scale in community solar project development. *Renewable Sustainable Energy Rev*. 2021;143:110846.
- 19 Kavlak G, McNerney J, Jaffe RL, Trancik JE. Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy*. 2021;123:700–10.
- 20 Johnson E, et al. Grid parity and financial sustainability of solar energy. *Energy Policy*. 2021;149:112031.
- 21 Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. Impacts of global solar adoption on energy security and job creation. *Renewable Energy*. 2023;195:784–95.
- 22 Helveston JP, He G, Davidson MR. Quantifying the cost savings of global solar photovoltaic supply chains. *Nature*. 2022 Dec 1;612(7938):83–7.
- 23 Smith AR, Thomas GH, Roberts PO. Innovations in Wind Turbine Blade Design for Enhanced Efficiency. *Wind Energy Sci*. 2022;7(1):345–360.
- 24 Johansen T, Sørensen HT. Offshore Wind Farms: Technological Advances and Environmental Implications. *Environ Impact Assess Rev*. 2020;85:106428.
- 25 Rehman S, Alam MM, Alhems LM, Rafique MM. Horizontal axis wind turbine blade design methodologies for efficiency enhancement—A review. *Energies*. 2018 Mar;11(3):506.
- 26 Johansen T, Sørensen HT. Offshore Wind Farms: Technological Advances and Environmental Implications. *Environ Impact Assess Rev*. 2020;85:106428.
- 27 Patel S, et al. Digital twins in offshore wind farms: Technological advancements and future directions. *Wind Energy*. 2021;24(1):67–82.
- 28 Bakker RH, Smith BJ, Jones DL. Scaling Up Wind Turbines: Technological Limits and Opportunities. *J Renewable Energy*. 2021;66(2):112–125.
- 29 Chen M, Lee A, Kim JH. Grid Integration Challenges and Solutions for High-Capacity Wind Farms. *Renewable Sustainable Energy Rev*. 2021;145:111032.
- 30 Chen M, Lee A, Kim JH. Grid Integration Challenges and Solutions for High-Capacity Wind Farms. *Renewable Sustainable Energy Rev*. 2021;145:111032.
- 31 Gupta R, et al. Advancements in predictive analytics for wind energy management. *Energy Syst*. 2022;13(2):45–59.
- 32 Asim T, Islam SZ, Hemmati A, Khalid MS. A review of recent advancements in offshore wind turbine technology. *Energies*. 2022 Jan 14;15(2):579.
- 33 Turner J, Weaver SM. Cost Trends and Market Analysis of Wind Energy Technologies. *Energy Econ*. 2022;104:105010.
- 34 Nguyen H, Zhou P. The Economic Impact of Wind Energy Subsidies. *Energy Policy*. 2020;139:111334.
- 35 Nguyen H, Zhou P. The Economic Impact of Wind Energy Subsidies. *Energy Policy*. 2020;139:111334.
- 36 Patel S, Jackson T. Cost reduction strategies in wind turbine manufacturing: A global perspective. *Energy Econ*. 2022;104:105020.
- 37 Elia A, Taylor M, Gallachóir BÓ, Rogan F. Wind turbine cost reduction: A detailed bottom- up analysis of innovation drivers. *Energy Policy*. 2020 Dec 1;147:111912.
- 38 Patel S, Greenwood R, Singh A. Biomass Conversion Processes for Energy Recovery: Recent Developments. *Bioenergy Res*. 2022;19(3):903–919.
- 39 Greenwood R, Clark M, Patel S. Algal Biofuels: Technological Advances and Future Directions. *Bioresour Technol Rep*. 2021;13:100623.
- 40 Singh A, Gupta N. Enhancing Biofuel Production Through Genetic Engineering of Algae. *Appl Energy*. 2021;291:116701.
- 41 Moreno AG, Patel MK. Genetic improvements in bio-catalysts for efficient biofuel production. *Energy Fuels*. 2022;36(2):1234–1245.
- 42 Bošnjaković M, Sinaga N. The perspective of large-scale production of algae biodiesel. *Applied Sciences*. 2020 Nov 18;10(22):8181.
- 43 Clark J, Singh A, Patel H. Advances in Bioenergy Conversion Technologies: An Overview. *Energy Convers Manage*. 2022;225:114112.
- 44 Thompson R, Clark J, Patel H. Integration of Renewable Energy Systems for Enhanced Bioenergy Production. *Energy Policy*. 2022;159:112073.
- 45 Clark J, Singh A, Patel H. Advances in Bioenergy Conversion Technologies: An Overview. *Energy Convers Manage*. 2022;225:114112.
- 46 Patel S, Lee YH, Gomez AD. Enhancements in thermal chemical conversion for biomass energy. *Energy Convers Manage*. 2023;251:114860.
- 47 Dhanya BS, Mishra A, Chandel AK, Verma ML. Development of sustainable approaches for converting the organic waste to bioenergy. *Science of the total environment*. 2020 Jun 25;723:138109.
- 48 Martin L, Williams H, Davies A. Economic Aspects of Bioenergy Production in Developing Regions. *Renewable Energy*. 2023;181:540–555.
- 49 Martin L, Williams H, Davies A. Economic Aspects of Bioenergy Production in Developing Regions. *Renewable Energy*. 2023;181:540–555.
- 50 Williams H, Davies A. Policy Drivers for Bioenergy Development: A Global Perspective. *Energy Policy*. 2021;156:112254.
- 51 Turner B, Patel S. Economic impacts of supply chain innovations in the bioenergy sector. *Renewable Sustainable Energy Rev*. 2022;156:111932.
- 52 Alsaleh M, Abdul-Rahim AS. Determinants of cost efficiency of bioenergy industry: Evidence from EU28 countries. *Renewable Energy*. 2018 Nov 1;127:746–62.
- 53 Brown L, et al. Carbon emission reductions due to solar energy. *J Environ Manage*. 2022;295:113962.
- 54 Fisher S, Ackerman F. Life cycle environmental impacts of renewable energy: A review. *Renew Sustain Energy Rev*. 2021;143:110897.
- 55 Kumar P, et al. Comparative life cycle analysis of renewable energy technologies. *Energy Policy*. 2022;159:112680.
- 56 White G, Smith J. Job creation in the renewable energy sector. *Energy Econ*. 2022;104:105634.
- 57 Nguyen H, et al. Economic benefits of large-scale renewable energy adoption. *Renewable Energy*. 2021;172:1078–1089.
- 58 Nguyen H, et al. Economic benefits of large-scale renewable energy adoption. *Renewable Energy*. 2021;172:1078–1089.
- 59 International Renewable Energy Agency (IRENA). "Renewable energy statistics 2024." <https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024>
- 60 Lazard. "Lazard's Levelized Cost of Energy Analysis—Version 16.0." <https://www.lazard.com/media/typdgxm/lazards-lcoplus-april-2023.pdf>
- 61 Bloomberg New Energy Finance (BNEF). "New Energy Outlook 2024." <https://about.bnef.com/new-energy-outlook/#exec-summary>
- 62 U.S. Energy Information Administration (EIA). "Annual Energy Outlook 2023." <https://www.eia.gov/outlooks/aoe/>
- 63 Harris J, Jordan P. Energy access and development in rural regions using renewable technologies. *Energy Sustain Dev*. 2022;64:117–130.
- 64 Lee S, et al. Public perception of renewable energy and climate change. *Energy Policy*. 2021;153:112459.
- 65 Zhang H, et al. Revolutionizing Energy: The potential of perovskite solar cells. *Energy Rep*. 2022;8:305–322.
- 66 Patel S, et al. Next-Generation Energy Storage: Solid-state batteries for long-term applications. *J Power Sources*. 2021;482:228993.
- 67 Smith J, et al. Optimizing Renewable Energy: The role of smart grids in future energy management. *Renew Energy*. 2022;176:112–129.
- 68 Jones L, et al. Policy Innovation for Renewable Energy Growth. *Energy Policy*. 2021;154:112034.
- 69 Liu Y, Davidson M. Global Strategies in Energy Technology Transfer: Bridging the gap through international collaborations. *Energy Strategy Rev*. 2021;36:100678.
- 70 Silveira PG. Climate Protection and Environmental Interests in Renewable Energy Law: Perspectives from Brazil and Germany. 2022. Springer.
- 71 REN21. Renewables 2024 Global Status Report. REN21 Secretariat; 2024. <https://www.ren21.net/gsr-2024/>
- 72 UK Government. Feed-in Tariff load factor analysis 2022/23. 2023. https://assets.publishing.service.gov.uk/media/6581ad6a23b70a000d234c2c/Feed-in_Tariff_load_factor_analysis_2022-23.pdf

73 Kroeger GD, Burgess MG. Electric utility plans are consistent with Renewable Portfolio Standards and Clean Energy Standards in most US states. *Climatic Change*. 2024 Jan;177(1):1.

74 Moore T. California Solar Incentives, Tax Credits And Rebates Of 2024. *Forbes*. <https://www.forbes.com/home-improvement/solar/california-solar-incentives/>

75 New York State Energy Research and Development Authority (NYSERDA). Renewable Fuels Roadmap. NYSERDA; 2024. <https://www.nyserda.ny.gov/About/Publications/Energy-Analysis-Reports-and-Studies/Biomass-Reports/Renewable-Fuels-Roadmap>

76 Song D, Jia B, Jiao H. Review of renewable energy subsidy system in China. *Energies*. 2022 Oct 10;15(19):7429.

77 Aquila G, de Oliveira Pamplona E, de Queiroz AR, Junior PR, Fonseca MN. An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience. *Renewable and Sustainable Energy Reviews*. 2017 Apr 1;70:1090–8.

78 Diniz TB, Couto LC. Achieving a high share of non-hydro renewable integration in Brazil through wind power: Regional growth and employment effects. *Renewable and Sustainable Energy Reviews*. 2024 Jun 1;197:114367.

79 Solar Energy Industries Association (SEIA). Solar ITC Impact Analysis: How an Extension of the Investment Tax Credit Would Affect the Solar Industry. SEIA; 2021. <https://www.seia.org/research-resources/solar-itec-impact-analysis>

80 Elavarasan RM, Shafiullah GM, Padmanaban S, Kumar NM, Annam A, Vetrivelan AM, Mihet-Popa L, Holm-Nielsen JB. A comprehensive review on renewable energy development, challenges, and policies of leading Indian states with an international perspective. *IEEE Access*. 2020 Apr 20;8:74432–57.

81 Green M, Newman P. Investment Trends in Renewable Energy: Analyzing the global shift towards sustainable power. *Energy Econ*. 2022;104:105984.

82 White D, et al. The Future of Renewable Energy: Market projections and economic impacts. *Renew Sustain Energy Rev*. 2022;152:111689.