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Renewable Energy Technologies within Intellectual Property: Advances, Challenges, and the Path Forward

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Abstract

Current literatures have widespread knowledge on renewable energy technologies and their associated intellectual property. The primary objective of this paper is to synthesize recent advances, patent trends, and cost trajectories within a cohesive framework. It reviews developments by analyzing intellectual property through patent filing trends from 2000 to 2023 and explores improvements across major categories of renewable energy generation and enabling technologies. China, the United States, and Japan lead global innovation in renewable energy. In 2022, approximately 97% of all filed patents focused on solar, wind, hydropower, and bioenergy. The paper also examines cost reductions in electricity production driven by technological advancements in renewables. These developments highlight significant progress in innovation and adoption; however, challenges remain. Key obstacles include technical limitations in scaling deployment, uneven regional adoption, and complex intellectual property and patenting dynamics. Expanding renewable technology adoption will require sustained investment in research and development, robust policy frameworks, and international collaboration on technology licensing and transfer.

Keywords: Renewable energy, Solar PV, Wind energy, Hydropower, Geothermal energy, Bioenergy, Energy storage

1. Introduction

Following the disruptions caused by the COVID-19 pandemic and the subsequent global economic recovery, the world economy experienced a moderation in growth trends in 2024. Global GDP (Gross Domestic Product) growth averaged 3.2%, which is close to the pre-pandemic average of 3.4% observed from 2010 to 2019. In 2024, global energy demand increased by 2.2%, a significantly faster rate compared to the annual average of 1.3% recorded between 2013 and 2023. Electricity demand increased by 4.3%, outpacing overall energy demand (IEA, 2025). This surge was fueled by record high temperatures, greater access to electricity-intensive appliances like air conditioning, a shift towards manufacturing processes that require more electricity, and rising power consumption due to digitalization, AI, and the growing electrification of end-users (IEA, 2025).

Energy supply sources can be broadly divided into three main categories: fossil fuels (oil, natural gas and coal), nuclear resources, and renewable energy sources (Hussain, et al., 2017). Although fossil fuels remain the dominant energy source today, their lifecycle—extraction, processing, transportation, and combustion or conversion into petrochemicals—emits significant greenhouse gases and harmful pollutants (Wolf et al., 2025). Furthermore, fossil fuel reserves are finite and will eventually be depleted. In contrast, renewable energy offers a clear advantage: its resources are virtually inexhaustible.

Renewable energy can be used for electricity generation, space and water heating/ cooling and transportation. According to the report released by International Energy Agency in 2019, renewable energy sources expanded at an average annual growth rate of 2.0% from 1990 to 2017 (IEA, 2019). In 2017, renewable energy contributed to 13.6% of the world's Total Primary Energy Supply (TPES) (Table 1). In 2024, renewable technologies contribute the most to the growth in global energy supply, accounting for 38%. This is followed by natural gas at 28%, coal at 15%, oil at 11%, and nuclear at 8% (IEA, 2025). It is projected by International Energy Agency (IEA) that renewable energy consumption in the power, heat and transport sectors increases near 60% over 2024-2030 (IEA, 2024). The increase boosts the share of renewables in final energy consumption to nearly 20% by 2030.

Table 1. Energy Shares in Global Total Primary Energy Supply (TPES) in 2017. (IEA, 2019)

Energy Sources	Fossil Fuels			Nuclear	*Renewable*	Others
	Oil	Natural Gas	Coal			
Percentage (%)	31.8	22.2	27.1	4.9	*13.6*	0.4

In terms of global electricity production, in 2017, renewable energy was the second-largest source of global electricity production that year, accounting for 24.5%, behind coal at 38.5% (Table 2) (IEA, 2019). By 2022 and 2023, renewables represented 29% and 30% of the total global electricity generation, respectively (Energy Institute, 2024). From 2026 to 2030, several renewable energy milestones are expected to achieve, including wind and solar power generation both surpasses nuclear in 2026 and wind-based electricity generation surpasses hydropower in 2030 (IEA, 2024). By 2030, the IEA projects that renewable energy may expand to 46% of global electricity generation, with wind and solar PV accounting for 30% combined (IEA, 2024).

Table 2. Energy Shares in Global Electricity Production in 2017. (Reference: IEA, 2019)

Energy Sources	Fossil Fuels			Nuclear	*Renewable*	Others
	Oil	Natural Gas	Coal			
Percentage (%)	3.3	23.0	38.5	10.3	*24.5*	0.4

Current literatures have widespread knowledge on renewable energy technologies and their intellectual property. This paper aims to synthesize recent advances, patent trends, and cost trajectories within a cohesive framework. It begins with an overview of diverse renewable energy sources, including solar, wind, hydropower, geothermal, bioenergy, and ocean energy. The discussion then explores recent technological developments, supported by intellectual property data on patent filings from 2000 to 2023. Key areas of focus include improvements in solar PV efficiency, innovative wind turbine designs, enhanced bioenergy conversion processes, advancements in energy storage, and the integration of artificial intelligence for optimizing renewable energy distribution. Subsequently, the paper examines cost reductions in electricity generation driven by these technological advancements. While significant progress has been made, the study also addresses persistent challenges such as technical limitations in scaling deployment, uneven regional adoption, and complex intellectual property and patenting dynamics. This paper will shed light to inform policy development and guide investment decisions in the renewable energy sector.

2. Types of Renewable Energy Generations

Renewable energy is generated by harnessing natural resources that are inexhaustible. These resources include sunlight, wind, water, geothermal heat, and biomass. Unlike fossil fuels, which can be depleted, renewable energy sources are continuously replenished by natural processes, making them sustainable and environmentally friendly options for power generation (UNICEF, 2023). In this session, the main six types of renewable energy technologies will be briefly introduced.

2.1 Solar Energy

Solar radiation, also referred to as electromagnetic radiation, is the light emitted by the sun. Although every location on Earth receives sunlight throughout the year, the amount of solar radiation that reaches a specific spot on the Earth's surface can vary. Solar technologies are designed to capture this radiation and convert it into useful forms of energy. The two primary types of solar energy technologies are photovoltaic (PV) and concentrating solar-thermal power (CSP). Photovoltaic technology uses solar panels to absorb sunlight and convert it into electricity through PV cells. When sunlight strikes the PV cells, it generates electrical charges that move in response to an internal electrical field, resulting in the flow of electricity. On the other hand, concentrating solar-thermal power employs mirrors to

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reflect and concentrate sunlight onto receivers that collect solar energy and transform it into heat. This heat can then be used to generate electricity or stored for future use.

2.2 Wind Energy

Wind energy utilizes the power of the wind to generate electricity. Wind formation is primarily driven by four physical factors: the pressure gradient force, temperature differences, Earth's rotation, and friction. These elements interact to move air across the planet's surface, shaping weather patterns and climate. The pressure gradient force is the main mechanism, pushing air from regions of high pressure toward areas of low pressure. Temperature contrasts—such as those between the equator and the poles—further influence wind behavior. Additionally, Earth's rotation introduces the Coriolis effect, which deflects air movement, while friction from terrain and obstacles like trees and buildings reduces wind speed. Modern wind turbines, which are advanced versions of windmills, capture and convert the kinetic energy produced by wind into electrical energy. Wind turbines operate by capturing wind with their blades, which then turn a rotor connected to a generator. This generator transforms the mechanical energy into electrical energy, which is subsequently fed into the power grid. Wind farm can be built on land (onshore) or in the sea (offshore).

2.3 Hydropower

Hydropower, also known as hydroelectric power, is one of the oldest and most significant sources of renewable energy. It generates electricity by harnessing the natural flow of moving water. This process typically involves a dam or diversion structure that creates an elevation difference, allowing water to flow from a higher point to a lower point, turning turbines that generate electricity. Hydropower facilities can vary in size, from large dams to small-scale systems that utilize municipal water flows or irrigation ditches. Hydropower is an affordable source of electricity, often resulting in lower energy bills for states that rely heavily on it. It also has relatively low costs throughout the duration of a project, including maintenance, operations, and fuel.

2.4 Geothermal Energy

Geothermal energy comes from the Earth's natural heat, which is produced by the decay of radioactive materials and the residual heat from the planet's formation. This heat can be accessed by drilling wells into geothermal reservoirs, which are areas where hot water and steam are trapped beneath the Earth's surface. The heat energy is then brought to the surface and used for various applications, such as electricity generation, heating, and cooling. Geothermal energy offers several advantages, including its ability to consistently produce electricity, low environmental impact, and potential to provide heating and cooling without the need for imported fuel.

2.5 Bioenergy

Bioenergy is derived from recently living organic materials known as biomass, which can be utilized to produce transportation fuels, heat, electricity, and various other products. Biomass includes crop residues, forest byproducts, purpose-grown grasses, woody energy crops, microalgae, urban wood waste, and food waste. It can be converted into liquid fuels, called "biofuels," that function similarly to fossil-based fuels such as gasoline, jet fuel, and diesel, with ethanol and biodiesel being the most common first-generation biofuels. Biopower technologies convert renewable biomass into heat and electricity through processes similar to those used with fossil fuels, primarily via combustion, anaerobic decomposition, or conversion to gas or liquid fuels. As a critical link between energy, agriculture, and waste management, bioenergy promotes sustainable development and supports resilient, low-carbon systems that adapt to climate and economic changes.

2.6 Ocean Energy

Ocean energy, also referred to as marine energy or hydrokinetic energy, is a renewable resource that generates electricity by harnessing the natural movement of ocean water. This energy can be captured from various sources,

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such as waves, tides, and ocean currents. Ocean energy and hydropower differ primarily in their sources, technologies, and maturity: hydropower harnesses river flow through turbines and is a fully commercialized technology (TRL 9), while ocean energy relies on tides, waves, currents, and thermal gradients using devices like tidal stream turbines and wave converters, most of which remain at early to mid-development stages (TRL 3–7). Recent pilots illustrate this gap: Eco Wave Power's Los Angeles project (2025) marks the first U.S. onshore wave energy installation (Los Angeles Times, 2025). Both hydropower and ocean energy face environmental and permitting challenges—hydropower projects often require lengthy licensing to address habitat and fish migration concerns, whereas ocean energy developments navigate complex maritime regulations and ecosystem impact assessments.

3. Recent Advances in Renewable Energy Technologies

Renewable energy generation technologies have grown rapidly over the past two decades, driven by advancements in technologies, increased investments (Tiismus, et al., 2025).

3.1 Technology Advancements in Terms of Intellectual Property- Filed Patents

Innovative ideas are typically secured through filed patents to safeguard intellectual property. The source data presented in this section was obtained from IRENA INSPIRE- International Standards and Patents in Renewable Energy Platform by International Renewable Energy Agency (www.irena.org/Inspire) in November 2025 and subsequently replotted. This dataset originates from the EPO PATSTAT 2024 Autumn edition and follows the Climate Change Mitigation Technologies (Y02) classification by EPO (IRENA INSPIRE, 2025). As stated on their website, IRENA INSPIRE offers comprehensive—though not exhaustive—information on patents filed worldwide for renewable energy technologies. It is important to note that there is usually an 18-month gap between a patent application's filing date and its publication date. Thus, data from the two most recent years (2024–2025) are incomplete at the time of this paper drafting and have been excluded from this section.

Filed Patents in Main Renewable Energies from Year 2000 to 2023

Figure 1 shows annual added filed patents in renewable energy technologies from 2000 to 2023 in the six main areas (IRENA INSPIRE, 2025). After 2010, there is a notable increase in the number of patents over the years, indicating a surge in research and development activities in renewable energy technologies. In 2022, around 113,900 patents were filed in the areas of solar, wind, hydropower and bioenergy, about 97% of total filed patents among all renewable technologies.

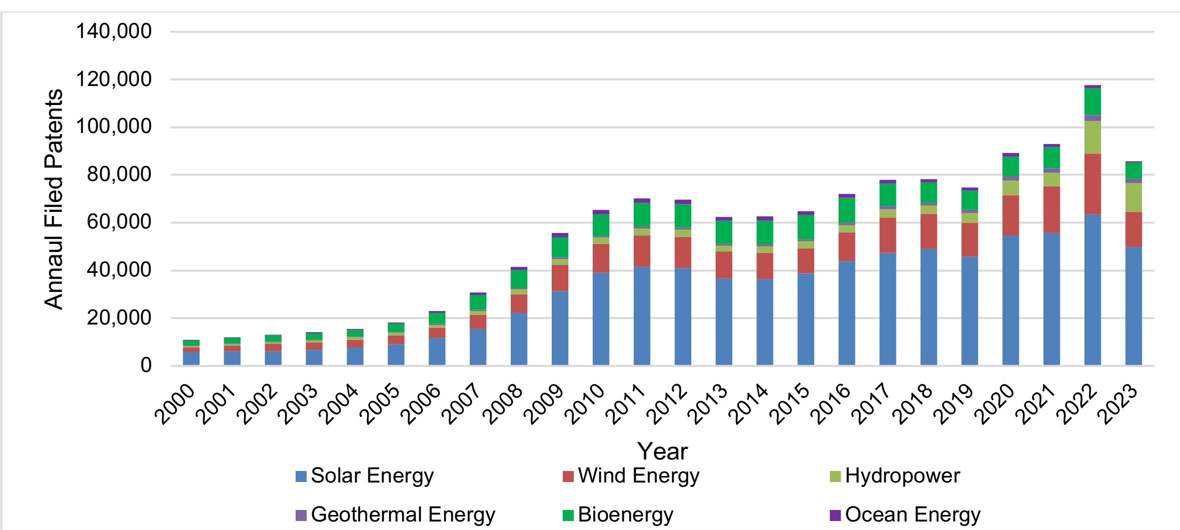

Figure 1. The annual number of filed patents in the six main renewable energies from the year 2000 to 2023. Source: IRENA INSPIRE (November 26, 2025) and replotted.

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Cumulative Filed Patents in Renewable Energies From 2000 to 2023 by Represented Countries

Table 3 presents the cumulative number of patents filed in renewable energies from 2000 to 2023, ranked by represented countries from highest then went down. China, United States and Japan are leading the way on innovations in renewable energies.

Table 3. Cumulative Number of Filed Patents in Renewable Energies From 2000 to 2023 by Represented Countries.

Country	Filed Patents from 2000-2023 in Renewable Energies
China	700,402
United States	154,845
Japan	107,718
South Korea	96,318
Germany	41,163
Australia	23,201
Canada	22,736
Spain	18,394
Brazil	14,545
Russian	13,504
France	8,665
Mexico	7,525
South Africa	4,509
New Zealand	2,725
Norway	1,939
Argentina	1,923
Finland	1,246
India	1,224
Sweden	1,087
Saudi Arabia	554
Egypt	236

Filed patents in Enabling Technology Areas from Year 2000 to 2023

Transforming an innovative concept into a practical end-user product typically requires what is known as "*enabling technology*." This technology acts as a bridge, connecting innovations across different sectors. An enabling technology is an invention or innovation that provides the foundational tools, inputs, or infrastructure necessary for developing new products, services, or processes. Unlike end-user products, enabling technologies are not the final deliverables; rather, they serve as essential prerequisites that drive innovation across multiple domains. Figure 2 shows annual number of filed patents in enabling technologies areas including batteries, electromobility, energy efficiency, fuel cells, smart grids and hydrogen from the year 2000 to 2022. A clear increasing trend is shown among all enabling technologies. In 2022, around 115,000 patents were filed in the areas of batteries and electromobility (including energy storage and charging stations), about 82% of total filed patents in enabling technologies.

3.2 Advances in Renewable Energy Generations and Enabling Technologies

This section outlines the progress made in developing the four leading renewable energy generation technologies, along with advancements in energy storage and the integration of artificial intelligence for renewable energies distribution.

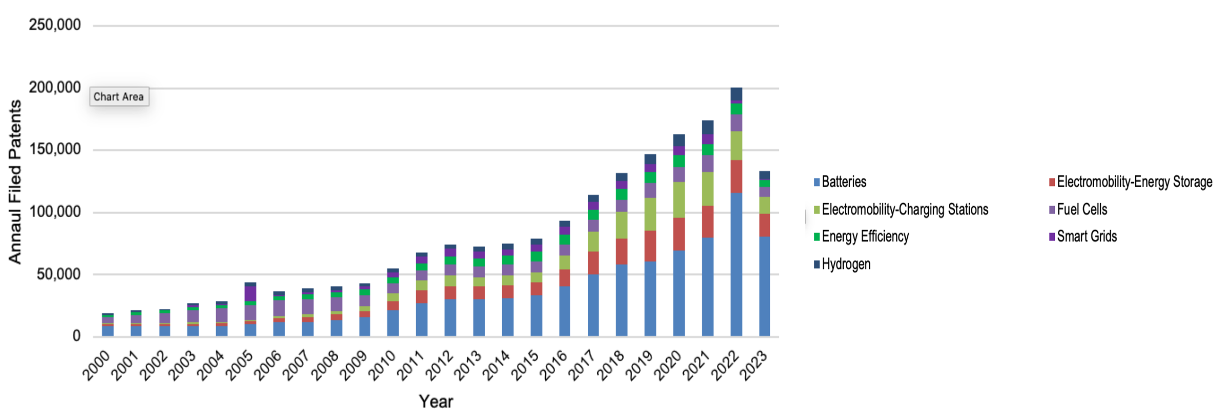

Figure 2. The annual number of filed patents in enabling technologies areas from the year 2000 to 2023. Source: IRENA INSPIRE (November 26, 2025) and replotted.

Advances in Solar Energy

Recent advancements in solar PV technology have focused on improving the efficiency of solar cells and reducing the cost of solar energy generation through the development of new materials, novel cell architectures, and manufacturing techniques (Ali, et. al., 2025). Shifting from traditional crystalline silicon cell technology, new technologies such as perovskite, quantum dot, and organic solar cells have garnered more attention and shown potential to achieve more efficiency.

One significant breakthrough is the development of all-perovskite tandem solar cells, which have achieved record-breaking efficiency levels (Liu, et al., 2025). These cells stack multiple layers that absorb different parts of the solar spectrum, making them more efficient and less expensive than traditional silicon-based solar cells. Researchers have been working on stabilizing perovskite materials to prevent degradation, and the latest advancements have shown promising results in improving light absorption and efficiency.

Emerging solar PV applications have expanded beyond their conventional installations. Agrivoltaic systems integrate solar panels with agricultural lands to enhance agricultural productivity under optimized conditions. Aquavoltaic systems are to deploy floating PV arrays in reservoirs to address land scarcity while reducing improving solar panel efficiency (Gadhiya, et al., 2024).

Advances in Wind Energy

Wind energy has gone through rapid growth over the past decade, similar to PV technologies. Wind power generation is now considered to be a mature technology (Zhang, et. al., 2020). In twelve years from 2010 to 2022, the global cumulative onshore wind generation increased from 178 to 837 GW, by five folds (GWEC, 2023), with China leading the way in both onshore and offshore wind power capacity. The recent advancements in wind energy are mainly derived to overcome the intermittency, the wind's inherent shortcoming. There have been extensive research efforts to enhance energy harvesting, stabilize the intermittent power generation and storage. Advancements in turbine design are to optimize aerodynamics and new materials exploration, and development are to boost reliability and cost-effectiveness of turbines (Jain and Trumboo, 2024).

Floating wind and airborne wind energy are two emerging technologies in wind energy development that can tap into previously untapped sources in deep offshore and high-altitude winds (Tiismus, et al., 2025).

Floating wind technology utilizes new foundation designs, such as floating platforms, to anchor wind turbines in deep waters far from the coast. These offshore areas benefit from higher and more consistent wind speeds, making them ideal for energy generation. By placing wind turbines on floating platforms, it becomes possible to harness the energy from these deep-water locations, which were previously inaccessible with traditional fixed-bottom turbines. The main engineering challenges for floating wind technologies deployment are the high logistical requirements, complex construction and maintenance, especially harsh working environment and concerns for marine biodiversity.

Airborne wind energy (AWE) technology, on the other hand, generates electrical energy using tethered flying devices. These devices, often resembling kites or drones, are designed to capture the strong and steady winds found at higher altitudes. By flying at altitudes where wind speeds are more consistent and powerful, airborne wind technology can produce a significant amount of energy. The tethered devices convert the kinetic energy of the wind into electrical energy, which is then transmitted to the ground through the tether. AWE technology is fundamentally new, different from traditional wind turbines. Their design, manufacture, supply chain, logistics, installation, operations and maintenance remain both challenges and opportunities.

Both floating wind and airborne wind technologies represent innovative approaches to expanding the potential of wind energy. Exploring these new frontiers can increase the overall capacity for renewable energy generation and contribute to a more sustainable energy future.

Advances in Hydropower Energy

Compared to solar and wind energy, hydropower is the most mature renewable technology, having provided clean energy for over a century. The development of hydropower technology is now primarily focused on integrating untapped resources. Since most of the current global technical hydropower potential is relatively mature in high hydraulic head and high flow resources, the new focus of research is on generating energy without a significant hydraulic head and large reservoirs or dams.

One of the key areas of research is the development of ultra-low head hydraulic turbines. These turbines are designed to generate electricity from site conditions where the static hydraulic head is less than 3 meters or where the

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water flow is more than 0.5 meters per second without a hydraulic head (Zhou and Deng, 2017). This approach allows for the utilization of low-head and low-flow water resources, which were previously considered unsuitable for hydropower generation.

By focusing on these innovative technologies, researchers aim to expand the potential of hydropower to more diverse and geographically widespread locations. This not only increases the overall capacity for renewable energy generation but also reduces the environmental impact associated with large dams and reservoirs. The advancements in ultra-low head hydraulic turbines and other similar technologies are crucial for making hydropower a more versatile and sustainable energy source for the future.

Advances in Bioenergy

Biomass production is estimated to be around 146 billion metric tons annually on a global scale, with the primary sources being natural plants and crops. Biofuel and bioenergy derived from biomass not only offer an alternative to fossil fuels but also contribute to effective waste management.

Recent advancements in pre-treatment methods, as well as biochemistry and thermochemical processes, have significantly improved the conversion rate and efficiency of biofuel and bioenergy production. These advancements enable more efficient breakdown and utilization of biomass, leading to higher yields of energy.

Additionally, innovations in bioreactor design and the development of novel biocatalysts have further boosted biofuel and bioenergy production. Improved bioreactor designs enhance the conditions for microbial and enzymatic activity, optimizing the conversion processes. Novel biocatalysts, which are specialized enzymes or microorganisms, have been engineered to increase the efficiency and speed of biochemical reactions involved in converting biomass into energy.

These technological advancements are crucial for making biofuel and bioenergy more viable and competitive with traditional fossil fuels, ultimately supporting the transition to a more sustainable and environmentally friendly energy system (Chaudhary, et. al., 2025).

Advances in Energy Storage Solutions

To ensure a stable balance between energy generation and consumption, energy storage systems play a vital role in enabling the smooth integration of renewable sources into the power grid. These systems help mitigate the intermittency and variability associated with resources like solar and wind. Energy storage technologies are generally categorized as mechanical, chemical, electrical, and thermochemical, based on the type of energy stored (Khan et al., 2024). Among electrochemical storage options, commonly used batteries include lead-acid, lithium-ion, and sodium-sulfur types. Innovations in solid-state batteries and flow batteries are significantly enhancing energy storage capabilities, thereby making renewable energy more reliable. These advancements are addressing some of the key challenges associated with energy storage, such as energy density, lifespan, and efficiency. Solid-state batteries, which use solid electrolytes instead of liquid ones, offer higher energy densities and improved safety. Flow batteries, which store energy in liquid electrolytes contained in external tanks, provide scalable and long-duration energy storage solutions. Although these technologies are still in the early stages of development, they hold great promise for the future of renewable energy.

Advances in Integration of Artificial Intelligence for Renewable Energy Distributions

To reduce the need for costly energy storage systems, renewable energy sources could be managed through proactive distribution strategies (Alazemi, Darwish, and Rahi, 2024). Traditionally, forecasting has relied on physical-based models or statistical models. Examples of physical-based models are weather research and forecasting models, which are computationally intensive and struggle with unexpected errors, making them unsuitable for short-term applications. Statistical models, while offering higher spatio-temporal resolution, typically assume linear relationships, limiting their effectiveness for long-term forecasting.

Over the past few years, advancements in artificial intelligence (AI) have equipped researchers with powerful data-driven tools that often surpass traditional physical and statistical approaches. Among these, machine learning (ML) techniques stand out for their ability to model complex, non-linear relationships without relying on predefined parameters. By learning from historical data, ML enables the analysis of large-scale datasets, even when faced with irregular patterns or noisy inputs.

Alazemi, Darwish, and Rahi (2024) have reviewed the selected articles published between 2014 and 2023, and they found that Artificial Neural Networks (ANN)-based models are the most popular ML-based models to forecast solar and wind power outputs. ANN-based models consist of multiple processing units, called neurons, which store knowledge for use when needed. Patterns are introduced to the network through the input layer, passed to hidden layers where computations occur using weighted connections, and finally delivered to the output layer. The key input data for photovoltaic power forecasting model includes PV power, ambient temperature, solar radiation, wind speed and direction, humidity, air pressure, cloud cover, and weather images etc. The key input data for wind power forecasting model includes wind speed and direction, wind turbine power, temperature, humidity and wind turbine capacity etc. The implementation of ML-based model involves processing steps from data pre-processing, to feature extraction, feature selection, optimization of model, model training, validation then performance evaluation. The primary challenge in modeling renewable energy power output lies in capturing both its autoregressive behavior and its dependence on uncertain, non-linear, and complex atmospheric spatial features. Pierro et al. (2018) presented a real-world case study on forecasting photovoltaic (PV) generation for power transmission scheduling. The study employed an ANN-based model to predict day-ahead PV power output, aiming to minimize grid power imbalance. Model inputs included sun azimuth and elevation, clear-sky irradiance (CSI), and ground temperature estimated by the WRF model. Additionally, relative humidity across 20 vertical atmospheric levels—forecasted by the Numerical Weather Prediction (NWP) model—was pre-processed using PCA. The predicted PV output was then integrated into a power transmission scheduling framework, achieving a 7% reduction in grid imbalance.

AI can facilitate the integration of renewable energy into existing grids by managing the complex interactions between different energy sources and storage, distribution systems. Smart grid technologies, powered by AI, can dynamically adjust energy flows to balance supply and demand, enhance grid stability, and reduce the need for costly infrastructure upgrades.

3.3 Cost of Electricity Production Reduction Due to Renewable Energy Technology Advances

The advancements of the renewable energy technology development in the past two decades have driven the massive infrastructure installation and reduction of the electricity production cost dramatically. The cost of electricity production is related to the costs during the expected lifetime of the generator and the amount of electricity the generator is expected to produce over its lifetime. The levelized cost of electricity (LCOE) is the average cost in currency per energy unit (Branker, et. al., 2011). It is used to compare the cost of electricity generation using different methods. Table 4 lists the total installed cost and LCOE by type of renewable technologies in the year 2010 and 2023. Wind energy is categorized separately for onshore and offshore in the table (IRENA, 2024). The LCOE of solar PV plants declined by 90% between 2010 and 2023, from \$0.460/kilowatt hour (kWh) to \$0.044/kWh.

Table 4. Total Global Installed Cost and Average LCOE by Type of Renewable Technology.

	Total Installed Cost (\$/kW)			LCOE (\$/kWh)		
	2010	**2023**	**Percentage of Change**	**2010**	**2023**	**Percentage of Change**
Solar PV Energy	5,310	758	-86%	0.460	0.044	-90%
Onshore Wind Energy	2,272	1,160	-49%	0.111	0.033	-70%
Offshore Wind Energy	5,409	2,800	-48%	0.203	0.075	-63%
Hydropower	1,459	2,806	92%	0.043	0.057	33%
Geothermal Energy	3,011	4,589	52%	0.054	0.071	31%
Bioenergy	3,010	2,730	-9%	0.084	0.072	-14%

As a comparison, the levelized cost of electricity (LCOE) for fossil fuels was \$0.090/kWh in 2010 and \$0.100/kWh in 2023. The LCOE for solar PV and both onshore and offshore wind were way above fossil fuel in 2010. Excitingly, their LCOEs were all below fossil fuel in 2023. As listed in Table 2, in 2017, renewable energy accounted for 24.5% of global electricity production. Within this percentage, hydropower contributed the most (15.9%), followed by the combination of wind, solar, geothermal and ocean energy (6.5%), then bioenergy contributed to 2.0% (IEA, 2019). In 2024, the combination of solar PV and wind energy for electricity generation surpassed hydropower generation. In 2029, it is projected by IEA that solar PV electricity generation will become the largest renewable power source, surpassing hydropower energy (IEA, 2024).

4. Challenges in Renewal Energy Technologies

Renewable energy technologies have demonstrated lower carbon footprints and lower Levelized Cost of Energy (LCOE) compared to fossil fuel-based technologies. Despite technological progress, several challenges persist.

4.1 Core Challenges in Expanding Renewable Energy

Technical Challenges

The most significant disadvantage of most renewable energy technologies is their intermittent availability and variation in energy intensity. Solar and wind depend on weather and time of day, creating grid stability issues without robust storage solutions. Efficient and scalable energy storage solutions and smart grid upgrades from existing grid infrastructures are essential for unlocking the full potential of renewable energy and ensuring a smooth transition to a low-carbon energy system. Currently, battery technologies such as lithium-ion batteries have limitations in terms of energy density, lifespan, and efficiency. Although recent advancements in solid-state batteries and flow batteries are promising, they are still in the early stages of development and face challenges related to scalability and cost. Also, dependance on critical minerals for batteries introduces supply chain vulnerabilities and geopolitical risks.

Economic and Financial Barriers

The primary obstacle to the widespread deployment of renewable technologies lies in the significant financial investment and economic considerations, particularly the high initial costs associated with constructing the necessary infrastructures. Renewable energy infrastructures, such as solar power plants, wind farms, and hydroelectric dams, demand substantial upfront capital-intensive investments.

The costs of renewable energy technologies and materials remain high. Although the prices of solar panels and wind turbines have decreased over the years, they still constitute a significant portion of the overall infrastructure cost. The solar PV module manufacturing cost was $2.1/W-dc in 2010, down to $0.88/W in 2015, $0.26/W in 2020, then $0.20/W in 2024 (Woodhouse, et al., 2024). Wind turbine prices have declined from $1.8/W in 2008 to $0.77–$0.85/W in 2021 (DOE, 2021). Furthermore, the production of advanced materials and components, such as high-efficiency solar cells and large wind turbine blades, involves complex manufacturing processes that contribute to these high costs.

4.2 Comparative Analysis of Technology Adoption and Region

Solar energy is the most scalable globally but faces intermittency and land-use issues. It has strong adoption in Asia and Africa where sunlight is abundant, yet grid and financing gaps persist. Wind energy is highly competitive in Europe and North America. Hydropower is most mature technology but constrained by ecological impacts and high land requirements. It is dominant in Latin America and parts of Asia. Geothermal energy is technically efficient and land-sparing, but geographically limited to tectonic zones, such as Iceland and East Africa.

4.3 Intellectual Property & Patenting Dynamics

As presented in Section 3.1, renewable energy patents cluster heavily in high-income jurisdictions—primarily the US, EU, Japan, and increasingly China. Strong IP regimes can affect licensing, technology transfer, and equitable access.

5 Conclusions and The Way Forward

Renewable energy technologies are leading the global push towards a sustainable and environmentally friendly energy future. This article reviews recent advancements by analyzing patent filing trends from 2000 to 2023 and examining improvements in energy generation and enabling technologies. Advancements in solar, wind, hydropower, geothermal, biomass, and ocean energy are creating a transformative shift in how energy is generated and consumed. These technologies have immense potential to reduce dependence on fossil fuels, lower greenhouse gas emissions, and mitigate the impacts of climate change.

However, the path to a fully renewable energy-powered world presents challenges. Issues such as core technical challenges, energy storage, high initial costs, uneven regional adoption, and complex intellectual property and patenting dynamics must be addressed. Overcoming these obstacles requires a concerted effort from governments, industries, and individuals alike.

Moving forward, continued investment in research and development, implementation of supportive policies and incentives, infrastructure upgrades, public awareness initiatives, and global cooperation allowing technology licensing/ transfer from patent concentrated countries to others are essential. Through collective action, the power of renewable energy can be harnessed to create a cleaner, more sustainable future.

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