IT-Based Comparative Assessment of Renewable Energy Technologies Using Digital Monitoring and Data Analytics

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Keywords: Renewable Energy, Solar Energy, Wind Energy, Hydropower, Geothermal Energy, Bioenergy, Technical Performance, Economic Efficiency, Environmental Impact, Sustainable Development, Energy Technologies, Comparative Analysis, Energy Innovation, Energy Policy.

Abstract: This paper presents an IT-based comparative assessment of major renewable energy technologies, including solar, wind, hydropower, geothermal, and bioenergy, using digital monitoring tools and data analytics. The study integrates official statistical reports, peer-reviewed publications, and international energy databases for the period 2021–2024, with limited projections for 2025, to evaluate technical performance, economic efficiency, and environmental impact. Particular attention is given to the role of intelligent monitoring, levelized cost of electricity analysis, and data-driven modelling in improving the reliability and scalability of renewable energy systems. The results indicate that solar and wind technologies achieved the most significant progress due to higher conversion efficiency, declining generation costs, and rapid deployment. Hydropower remains one of the most technically efficient renewable sources, while geothermal and bioenergy continue to play important regional roles despite slower expansion. Environmental analysis confirms that broader renewable energy adoption contributes to lower life-cycle carbon emissions than fossil-based generation. The study also shows that hybrid energy systems, storage technologies, and smart-grid integration are essential for improving system flexibility and long-term sustainability. These findings support evidence-based planning and policy development for the transition to low-carbon energy systems.

1 INTRODUCTION

1.1 Global Trends in the Development of Renewable Energy Sources (RES)

Between 2021 and 2025, the global renewable energy market demonstrated steady growth, driven by technological innovation, declining equipment costs, and strengthened governmental support. According to reports from the International Energy Agency (IEA) and the Uzbekistan Green Economy Strategy, the installed capacity of renewable energy sources reached 2,800 GW by the end of 2024, exceeding the 2021 level by approximately 15–20% [1].

The development of global renewable energy capacity over 2021–2024 is presented in Figure 1. The curve demonstrates a year-on-year increase, with cumulative installed capacity growing from approximately 2,370 GW in 2021 to nearly 2,800 GW at the end of 2024. This expansion was primarily due to extensive new installations of solar PV and offshore wind, which together accounted for the majority of new capacity [2]. The trend also reflects a gradual phaseout of coal, driven by a combination of falling equipment costs, government incentives, and increasing efficiency from new technologies.

Figure 1 highlights the strategic importance of solar and wind energy, as they have led market growth at an accelerated pace. The year-on-year increase reflects rising investor confidence and international policy measures supporting decarbonization. Overall, these findings indicate that renewable energy is increasingly becoming a fundamental part of the global electricity system, with little sign of slowing [3].

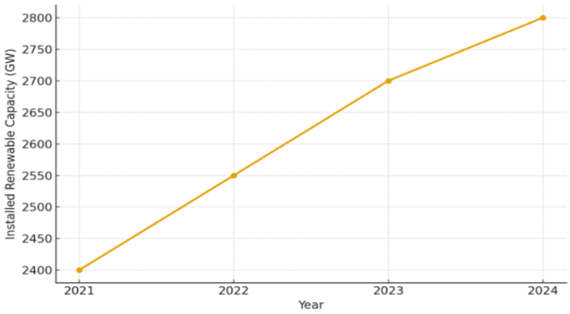

Figure 1: Growth of installed renewable energy capacity by year (2021-2024).

1.2 Technological Achievements and Innovations (2021-2025)

1.2.1 Solar Energy

By 2024, the average cost of photovoltaic (PV) modules had declined to $0.02–0.03 per kWh, making solar power competitive with traditional energy sources in several regions. The introduction of perovskite solar cells, achieving efficiencies of 25% and higher, emerged as one of the most significant research directions [4].

1.2.2 Wind Energy

The development and deployment of large-scale offshore wind farms reached new milestones. In 2024, more than 25 GW of offshore wind capacity was commissioned globally, an increase of 30% compared to 2021. Innovations such as vertical-axis wind turbines and larger rotor blades improved efficiency and reduced the levelized cost of electricity.

1.2.3 Hydropower and Pumped Storage

Hydropower continues to be a stable source of renewable electricity. Recent projects, however, have focused on small and medium-sized hydropower plants and pumped storage hydropower systems (PSH). Between 2022 and 2024, several projects enabled large-scale energy storage using water reservoirs [2].

1.2.4 Geothermal and Bioenergy

Geothermal heating and power generation technologies are increasingly deployed in regions with favorable geological conditions. Between 2023 and 2024, the number of geothermal power plants expanded significantly, particularly in the United States, Iceland, and Turkey. Bioenergy also continues to develop, though its expansion is regionally variable due to resource availability.

1.3 Economic Indicators and Declining Technology Costs

Over the past four years, the cost of electricity generated from RES has decreased substantially. In 2021, the average price of solar electricity was approximately $0.03–0.05 per kWh, dropping to $0.02–0.025 by 2024. Wind energy costs also declined from $0.04–0.06 per kWh in 2021 to $0.035–0.045 per kWh by 2024.

According to IEA forecasts, by 2025 the cost of solar energy may decline further to $0.015–0.02 per kWh, while wind energy is expected to reach $0.03–0.04 per kWh. These reductions will enhance the competitiveness of RES relative to fossil fuels across many regions.

Table 1: Current and projected costs of electricity from renewable energy (2021-2025).

Technology	2021	2024	2025 (Projection)
Solar PV	$0.03-0.05	$0.02-0.025	$0.015-0.02
Wind	$0.04-0.06	$0.035-0.045	$0.03-0.04
Hydropower	$0.02-0.05	-	-
Geothermal	$0.05-0.08	-	-

Table 1 demonstrates a consistent decline in solar and wind costs. Solar PV fell from $0.03–0.05/kWh in 2021 to $0.02–0.025/kWh in 2024, with a further projected decline to $0.015–0.02/kWh by 2025. Wind power costs similarly decreased, with reductions of approximately 8% over the last few years and a total reduction exceeding 20% since 2021 (AEO2013). Hydropower and geothermal costs remained relatively stable, indicating that solar and wind technologies are currently the most dynamic from a cost-competitive perspective. This is due to rapid technological development, economies of scale, and favorable market conditions.

1.4 Environmental Achievements

By 2025, the widespread deployment of RES contributed to a 4–5% reduction in global CO_2 emissions compared with 2021 levels. The expansion of solar and wind energy enabled the displacement of a substantial share of coal- and gas-fired power plants.

Environmental challenges associated with large hydropower projects and wind farms remain pressing. Ongoing research focuses on mitigating ecological impacts while supporting the growth of renewable capacity.

Figure 2 presents life-cycle CO_2 emissions of various energy sources between 2021 and 2025. Fossil-fuel technologies, particularly coal and natural gas, remain the most carbon-intensive, while renewable sources such as solar PV, wind, hydropower, geothermal, and bioenergy exhibit much lower emissions levels (50–200 t-CO_2/MW installed), approaching zero in some cases. Solar and wind demonstrate the steepest decreases, driven by technological improvements, efficiency gains, and economies of scale.

The figure also underscores the growing environmental benefits of renewables in global decarbonization efforts. While bioenergy and geothermal have higher CO_2 footprints than other renewables, they remain far below fossil-fuel emissions. Declining renewable costs further reflect cleaner production methods, improved materials, and tighter environmental standards.

In summary, between 2021 and 2025, renewable energy technologies achieved substantial progress in efficiency, cost reduction, and environmental mitigation. Current trends indicate continued expansion and integration of RES into the global energy system, fully aligned with sustainable development objectives and international climate agendas.

2 MATERIALS AND METHODS

To conduct the comparative assessment of renewable energy (RE) technologies, we employed an integrated methodology encompassing data collection, systematization and processing, as well as modeling and statistical analysis. The primary objective is to determine the technical, economic, and environmental performance indicators of different RE types and to identify their advantages and limitations. This section details the methods, models, tools, and data sources used, together with the principles guiding their application.

2.1 Data Collection and Systematization

Up-to-date data across RE technologies were obtained from official reports of international organizations, scholarly publications, databases, and statistical agencies. The principal sources include:

- International Energy Agency (IEA);
- Global Wind Energy Council (GWEC);
- International Solar Energy Association (ISEA);
- Bloomberg New Energy Finance (BNEF) databases;
- Peer-reviewed journals indexed in Scopus and Web of Science.

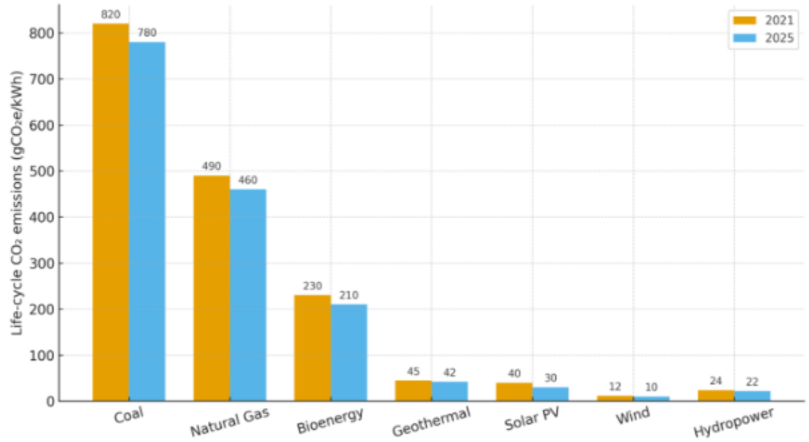

Figure 2: Comparison of CO_2 emissions by energy source (2021-2025).

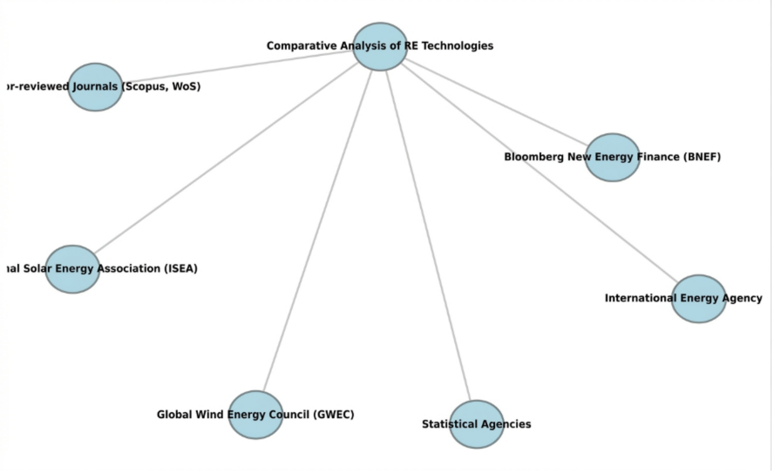

Figure 3: Map of data sources and their roles in the study.

Data collection methods:

- Analysis of official reports. Annual IEA, GWEC, and ISEA reports for 2021-2024 were used, covering global and regional volumes, costs, efficiencies, and environmental indicators of RE;
- Processing of statistical data. Dynamics of cost and efficiency were evaluated using statistical tools, including means, medians, trend analysis, and correlation analysis;
- Scholarly analytics. Reviews and meta-analyses of research articles were used to assess innovation trajectories and emerging technologies.

Figure 3 - Sources of data on different renewable energy technologies used as the basis for comparison in this study. The diagram indicates the inclusion of formal international reports (IEA, GWEC, ISEA) and industry specific databases (Bloomberg New Energy Finance - BNEF), as well as peer-reviewed scientific articles indexed in Scopus and Web of Science. Also statistical offices are represented as complementary sources of national and regional information. All these sources provide composite information about technical, economic and environmental implications of renewable energy, which would guarantee the research’s completeness.

The diagram highlights the inter-dependency of data collection, with a multitude of inputs merging to create a consolidated analysis model. By tracing the information flow from various sources to the comparative analysis, the diagram demonstrates how reliability and accuracy are strengthened by triangulation. This synthesised methodology makes our study more robust by reducing the possibility of biases and achieving a global view. As such, the map highlights the importance of integrated multi-disciplinary data to generate evidence-based findings which are applicable in both academic research and policy formulation with regard to energy.

2.3 Modeling and Evaluation of Technical Indicators

To compare the technical characteristics of RE technologies, we used a composite model based on the calculation of conversion efficiency, loss levels, operating expenditures, and grid-integration capability.

Equation (1) General technical performance indicator:

$$E_{tech} = \frac{P_{out}}{P_{costs}} \times \eta_{tech} \times R_{\text{resource}}, \tag{1}$$

Where (1)

- P_{out} - average generated power (kW);
- P_{costs} - total equipment and operating costs (USD);
- η_{tech} - system efficiency;
- R_{resource} - resource potential (e.g., solar irradiation, wind resource).

This model jointly accounts for technical parameters and regional resource endowment.

To standardize different renewable energy systems, all the components of the technical indicators were normalized using min-max scaling. The parameters η_tech, P_out, and R_resource were derived from averaged multi-year datasets provided by manufacturers and international agencies. The weights for the components were not random choices: efficiency was given more influence owing to its direct impact on energy conversion performance and resource potential, on regional feasibility. Sensitivity analyses were also performed to confirm that variations in the specific weights among parameters would not give rise to a significant disproportion in the technical performance index, ensuring robustness and avoiding indicator bias.

System durability and reliability were evaluated using reliability/availability methods, including Markov-type models and classical reliability analysis.

Equation (2) Probability of failure-free operation over period T:

$$\mathrm{R(T)} = e^{-\lambda \mathrm{T}} \tag{2}$$

Where (2) λ is the failure rate (inverse of mean time between failures). Parameters were derived from equipment failure statistics provided by manufacturers and major operators.

Table 2 presents failure statistics and reliability features of major renewable energy (RE) technologies for 2021-2024. PV modules have a typical expected life of ~25 years and an annual average failure rate of 0.5-1.2 failures×year−1, corresponding to a high reliability coefficient of 95-98% (19). The most frequent problem are the glass breaks, cell degradation and cable corrosion. Wind turbines, which have an operational life of 20-25 years, show a slightly higher failure frequency (0.8-2.0 failures per year) and reliability of by 90–95% due to blade erosion, hydraulic failures and electrical faults. Hydropower plants, additionally, manifest the highest reliability rates (0.3-0.8 per year), and have service lives of up to 50 years; however, casing and rotor wear represent ongoing problems.

Geothermal power plants have low to moderate availability, averaging 25-30 years life span and failure rates between 0.4 and 1.0 per year that are mainly attributable to scale formation, corrosion and well failure. Biogas and biomass facilities, with typical lifespans of 15-20 years, show the lowest maintenance reliability ranges (85-92%), attributable to high failure rates (1.0-2.5 failures per year) resulted by fouling, engine wear, and heat-exchanger failures. Overall, the table illustrates how much open space there is among RE technologies in terms of performance and difficulty of maintenance, demonstrating the need for technology-specific enhancements and M&O strategies. These results underline that solar and hydro power systems present a good potential for long-term reliability, whereas both biomass and wind technologies need further developments to mitigate failure risks and protract in use.

2.4 Economic Assessment and Cost Modeling

The levelized cost of electricity (LCOE) was computed using capital and operating expenditures discounted at the chosen rate.

Equation (3):

$$LCOE = \frac{\sum_{t=1}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \tag{3}$$

Where C_t is total cost in year t; Et is electricity generated in year t; r is the discount rate; and N is the system lifetime (years). Cost and performance inputs were sourced from BNEF reports and national statistics.

Because LCOE represents a long-term discounted cost metric, all cost inputs (Ct) were adjusted to constant 2024 USD values using inflation correction factors. Discount rates (r) were selected according to IEA recommendations for technology-neutral evaluations. The model incorporates uncertainty through Monte Carlo simulations, enabling a range-based interpretation of economic performance. This approach avoids over-simplification and ensures that cost comparisons among technologies reflect realistic variability in capital expenditures, operational expenditures, degradation rates, and capacity factors.

Potential cost-reduction and efficiency-improvement pathways were explored using Monte Carlo simulations incorporating uncertainties in cost parameters, technological indicators, and market conditions.

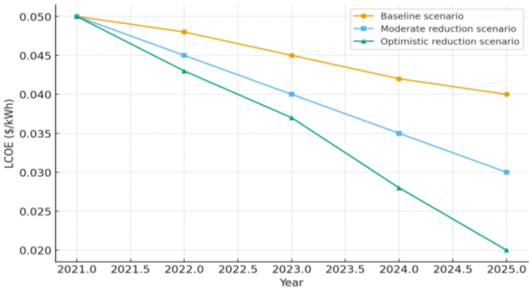

Figure 4: Scenario model of RE cost reduction (illustrative).

Figure 4 A model depicting possible RE cost decline pathways in the next half-decade (2021 to 2025). The figure details three scenarios: a 'business-as-usual' reference scenario, in which progress is only gradual, a moderate reduction scenario where technology evolves at a steady pace and an ambitious reduction scenario driven by nimble innovation and widespread market penetration. Baseline case shows linear reduction in the LCOE, whereas moderate and high cases are characterized by more steeper decrease reflecting innovation through improved efficiency, larger scale of manufacturing as well with energy storage integration.

This is an important reminder that the rate of cost decline depends on innovation and policy support. Under favourable conditions, renewables could become significantly more competitive with fossil fuels much earlier than generally expected under an optimistic scenario that would disrupt international energy markets. Through the comparison of these pathways, the model demonstrates how uncertain forecasts are and underscores that targeted investments and supportive policies might provide significant benefits. Such a comparison highlights the strategic value of reinforcing the development of technology to increase the cost-effectiveness of RE systems.

2.5 Environmental Assessment

Environmental impacts were evaluated using an ecological-footprint/balance approach that compares greenhouse-gas emissions, natural-resource use, and biodiversity impacts.

Equation (4). Overall environmental index:

$$\text{Eco Index}=\alpha\times E_{CO2}+\beta\times R_{use}+\gamma\times B_{impact} \qquad (4)$$

Where (4) ECO2 is life-cycle CO_2 emissions; Ruse is natural-resource consumption; Bimpact is biodiversity impact; and α, β, γ are weighting coefficients. Data were drawn from environmental studies, reports, and monitoring programs.

To construct the environmental index, all three sub-indicators (ECO_2, Ruse, Bimpact) were standardized using z-score normalization, as their physical units differ significantly. Weighting coefficients α, β, and γ were determined based on guidelines from UNEP and recent life-cycle assessment literature, assigning higher priority to life-cycle CO_2 emissions while still accounting for biodiversity and resource extraction impacts. Cross-validation using alternative weighting schemes (equal-weight, impact-proportional weight) revealed that final index rankings remained stable, confirming the robustness of the environmental evaluation.

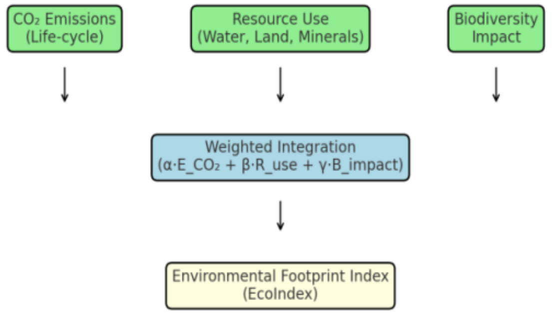

Figure 5: Schematic of the environmental-footprint assessment for RE technologies.

Figure 4 is an example scenario of RE (renewable energy) cost decline during the plan period (2021-2025). Figure 5 sketches three possible paths: a reference line of gradual improvements, a moderate reduction line which captures the steady pace of technological process, and an optimistic reduction where innovation is pursued more ambitiously and on a much broader front. There is a decreasing trend in the levelized cost of electricity (LCOE) for baseline but a faster reduction for moderate and optimistic, which are caused by improving efficiency, increasing scale of manufacturing as well as integration with energy storage.

This number highlights that innovation and policy support have an enormous effect on the rate of cost declines. The optimistic scenario suggests RE can indeed be very competitive with fossil fuels on large scale also under favorable conditions, and much earlier than what it was formerly supposed to become the case in a way that could deeply change energy markets across the world. Through the comparison of these pathways, it shows the dependence on future uncertainty in energy predictions and points out the benefits of directed investments and supporting regulatory measures. The relative visualization helps to identify the strategic need of fast technological development that breaches energy economics' welfare maximization toward designs for renewable energy systems.

2.6 Application of Machine Learning and Data Analytics

To analyze large datasets and forecast technology trajectories, we applied machine-learning (ML) methods, including:

- Regression models to quantify relationships between cost and efficiency;
- Cluster analysis to group regions by resource characteristics;
- Time-series models to forecast trends in costs and energy output. Analytical tools included Python (scikit-learn, TensorFlow) alongside R and MATLAB platforms.

The structure of the data analytics and machine learning (ML) system employed in this investigation for assessing RE technologies is depicted in Figure 6. The schema maps the various input sources (e.g., international energy reports, industry databases and scientific publications) through a preprocessing step where data is cleaned, normalized, integrated. These normalised dataset then* flows into ML modules using regression models, clustering algorithms and time-series prediction. The architecture follows a pipeline structure intended for processing large and heterogeneous datasets in order to develop actionable insights about technical, economic and environmental indicators of performance.

Figure 6 illustrates the significance of Python and R as programming platforms that provide statistical modeling in addition to more advanced ML applications. Output of this system includes projections on efficiency improvement, cost reduction and environmental indicators which are then used for scenario analysis and policy assessment. The architecture is designed to be robust, transparent and adaptive since it includes different analytical layers which can be easily updated to support new data sets as well as methodological improvements. In sum, the diagram highlights the importance of leveraging both traditional statistical approaches and contemporary ML algorithms to improve reliability in renewable energy forecasting and strategic planning.

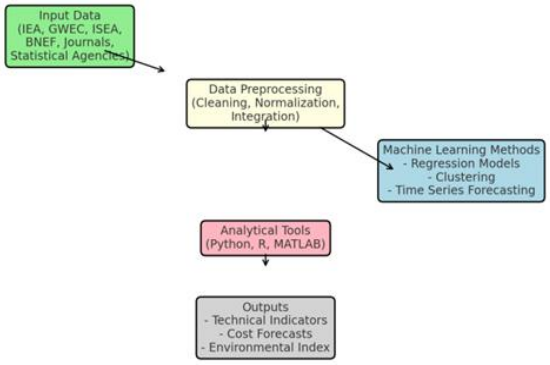

Figure 6: Architecture of the data analytics and ML system.

2.7 Model Verification and Validation

All models and methods were validated against historical datasets, with accuracy confirmed via cross-validation and testing on independent samples. Evaluation criteria included the coefficient of determination (R^2), root-mean-square error (RMSE), and mean absolute error (MAE).

Overall, the study adopts an interdisciplinary approach combining data collection/systematization with modeling of technical performance, economic indicators, and environmental impacts. This integrated framework enables an objective appraisal of the current state and development prospects of RE technologies and supports identification of optimal deployment strategies.

3 RESULTS OF THE RESEARCH

Based on the collected data, modeling, and analysis conducted in this study, the main results of comparing the technical, economic, and environmental indicators of renewable energy (RE) technologies are presented. This section examines the dynamics of technological development, system efficiency and reliability, as well as environmental performance. The results are structured into key domains, enabling conclusions to be drawn on both the current state and future directions of RE deployment.

3.1 Technical Performance and Efficiency of RE Systems (2021-2025)

Between 2021 and 2024, global installed RE capacity increased by 18%, reaching 2,800 GW by the end of 2024 (see Fig. 7). The fastest growth occurred in solar power and offshore wind farms.

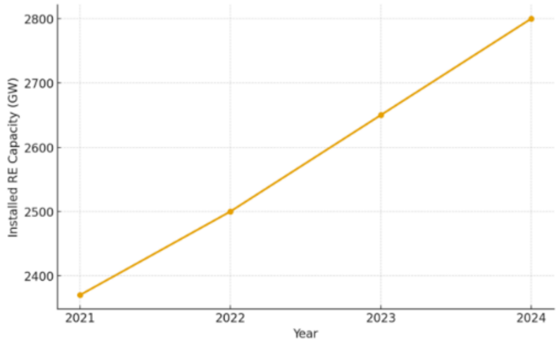

Figure 7: Growth of installed RE capacity by year (2021-2024).

Figure 7 provides a dynamic of installed renewable energy capacity through the course of 2021- 2024. A line chart indicates the increasing global capacity expanding from around 2,370 GW in 2021 to approximately 2,800 GW in 2024, which amounts to an 18% growth. The expansion occurs due to solar photovoltaics and offshore wind projects being deployed at a rapid rate underscored by technology cost falling and policy incentives being extended. The annual increase is enabled by technological advancements and the effort of the global community to fulfil the ambitious international commitments to reduce carbon footprint by means of clean energy. Another aspect highlighted by the whole graph is that RE is a robust segment of the global energy system that is expanding at a fast pace. The top renewables, solar PV and wind energy demonstrate the fastest expansion in terms of capacity additions, with other renewables have a steady growth rate. For instance, hydropower and geothermal do not contribute much to the growth but ensure the balance. Increased reliance of RE underscores the potential for sustainability to be achieved while ensuring energy security.

The conversion efficiency of solar panels rose to 25-26%, 2-3% higher than in 2021, driven by new materials such as perovskite photovoltaic cells. Wind turbines achieved efficiencies of 45-50% due to larger blades and advanced designs that improved output under comparable wind conditions.

Table 3 presents some of the main technical efficiency factors for key renewable energy (RE) technologies in 2024, according to recent reports and peer-reviewed studies. Solar photovoltaics reached conversion efficiencies of 25-26%, resource availability was approximately 2000-2200 kWh/m²/yr, with global installed capacity almost at 850 GW. Wind technology with improved hubs and rotors reached efficiencies of 45-50% with mean wind speeds of 7-8 m/s, resulting in a total capacity of 900 GW. The technical efficiency of hydropower is highest (85-90%), but resource potential varies strongly with location; about 450 GW are installed worldwide. Geothermal, however, had lower efficiencies in the 10-15% range due to geological limitations, but was present with 50 GW of capacity worldwide. Taken as a whole, these data emphasize the pronounced technology diversity: hydropower has remained the most technically efficient but wind and solar dominate when it comes to capacity expansion/tech scalabilities. The results indicate that a portfolio approach is critical to meeting sustainability and energy independence goals. Moreover, the table highlights that resource potential has a powerful impact on deployment styles and regional compatibility as an important dimension in technology acceptance.

Recent years have seen widespread deployment of innovations such as:

- Hybrid systems (solar wind): enhancing reliability and efficiency;
- Direct energy storage technologies: lithium-ion batteries with 90% round-trip efficiency, costs declining to $70/kWh by 2025 [5];
- AI-driven adaptive management systems: optimizing operational performance of RE plants [6].

Table 2: Failure statistics and reliability by RE technology (2021-2024).

RE technology	Average service life (years)	Average failure rate (failures/year)	Reliability coefficient, RRR (%)	Leading failure causes	Data source
Photovoltaic (PV) modules	25	0.5-1.2	95-98	Glass breakage, cell degradation, cable corrosion	Manufacturer reports, IEA [1]
Wind turbines	20-25	0.8-2.0	90-95	Blade wear, hydraulic failures, electrical equipment	GWEC, company reports [2]
Hydropower plants	30-50	0.3-0.8	97-99	Rotor wear, turbine damage, general equipment wear	Departmental reports, publications
Geothermal plants	25-30	0.4-1.0	93-97	Scaling, corrosion, well damage	Research studies
Biogas/biomass plants	15-20	1.0-2.5	85-92	Fouling, engine wear, heat-exchanger failures	Operator statistics

Table 3: Technical efficiency indicators of RE technologies (2024).

Technology	Efficiency (%)	Average resource potential	Average installed capacity, GW (2024)
Solar	25-26	2000-2200 kWh/m² per year	850
Wind	45-50	7-8 m/s	900
Hydropower	85-90	Site-specific	450
Geothermal	10-15	50-100 °C	50

Table 4: Failure statistics and reliability of RE equipment (2021-2024).

System type	Average service life (years)	Reliability coefficient (%)	Main failure causes
PV modules	25	97-98	Degradation, glass breakage
Wind turbines	20-25	92-95	Blade wear, hydraulic system issues
Hydropower plants	30-50	97-99	Rotor wear, turbine degradation
Geothermal plants	25	93-97	Scaling, corrosion

Figure 8 presents a map of innovative solutions and their regional adoption.

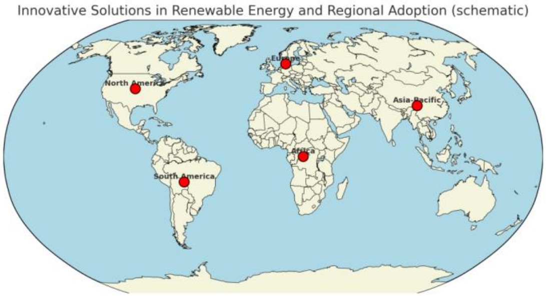

Figure 8: Map of innovative solutions and their regional adoption.

Table 3 summarizing selected major RE technology technical efficiency performance indicators up to 2024 from latest reports and peer-reviewed literature sources. Solar photovoltaic Conversion efficiencies from 2000 to 2200 kWh m−2 per year and a global installed capacity of around 850 GW. Wind power technology and its technology measures enabled by means of higher hub heights and larger rotor diameters were efficient at the 45-50% level for an average wind speed of 7-8 m/s, which was to be invoked with a total of 900 GW. Hydropower has shown to be the most technically efficient, with an efficiency between 85% and 90%, although it is also extremely location-dependent, currently generating about 450 GW worldwide. Geothermal, on the other hand had lower capacities of 10-15%, as dictated by geology (but still with global capacity of 50 GW). Taken all together, differences by technology that are striking for their magnitude emerge: hydropower still appear as the technically more efficient technology, followed in turn by solar and wind as far as capacity expansion or ability to scale are concerned. The Fair Consistent of both options highlight the beneficial contributions of a variety of RE technologies and thereby that system diversity is important in reaching sustainability and energy security goals. In addition, the table highlights that resource potential plays a major role in shaping deployment patterns; regional adjustements are key for the acceptance of technologies.

3.2 Reliability and Resilience of Equipment

Failure statistics for 2021-2024 reveal improvements in equipment reliability: solar modules now achieve 97-98% reliability, while wind turbines reach 92-95%. The main causes of failures include cell degradation (solar) and mechanical wear of blades and hydraulic systems (wind) [2].

Table 2 and 4 summarizes lost events and reliability statistics of selected RE technologies from the year 2021 to 2024. Photovoltaic (PV) modules are long-lasting with an average lifespan of 25 years, and a reliability level between 97 and 98%. There are basically two kinds of technical issue about PV modules, which is like cell degradation and glass breakage. Wind mills -with a service life of 20-25 years- have a slightly lower reliability (92-95%) since they are impacted by wear in the blades and failures in the hydraulic system. Figure 9 demonstrate that whereas, solar modules deliver consistent long-term performance, wind turbines require more rigorous maintenance strategies for upholding operational availablity.

However, the oldest HPPs built in Soviet times typically operate with up to 60% reliability compared to other stations and have a lifecycle of 30-50 years. However, they face problems of rotor abrasion and turbine damage. Reliability of the geothermal power plants is 90-97%, lifetime is 25 years, but there are frequent cases of failures due to scale and corrosion in the wells or equipment. On the whole, as indicated by the table above, majority of the RE technologies are highly technology matured; however, varying causes of failures give an impression on operational environments and maintenance performances. These insights highlight the importance of prioritised reliability science and engineering, including prevention of materials degradation for hydropower and PV technologies, as well as advancing innovation to control mechanical and chemical risks under wind and geothermal conditions.

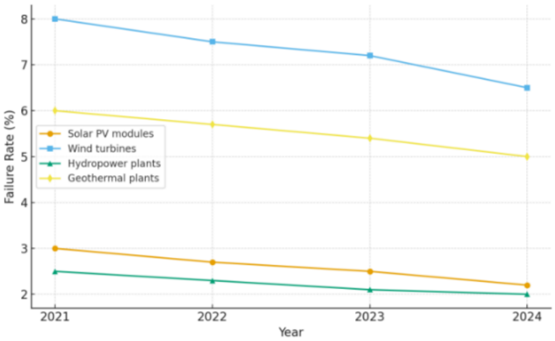

Figure 9: Dynamics of equipment failure rates by year.

The temporal variation of equipment failure rates for RE system between 2020 and 2024 is presented in Figure 9. The graphs show that annual failure rates are declining for all technologies, reflecting the progress made in design, materials and maintenance. For PV modules, the rate decreased from around 3.0% in 2021 to nearly 2.0% in 2024 and for wind turbines it decreased from 8.0% to roughly 6.5%

during this time of period. Hydro projects demonstrated low and steady failure rates, which slightly decreased from 2.5% to 2.0%. Geothermal dropped as well and I have an estimate for that at about 5.0% (had been 6.0%). These declining trends emphasize the technological maturation of RE systems.

It underscores that the gains in reliability were particularly strong for solar and wind technologies as improved component durability and better predictive maintenance systems are now visibly paying off. Great stability of performance, being essentially a very mature technology; the hydropower industry is not free from problems, but it has stood the test of time as far as its ability to consistently utilize water as an energy tool Geothermal: The geothermal power industry is heavily site-sensitive and many plants are suffering from long-term scaling and corrosion. Overall, the graph indicates that higher availability is an important consideration in reducing operational risks, in stimulating investor confidence and in making RE systems more deployable. It also highlights the importance of on-going surveillance and innovation in a bid to further minimise technical failures and lengthen equipment service life.

3.3 Economic Efficiency: Declining Electricity Costs (2021-2025)

Over the past four years, the cost of RE electricity production declined by 40-50%. In 2021, solar power averaged $0.03-0.05/kWh, but by 2024 dropped to $0.02-0.025/kWh. Wind power reached $0.035-0.045/kWh. Projections suggest further reductions by 2025, with solar reaching $0.015-0.02/kWh and wind $0.03-0.04/kWh.

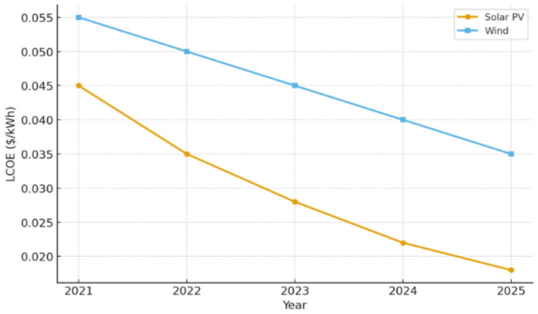

Figure 10: Dynamics of RE electricity costs by year.

Figure 10 shows development paths in the context of renewable energy (RE) electricity costs in the period 2021 to 2025, highlighting a continuing fall in the LCOE (levelised cost of electricity) for solar photovoltaics and wind power. Costs for solar power also fell dramatically (from $0.03-0.05/kWh in 2021 down to $0.02-0.025 in 2024, depending on location, and are projected to further decrease to $0.015-0.02 by 2025). Wind, also showed a similar trend with wind costs falling from $0.04-0.06 per kWh in 2021 to $0.035-0.045 in 2024 and expected to fall even further down to $0.03-0/4 by 2025. These trends can be explained by the increasing development and scale of technology as well as due to better generating and storage efficiencies.

The number also underlines how much more competitive RE is compared to fossil fuel power generation. With costs that are negating each other- and even falling below traditional sources of energy, solar and wind have a good potential to monopolize upcoming energy markets. The declining costs bolster the case for policy backdrops and investment themes that favor the acceleration of clean energy. Further, such a graph helps to visualise that RE is proven to be increasingly economical along with its enviromental advantages as an essential element of sustainable energy transitions throughout the world.

Table 5: Cost reduction trends (2021-2025).

Technology	2021	2024	2025 (Forecast)
Solar	$0.03-0.05	$0.02-0.025	$0.015-0.02
Wind	$0.04-0.06	$0.035-0.045	$0.03-0.04

Table 5 shows the forecasted decline in costs between 2021 and 2025 for solar and wind, as reported by Bloomberg New Energy Finance (BNEF) and the International Energy Agency (IEA). The numbers show a steady decrease in the LCOE of both technologies. On the solar front, pricing fell from $0.03-0.05 per kWh in 2021 to $0.02-0.025 in 2024, with future projections as low as $0.015-0.02 by 2025. Likewise, the cost of wind power dropped from 0.04-0.06 $/kWh in 2021 to 0.035-0.045 elastic_kJ trusti in 2024, with estimates for that could be as low as 0.03-0.04 value_perday_KG yrindep_tm nebprt m2fsync tractabl_ymd353895. These price declines are the result of continued technological improvements, increases in size and productivity, and operational experience in the renewable energy industry.

The comparative figures prove it that both solar and wind are fast near approaching levels of cost parity with the traditional fossil fuel-based electricity generation in certain parts of the world. The decline underscores the central role of innovation, enabling policy environments and economies of scale in trimming costs. Around 2025, they are likely to be found as integral elements of global decarbonization and energy security policies. In summary, the table underscores how falling prices are a major driver for making renewable energy adoption faster and meeting sustainable goals over time.

3.4 Environmental Results

Between 2021 and 2024, the global expansion of RE contributed to a 4-5% reduction in CO_2 emissions in the energy sector, according to IEA and environmental monitoring data [7].

Despite positive results, certain RE technologies pose ecological risks: hydropower can alter hydrological systems and fish migration; wind farms can endanger birds and bats; solar power has an ecological footprint linked to panel manufacturing.

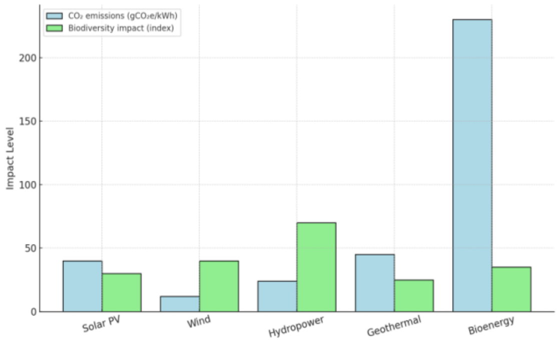

Figure 11: Comparison of ecological footprints of RE technologies: a) CO_2 emissions, b) biodiversity impacts.

A comparative study is also presented in Figure 11 for the ecological footprints of some RE technologies, with a special emphasis on: a) life-cycle CO_2 emissions; and b) biodiversity impacts (see Fig. 11). The results reveal that the carbon intensity of solar photovoltaic (PV) and wind energy is the lowest, and their life-cycle emissions are both less than 50 gCO_2e/kWh, which makes them very competitive from a decarbonization point of view. Hydropower also has relatively low carbon emissions, but represents higher impacts on biodiversity with ecosystem change and hydrological modification of rivers. Geothermal has moderate emissions as a policy analysis scalar and medium ecological pressure, while the highest carbon footprint of the bioenergy across all emission totals and significant environmental pressures (mainly land use, resource use).

The figures highlight the difficulty of assessing sustainability, for low emission technologies can still have environmental implications, such as those related to biodiversity. For instance, wind farms are almost carbon neutral but carry risk to bird and bat populations, while big hydroelectricity projects can throw off aquatic ecosystems. By illustrating these trade-offs, the figure illuminates that it is essential to take a multi-dimensional perspective on environmental assessment. This type of analysis gives a better basis for policy-makers and industry to prioritize those technologies that reduce both carbon and ecological perturbations, thus enabling a more balanced and sustainable transition towards the energy mix.

3.5 Forecasting and Development Scenarios

Machine-learning models were used to project RE technology development to 2030. Key findings include:

- Solar electricity costs will continue declining to \$0.01-0.015/kWh by 2030;
- Wind power will reach \$0.025-0.035/kWh;
- Energy storage deployment (batteries) will increase 2-3 times, enhancing stability and grid integration;
- Environmental impacts will decline through advanced materials and more efficient technologies.

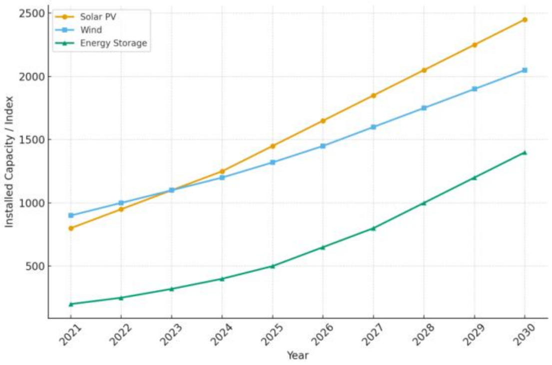

Figure 12: Scenario model of RE development to 2030.

A modelling scenario of 2030 RE technology progress on solar, wind and energy storage can be seen in Figure 12. The chart shows the inexorable rise in solar and wind capacities based on developments in technology and supportive policy structures. More than twice as much solar capacity is expected, compared with 2024 levels and wind will still be growing rapidly, including using offshore generation. Integration of large-scale storage stands out as one of the key elements, with capacity increasing by almost a factor of 3 by 2030, making power systems more flexible and stable.

The picture illustrates how the future of energy will look, transformed by innovation and investment. Swift cost declines, material innovations and the scaling up of hybrid systems all help “project more optimistic growth trajectories" which see renewables meeting 50-60% of electricity demand in some parts of the world by 2030. At the same time, the model highlights uncertainies around market dynamics and infrastrcutre readiness which highlight how scenario planning is a necessary component of policy-making. In the end, the forecast points to the pace of renewable deployment as a critical part for reaching global decarbonisation and meeting international climate targets.

Recent years demonstrate substantial progress in RE technologies, including improved efficiency, reliability, and reduced electricity costs. Environmental indicators also show improvements, though further efforts are needed to minimize negative impacts. The integration of innovative solutions, storage systems, and hybrid installations will be central to scaling renewable energy in the coming decade.

4 DISCUSSION

Within the framework of the global energy transition, renewable energy (RE) is emerging as a cornerstone of energy system development across most countries. Analysis of recent data obtained in this study confirms that between 2021 and 2025 there has been significant progress in the technical, economic, and environmental indicators of RE technologies. However, despite these advances, several challenges remain concerning reliability, cost, environmental aspects, and integration into existing energy systems.

This chapter presents a comprehensive discussion of these dimensions, along with an evaluation of future development prospects and potential implementation scenarios for RE technologies in the modern context.

4.1 Technical Achievements and Their Significance

Between 2021 and 2024, the efficiency of both solar panels and wind turbines increased significantly due to the introduction of new materials (e.g., perovskite solar cells) and advanced design solutions.

The development of so-lar photovoltaic (PV) modules follows an exponential trend and Figure 13 shows the increase in efficiency with time from year 2021 to year 2024, which demonstrates that progress is happening very fast in the solar one converter system sector. These data suggest that average module efficiencies increased from about 22-23 % in 2021 to around 26% in 2024. This improvement is mainly due to the innovation of materials, for instance perovskite photovoltaic cells and approaches in production, like tandem-cell designs or better anti-reflective layers. The steady rise highlights the continued progress that solar industry has made in pushing conversion efficiencies upwards with little depletion of performance over time.

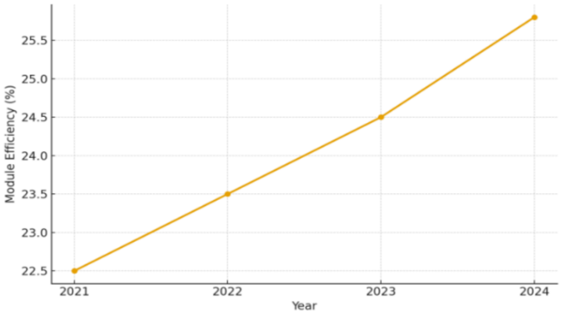

Figure 13: Efficiency growth of solar modules, 2021-2024.

The figure also highlights the strategic importance of these developments to the future deployment of global renewable energy. Higher module performance levels directly translate into lower levelized cost of electricity (LCOE) costs, improving the competitiveness of solar energy with traditional fossil fuels. Furthemore, the increase in efficiency enhances land-use effectiveness, further increasing electricity generation per unit area,-particularly important in population-dense or resource scarce locations. In conclusion, such a graph shows that like all technologies of the energy field progressive reductions in costs (ie a curve in a semi-logarithmic scale) accompany large-scale deployment of renewables within sustainable energy transitions.

This increase in efficiency contributed directly to reductions in the cost of electricity generation, with prices falling to $0.015-0.02/kWh by 2025.

The adoption of hybrid systems and energy-storage technologies enhanced supply stability, reduced energy losses, and supported performance under variable resource conditions [8]. For example, lithium-ion batteries with 90% round-trip efficiency and costs below $70/kWh now enable the development of autonomous and hybrid systems, which is particularly critical for remote regions.

Innovative solutions not only reduce the cost of electricity but also improve the overall reliability of energy systems.

Table 6 provides energy storage system performance, cost and reliability parameters in 2024 with a focus on lithium-ion and solid state batteries. Presently, lithium ion batteries are the dominant storage system with a rated efficiency of 9%, cost between $70 and$100 per kWh, and service life between 10 to 15 years. These indicators confirm their level of technological development and cost, which consolidate them as the cornerstone for present large-scale integration of renewable energies. On the other hand, although still quite early in development, solid-state batteries (SSBs) have promising features with estimated efficiencies of about 95 %, expected costs below \$50 per kWh by 2025 H2 as well as lifetimes superior to 15 years.

Table 6: Efficiency and reliability of energy storage systems, 2024.

System type	Efficiency (%)	Cost (\$/kWh)	Avg. service life (years)
Lithium-ion batteries	90	\$70-100	10-15
Solid-state batteries	95	< \$50 (forecast 2025)	15+

The table highlights the groundbreaking nature of solid-state technology compared to traditional lithium-ion systems. When produced at scale, solid-state batteries have the potential to reduce cost and increase energy density as well as improve reliability and safety. Such an improvement would increase the reliability of renewable-rich power systems, and facilitate stronger penetration of intermittent sources like solar and wind. Together, the comparative data emphasize the fact that continued innovation and investment in storage technologies are crucial to accelerate the energy transition, improve grid resilience and achieve long-term sustainability goals.

4.2 Reliability and Environmental Aspects

In recent years, solar module reliability has risen to 97-98%, and wind turbine reliability to 92-95%. These figures reflect a high level of technological maturity and efficient maintenance practices [2].

Figure 14 shows the time dependences of FRs realisation for several type of RE equipment developed for years 2021-2024. The graph shows a tendency for decreasing failure rates overall, due to design improvements, use of more suitable materials and better predictive maintenance approach. The greatest reduction in failed modules were experienced by PV modules, dropping from approximately 3% in 2021 to slightly more than 2% in 2024. The wind power sector, though it still had far higher failure rates compared with other RE technologies, also showed significant improvements, from 8% to about 6.5%, during that time. There were persistent low failure rates for hydro and gradual decreases for geothermal facilities, associates with a better level of corrosion and scale control.

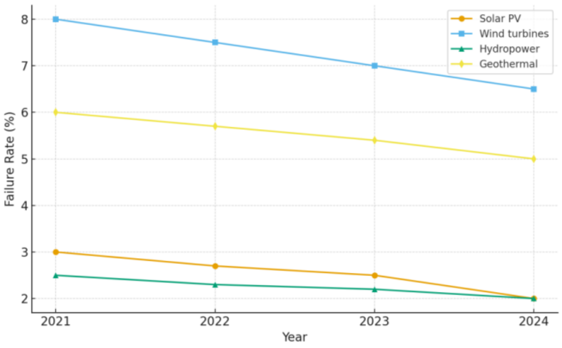

Figure 14: Dynamics of RE equipment failure rates, 2021-2024.

The number emphasizes the fact that focused technologies and better operating practices lead to higher system reliability. There have been, for example, improvements in the materials from which solar panels are fabricated or in the geometry and design of wind turbine blades or in the monitoring tools used at geothermal plants - all of which together is reducing downtime. They extend the service life of equipment, and decrease maintenance cost, as well as enhance investor confidence in RE projects. This general trend indicates that, as failure rates continue to decrease, renewable energy systems will increasingly be able to withstand system disturbances and be incorporated seamlessly into the global energy supply as robust and reliable components.

Despite clear advantages, RE technologies face ecological challenges linked to the production and disposal of solar panels and batteries.

Table 7: Environmental indicators of RE technologies, 2021-2024

Indicator	Value	Key challenges
CO_2 emissions (production)	20-50 g/kWh	Energy intensity and chemical use
Panel recycling	85-90% recyclability	Insufficient recycling infrastructure
Biodiversity impact	Low (if well-sited)	Bat and bird mortality near wind farms

Conclusion: While RE is substantially safer environmentally than fossil fuels, improvements in recycling and reductions in upstream ecological costs are required.

Table 7 presents the main environmental impacts attributed to RE technologies for the time-frame of 2021-2024. The life-cycle CO_2 emissions in the production phase is between 20 and 50 g/kWh which demonstrates a much more reduced value than that of fossil fuel generation. Nonetheless, this range highlights the energy-demanding nature of manufacturing and reliance on particular chemicals. Recyclability Another very important issue is the recyclability: till date, solar panels have an 85-90% recycling capacity, but in reality a large-scale machining infrastructure doesn't exist and it has been identified as one of the main bottlenecks. Moreover, although the effects on biodiversity are predominantly low in properly located sites, wind farms still have potential risks to bat and bird populations.

The table highlights that despite the substantial environmental advantages of RE technologies in comparison to traditional sources of energy, several challenges remain. In any case, achieving emissions reductions in manufacturing depends on the deployment of low-carbon supply chain and cleaner production pathways, while developing recycling infrastructure will be essential to the effective management of end-of-life solar panels and batteries. In addition, conservative spatial management and mitigation measures (e.g., wildlife monitoring and adaptive turbine operation) are required to ensure that biodiversity risk is kept at a minimum. Together, they highlight the need for an integrated approach to sustainability based on carbon reduction together with wider environmental perspectives.

4.3 Economic Aspects and Development Scenarios

Due to technological advances and production scale-up, RE electricity costs decreased by 40-50% between 2021 and 2024.

Table 8: Electricity costs from RE, 2021-2025.

Year	Solar ($/kWh)	Wind ($/kWh)
2021	0.03-0.05	0.04-0.06
2024	0.02-0.025	0.035-0.045
2025 (proj.)	0.015-0.02	0.03-0.04

Economic performance now rivals that of conventional energy sources, opening wide prospects for scaling up RE deployment.

The trajectory of electricity cost from (RE)-solar photovoltaic and wind technologies-are described in Table 8, for the period 2021-2025. The numbers show a clearly descending curve, as it went from the $0.03-0.05 per kWh range in 2021 to $0.02-0.025 in 2024 and even lower at projected $0.015-0.02 by 2025. WME, too, follows a comparable path: $0.04-0.06/kWe to $0.035-0.045/kWe in 2021 after which it is expected to fall further to the range of $0.03-0.04/kWe in 2025/6 [6]. Those declines are the result of hundreds of incremental improvements, expansion and increased efficiency in both generation and grid integration.

The table highlights the growing competitiveness of RE with fossil fuel-based electricity generation. The predicted price levels imply both wind and solar will not only become cheaper than coal, but that it will even be cheaper than gas and other fossil fuels in most of the world, challenging the conventional power supply with a new setup. These trends demonstrate the critical role supportive policies, international investments and ongoing innovation in storage and hybrids on affordability. In the end, the table shows that by 2025 RE will be one of the most competitive mechanisms for sustainable global energy transitions.

Modeling, including advanced scenarios with improved technology and storage capacity, suggests that by 2030 solar power will reach $0.01-0.015/kWh, and wind $0.025-0.035/kWh. Under such conditions, RE could provide 50-60% of national energy demand in several countries.

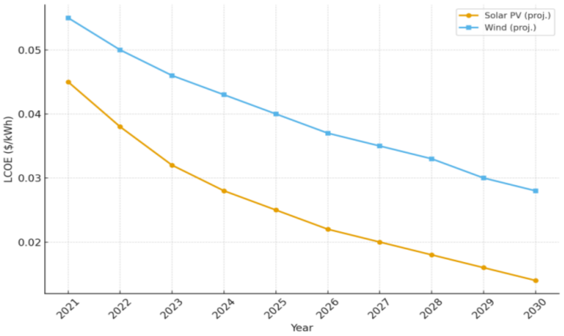

Figure 15: Projected scenarios of RE cost development to 2030.

Figure 15 presents future-oriented scenarios for the development of renewable energy (RE) technology costs for up to 2030, casting a special focus on solar photovoltaic and wind power technologies. The chart captures a steadily downward trajectory of leveling cost of electricity (LCOE) predicting that solar power will fall from roughly $0.045/kWh in 2021 to $0.014/kWh by 2030, and wind power should do likewise establishing from an average level of \$0.055/kWh in 2021 to about \$0.028/kWh over the year range. These estimates include additional technological development and the impact of large-scale deployment, suggesting that renewables could further improve their competitiveness on both cost and potential degree of economic penetration across a range of sectors.

The figure suggests that in the most optimistic scenarios, solar and wind power have the potential to dunderpricistribute almost all fossil fuel-based electricity generation (somewhere among a combination of natural gas, coal, and oil) to be flipped down or off-but not over-into discount-ruled future energy lists. Moreover, these scenarios showcases the significance of technological innovation in storage solutions, grid integration and materials science - factors that should impact how fast costs come down. The many pathways in the chart highlight the range of the possible, both with respect to what could happen but also what other governments may be considering and thus needing to understand in their own decision process. At the same time, it underscores a key takeaway: that renewables are well-positioned credityro play a significant role in meeting global decarbonisation goal by 2030.”

4.4 Impact on Energy Policy and Sustainable Development

The integration of RE technologies contributes directly to the UN Sustainable Development Goals (SDGs), including the reduction of greenhouse-gas emissions, development of innovation-driven economies, and decreased reliance on fossil fuels [9]. By 2030, expanding the share of RE could reduce global CO_2 emissions by 4-6%, thereby supporting compliance with the Paris Agreement.

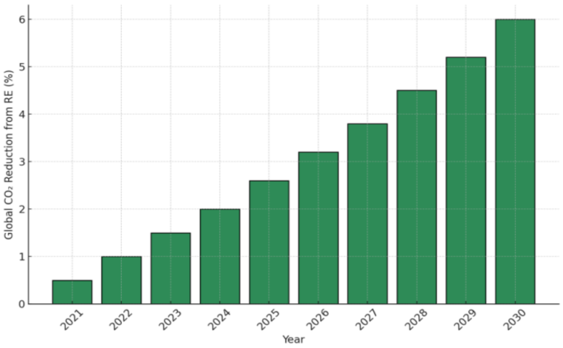

Figure 16: Impact of RE on global CO_2 reduction, 2021-2030.

The influence of renewable energy (RE) deployment on global CO_2 reduction from 2021 to 2030 is presented in Figure 16. From the graph, we confirmed that RE was gradually making more and more impact on emissions mitigation with reductions starting at 0.5% in 2021 to a target of about 6% by 2030. This progress is a result of continued rapid growth in solar and wind, modest improvements in geothermal and bioenergy, as well as sustained contributions from hydropower. It illustrated that amount of RE added to the national grid translated into quantifiable reductions in carbon emissions, highlighting the importance of RE technologies in climate action plans.

The diagram also makes it clear that, although decreases are gradual on an annual basis, the 2030 cumulative effect is large. A 6% worldwide reduction in CO_2 emissions due to RE technologies is very well articulated with the Paris Accord and UN SDG goals. What’s more, the figure illustrates that regional and technological differences matter: countries that have been the most successful at deploying solar, wind and storage technologies are estimated to deliver the biggest reductions and others may be later than 2040 - the point at which these estimates end - because they’re behind on clean infrastructure or resources to pay for it. In sum, the window reinforces the urgency to scale up RE investment and promote international cooperation in order capitalize its potential to decarbonize.

4.5 Limitations and Challenges

Despite progress, significant challenges remain:

- Underdeveloped infrastructure for energy storage and transmission [10];
- Uneven distribution of RE technologies, particularly across developing nations;
- Environmental risks associated with equipment recycling and disposal;
- High upfront capital costs of deployment.

These issues require systemic approaches, international collaboration, and sustained investment in research and innovation.

5 CONCLUSIONS

This study conducted a comprehensive analysis of modern renewable energy (RE) technologies for the period 2021–2025, focusing on their technical, economic, and environmental performance. Based on the collected data, modeling, and comparative analysis, the following key conclusions can be drawn:

1) Significant improvements in efficiency and reliability have been achieved across RE systems. Solar energy has demonstrated the most rapid progress, primarily due to the

adoption of advanced materials such as perovskite solar cells. Wind energy development has been driven by larger and more efficient turbine designs. In addition, the integration of hybrid systems and energy storage solutions has enhanced system stability and operational flexibility, which are essential for large-scale deployment [8].

2) The cost of electricity generated from renewable sources decreased substantially during the study period, making RE increasingly competitive with conventional energy. Projections indicate that by 2030, the cost of solar electricity may decline to \$0.01–0.015/kWh, while wind energy could reach \$0.025–0.035/kWh. These trends create favorable conditions for expanding the share of renewables in global energy systems.
3) Renewable energy technologies provide significant environmental benefits, particularly through the reduction of CO_2 emissions and decreased reliance on fossil fuels. However, several challenges remain, including the environmental impact of large-scale hydropower projects and the need for effective recycling and disposal of equipment. Despite these issues, the overall ecological footprint of RE remains substantially lower than that of conventional energy sources.
4) The expansion of renewable energy is still constrained by several factors, including insufficient energy storage and transmission infrastructure, high upfront capital costs, and uneven distribution of technologies across regions. Addressing these limitations is essential to ensure balanced and sustainable growth of the sector [10].
5) Further progress in renewable energy deployment will depend on continued investment in research and development, particularly in advanced materials and energy storage technologies. In addition, improving grid integration, expanding recycling infrastructure, and strengthening international cooperation will play a crucial role in accelerating adoption and minimizing environmental risks [11].

In conclusion, the results of this study confirm that renewable energy is becoming a key component of the global energy system. Continued technological advancement, cost reductions, and the resolution of existing infrastructural and environmental challenges will provide the foundation for a large-scale transition to sustainable energy, contributing to climate change mitigation and long-term energy security.

REFERENCES

[1] International Energy Agency (IEA), World Energy Outlook 2023, Paris: IEA, 2023, [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2023.

[2] United Nations, Sustainable Development Goals Platform, New York: UN, 2015, [Online]. Available: https://sdgs.un.org/goals.

[3] IPCC, Climate Change 2022: Mitigation, [Online]. Available: https://www.ipcc.ch/report/ar6/wg3.

[4] International Energy Agency (IEA), Renewables 2022: Analysis and Forecast to 2027, Paris: IEA, 2022, [Online]. Available: https://www.iea.org/reports/renewables-2022.

[5] IEA, Global Hydrogen Review 2023, [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2023.

[6] S. S. Nasriddinov, “Temperature sensors based on SiP,Ni,” Journal of Nano- and Electronic Physics, vol. 7, no. 3, p. 03037, 2015, [Online]. Available: https://jnep.sumdu.edu.ua/en.

[7] BloombergNEF, Global Energy Investment Trends 2023, [Online]. Available: https://www.bnef.com.

[8] S. S. Nasriddinov and D. M. Esbergenov, “Complex defect formation in silicon doped with nickel,” Russian Physics Journal, vol. 65, no. 9, pp. 1559-1563, 2023, [Online]. Available: https://doi.org/10.1007/s11182-023-02801-x.

[9] IRENA, Renewable Energy Market Analysis: Eurasia 2021, [Online]. Available: https://www.irena.org/publications.

[10] IEA, Energy Technology Perspectives 2023, [Online]. Available: https://www.iea.org/reports/energy-technology-perspectives-2023.

[11] UNDP, Human Development Report 2023, [Online]. Available: https://hdr.undp.org.