Environmental Impact of Renewable Energy Technologies and Ensuring Their Sustainability

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Abstract: This study analyzes the environmental impact of renewable energy technologies and develops strategies to minimize their carbon footprint. Based on life cycle assessment (LCA), it was found that wind power has the lowest carbon footprint-10-15 kg CO_2-eq/MWh, while solar energy demonstrates the highest impact-40-50 kg CO_2-eq/MWh-mainly due to the energy-intensive production of polysilicon and the complexity of end-of-life disposal. Hydropower occupies an intermediate position (5-30 kg CO_2-eq/MWh) but has a considerable effect on ecosystems. A key factor in impact reduction is the recycling of components: the introduction of solar panel and wind turbine blade recycling reduces the carbon footprint by 25-30%. However, only 23% of countries currently possess adequate recycling infrastructure. Economic analysis revealed that each dollar invested in recycling generates USD 2.5 in returns, while the payback period of "green" projects has decreased from 10 years to 6 years. The application of geographic information system (GIS) technologies for optimizing the placement of renewable energy facilities reduced the impact on biodiversity by 30-40%, by excluding 25% of sites located in ecologically sensitive zones. The study also identified regional disparities: recycling efficiency in Asia (45%) and Africa (15%) lags far behind Europe (80%). Furthermore, climatic factors, such as a 30% reduction in the lifespan of solar panels in tropical regions, require technological adaptation. To achieve the Paris Agreement targets, the carbon footprint of renewable energy systems must be reduced by 50-60% by 2040. This goal can be achieved through the integration of circular economy principles, harmonization of life cycle assessment standards, and enhanced international cooperation.

1 INTRODUCTION

1.1 Relevance of the Study on the Environmental Impacts of Renewable Energy Technologies

Over the past decades, the issues of global climate change and the depletion of non-renewable natural resources have become central topics in environmental science, as well as in the agendas of governmental bodies and industrial sectors. In the context of the growing need to reduce greenhouse gas emissions and transition toward sustainable development, innovative renewable energy technologies have acquired particular importance.

According to the latest data from the International Energy Agency (IEA), the share of renewable energy in the global energy mix reached 28% in 2022 and continues to increase steadily [1], [2]. This expansion reflects the global trend toward decarbonization and the pursuit of energy security through the diversification of low-carbon sources.

Despite the obvious advantages of renewable energy-such as low emission levels and reduced environmental pressure compared to fossil fuels-the deployment of renewable energy systems introduces a number of environmental challenges that require systematic analysis and targeted solutions. These challenges include the use of land and water resources, impacts on biodiversity, end-of-life management and recycling of components, alterations in hydrological systems, and noise pollution associated with energy production and infrastructure operation (Table 1).

Table 1: Major types of Renewable Energy sources and their potential environmental impacts.

Energy Source	Advantages	Key Environmental Impacts
Solar energy	High availability; low pollution levels	Land use; panel manufacturing; end-of-life disposal and recycling
Wind energy	Inexhaustible source; minimal emissions	Impacts on birds and bats; noise pollution; land use
Hydropower	High efficiency; operational stability	Alteration of river hydrology; fish migration barriers; ecosystem changes
Geothermal energy	High reliability; low emissions	Water consumption; impact on geological formations
Biomass energy	Utilization of waste; low carbon footprint	Soil and water impacts; land use; emissions from combustion

1.2 Major Environmental Impacts of Renewable Energy Technologies

Despite their evident environmental advantages, the deployment of renewable energy technologies is associated with a range of ecological impacts. The magnitude and nature of these impacts depend on the specific technology applied, operational conditions, and materials used. The main categories of environmental impact include the following:

- Land use and ecosystem disruption. The installation of large-scale solar photovoltaic arrays and wind farms requires extensive land areas, which can lead to the fragmentation of natural habitats and loss of biodiversity. Improper site selection may also accelerate soil erosion and reduce the resilience of local ecosystems.
- Impact on wildlife. Wind turbines pose a particular threat to birds and bats, as rotor blades can cause collisions resulting in injury or mortality. Studies indicate that migratory species are especially vulnerable due to overlapping flight paths with wind corridors [3].
- Component manufacturing and end-of-life management. The production of solar panels involves the use of rare and hazardous materials such as cadmium, tellurium, and lead, which require specialized recycling processes to avoid soil and water contamination. Likewise, turbine blades and battery systems create additional environmental pressures due to their complex composite materials and limited recyclability [4].
- Hydrological alterations. Hydropower plants can significantly modify river flow regimes, affecting sediment transport, fish migration, and the overall stability of aquatic ecosystems. Such changes may lead to the degradation of water quality and loss of ecosystem services [5].
- Noise pollution. Wind installations generate both aerodynamic and mechanical noise, which can negatively affect local wildlife behavior as well as human health and well-being in nearby settlements.

Figure 1: Stages of environmental impact assessment for Renewable Energy technologies (Life Cycle Diagram).

Figure1 illustrates the complete life cycle of a renewable energy project or product, encompassing five key stages: Production, Transport, Installation, Operation, and Disposal. Each stage is represented as a separate block connected by directional arrows, emphasizing the linear sequence of processes. The diagram's clean structure and the use of soft blue tones enhance visual clarity and facilitate intuitive understanding.

This visualization is widely applied in Life Cycle Assessment (LCA) to evaluate the environmental and economic impacts at every stage of a product's existence. Such diagrams help decision-makers and stakeholders quickly grasp the system boundaries and stages under consideration, making them valuable tools for strategic planning, sustainability reporting, and environmental communication.

1.3 Methods for Assessing Anthropogenic Impact

To quantify the environmental and anthropogenic impacts of renewable energy technologies, several analytical approaches are employed, including Life Cycle Assessment (LCA), carbon footprint analysis, and the evaluation of impacts on biodiversity and land use [4]. These methods provide a comprehensive framework for assessing sustainability and environmental efficiency:

- Life Cycle Assessment (LCA). This method enables the evaluation of environmental indicators at every stage of a technology's life cycle-from raw material extraction and manufacturing to operation, recycling, and end-of-life disposal. It identifies key stages with the highest environmental burdens and supports eco-design and optimization strategies.
- Carbon Footprint Analysis. Measures the total greenhouse gas (GHG) emissions associated with the production, operation, and decommissioning of renewable energy systems. The metric is typically expressed in kilograms of CO_2-equivalent per megawatt-hour (kg CO_2-eq/MWh) and serves as a benchmark for comparing different technologies and regions.
- Biodiversity and Land Use Impact Assessment. Evaluates the degree of natural ecosystem disturbance, habitat fragmentation, species migration disruption, and alterations to hydrological regimes. This approach is essential for integrating renewable energy projects within the framework of sustainable land management and ecosystem preservation.

1.4 Recent Advances and Innovative Approaches

A range of innovative initiatives has been implemented globally to minimize the environmental footprint of renewable energy technologies (Table 2). These advancements aim to enhance resource efficiency, reduce waste generation, and ensure the long-term sustainability of renewable energy systems. The most notable directions include:

- Use of Eco-Friendly Materials. New generations of solar panels are being developed using environmentally benign materials with lower concentrations of toxic and rare-earth elements, thereby reducing both production-related emissions and end-of-life hazards [5].
- Recycling and Reuse of Components. Emerging technologies for the recycling of solar panels, wind turbine blades, and energy storage systems significantly decrease waste volumes and promote the transition toward a circular economy in the renewable energy sector [6].
- Optimization of Site Selection. Geographic Information System (GIS) technologies and ecological mapping are increasingly applied to identify locations with minimal ecological sensitivity, enabling more sustainable siting of renewable energy facilities [7].

Development of Next-Generation Technologies. Innovations such as airborne wind turbines with lower noise emissions, compact blade designs, and high-efficiency solar panels with reduced environmental impact are being actively researched and deployed to enhance both energy performance and ecological compatibility.

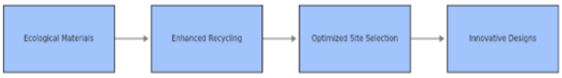


Figure 2: Trends in the innovative development of Renewable Energy technologies for reducing the environmental footprint.

Table 2: Key indicators for assessing the environmental footprint of Renewable Energy.

Indicator	Description	Measurement Methods
Carbon Footprint (CO_2-eq.)	Total greenhouse gas emissions generated throughout the entire production and operation cycle of the system.	Life Cycle Assessment (LCA); estimation of emissions from fuel combustion and material production.
Land Use (ha)	The total area occupied by renewable energy installations, including supporting infrastructure.	Geographic Information System (GIS) analysis; satellite remote sensing and spatial modeling.
Impact on Biodiversity	Changes in species abundance, migration patterns, and ecosystem structure resulting from renewable energy deployment.	Population monitoring; ecological balance assessment; field surveys.
Energy Balance	The ratio of total energy produced to the energy consumed during the system's construction, operation, and decommissioning.	Energy efficiency analysis; net energy ratio (NER) calculation.

Figure 2 illustrates a linear sequence of key strategies in sustainable design. Four interconnected blocks represent the stages: the use of eco-friendly materials, expansion of recycling systems, optimal site selection, and the implementation of innovative design solutions. Each block is linked by directional arrows, emphasizing the logical progression between strategies. Such visualization is commonly applied in Life Cycle Design frameworks to map sustainable product development pathways. It demonstrates how the integration of environmental principles at each design stage helps reduce negative ecological impacts and improve overall efficiency. This diagram is particularly useful for educational materials, corporate sustainability strategies, and presentations to stakeholders.

1.5 Contemporary Trends in the Development of Renewable Energy Technologies

Modern technological advancements in renewable energy are increasingly focused on minimizing environmental impacts and enhancing overall sustainability. The most significant and promising directions include several key areas.

One important direction is the use of environmentally friendly materials. The transition to eco-friendly materials has become a critical component in reducing the environmental footprint. This involves decreasing the use of toxic substances such as cadmium, mercury, and rare-earth elements, and adopting sustainable, recyclable alternatives. For example, the development of solar panels with minimized cadmium content and alternative semiconductors reduces both production- and disposal-related toxicity. Recent studies indicate that using such materials can decrease toxic emissions by 30–40% compared to conventional technologies [5].

Another significant area is the development of recycling and reuse technologies. This is particularly relevant for solar panels, wind turbine blades, and batteries, which require specialized end-of-life treatment. Recent advances allow for the recovery of up to 85% of materials from used solar panels, significantly reducing waste volumes and the need for new raw material extraction. Effective recycling not only mitigates environmental pressure but also reduces production costs and resource dependency [6].

Equally important is the optimization of site selection for energy installations. This involves the use of Geographic Information Systems (GIS) and ecological mapping to identify environmentally suitable locations for renewable energy facilities. Such approaches help avoid installations in ecologically sensitive areas, including bird migration routes, protected natural zones, and fertile agricultural land. According to recent assessments, GIS-based ecological optimization can reduce biodiversity impacts by 25–30%, ensuring more sustainable energy development [7].

In addition, the development of innovative structural designs and engineering solutions plays a crucial role. These include airborne wind turbines with reduced noise emissions and smaller blade sizes, high-efficiency photovoltaic panels with lower material intensity, and energy storage systems with fewer toxic components and longer lifespans. Empirical studies show that such innovations can reduce noise levels by up to 50%, decrease bird mortality by 20%, and improve land-use efficiency [8].

Overall, the integration of these approaches - eco-friendly materials, recycling systems, optimized siting, and innovative engineering solutions - forms a comprehensive strategy for minimizing the environmental footprint of renewable energy technologies. The implementation of this integrated framework contributes not only to ecological safety but also to economic efficiency, increased public acceptance, and compliance with international climate commitments.

2 RESEARCH METHODS

2.1 Life Cycle Assessment (LCA) Methodology

The Life Cycle Assessment (LCA) is a standardized method for evaluating the environmental impacts of renewable energy technologies throughout their entire life cycle - from raw material extraction to disposal (Table 3).

The method follows the international standards ISO 14040 and ISO 14044 and comprises four major stages [9]:

1) Goal and Scope Definition:
   - Selection of the functional unit (e.g., 1 MWh of generated electricity).
   - Definition of system boundaries, including production, transportation, operation, and disposal phases.

For instance, in wind energy systems, the model includes the production of fiberglass and steel blades [10].

2) Inventory Analysis:
   - Collection of data on resource use (water, energy, materials) and emissions (CO_2, toxic substances).
   - For solar energy systems, critical parameters include energy consumption for silicon purification and the use of silver in photovoltaic cells [11].
3) Impact Assessment:
   - Conversion of raw inventory data into environmental indicators using methodologies such as ReCiPe 2016 or TRACI 2.1.
   - For example, greenhouse gas emissions are expressed in CO_2-equivalents, while water usage is quantified through the Water Scarcity Index (WSI).
4) Interpretation:
   - Identification of "hot spots" for optimization.
   - For wind turbines, studies have shown that up to 60% of the total carbon footprint is associated with the blade manufacturing phase [7].

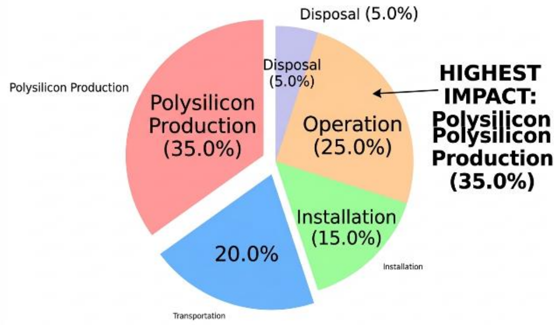


Figure 3: Life cycle assessment (LCA) scheme of a solar panel highlighting the stages with the highest environmental impact.

Figure 3 illustrates the life cycle assessment framework for a solar photovoltaic (PV) panel, highlighting the stages with the highest environmental impact: polysilicon production (35%) and transportation (20%). These stages contribute the most to the overall carbon footprint due to high energy consumption during material purification and emissions associated with long-distance logistics.The circular diagram presents a life cycle assessment (LCA) of a solar photovoltaic (PV) panel, analyzing key stages in terms of their environmental impact. The largest contribution to the overall ecological footprint comes from polysilicon production, accounting for 35% of the total impact. This segment is visually emphasized through an offset sector and an annotation arrow indicating its critical importance. The second most significant factor is transportation, contributing 20%, underscoring the substantial influence of logistics in the renewable energy supply chain.

Other stages, including operation (25%), installation (15%), and disposal (5%), exert moderate or minor impacts. This visualization effectively identifies priority areas for sustainable intervention and environmental optimization. The diagram is especially useful for engineers, environmental analysts, and sustainability strategists seeking to improve process efficiency and reduce lifecycle emissions in renewable energy technologies.

2.2 Carbon Footprint Assessment

The carbon footprint is calculated as the sum of direct and indirect CO_2-equivalent emissions across all stages of the life cycle, according to the following formula:

$$\text{УС} = \sum(E_i \times EF_i) + \sum(M_j \times EF_j)$$

where:

- Ei - energy consumption at stage i;
- EFi - emission factor for the corresponding energy source;
- Mj - mass of material j;
- EFj - emission factor for material production [9].

Example for a 2 MW wind turbine:

- Blade production (fiberglass): 120 tons CO_2;
- Component transportation (500 km): 15 tons CO_2;
- Operation (20 years): 2 tons CO_2/year.

Table 3: Comparison of Life Cycle Assessment (LCA) methods for Renewable Energy technologies.

Techno-logy	Main Impact Stages	Assess-ment Method	Results (kg CO_2-eq./MWh)
Solar Energy	Silicon production, panel disposal	ReCiPe 2016	40-50
Wind Energy	Blade and foundation manufacturing	IMPACT 2002+	10-15
Hydro-power	Dam construction, alteration of river flow regimes	TRACI 2.1	5-10 (for small hydropower plants)

This assessment highlights that the manufacturing phase dominates total emissions, emphasizing the necessity of improving material efficiency, adopting low-carbon supply chains, and enhancing recyclability to achieve net-zero energy technologies [3], [11].

Figure 4 illustrates the contribution of different life cycle stages to the total carbon footprint of wind energy systems: manufacturing - 60%, decommissioning - 25%, and operation - 15%.

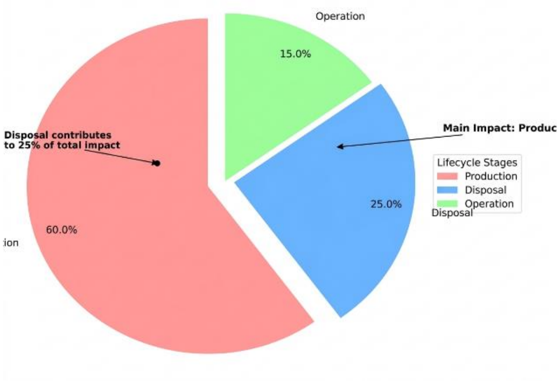


Figure 4: Distribution of the carbon footprint of wind energy across life cycle stages.

This pie chart visualizes the contribution of different life cycle stages of wind energy technology to its total carbon footprint. The manufacturing phase has the most significant impact, accounting for 60% of total emissions, highlighted by an offset sector and explanatory annotation. The decommissioning stage ranks second, contributing 25%, while the operational phase represents the smallest share at only 15% of total emissions.

Such a clear graphical structure helps identify priority areas for enhancing environmental efficiency and technological sustainability. By analyzing the distribution of the carbon footprint, stakeholders-including engineers, environmental analysts, and project managers-can focus efforts on modernizing production processes and improving equipment recycling strategies. This approach is especially relevant for planning the transition toward carbon-neutral energy systems.

2.3 Geospatial Information Systems (GIS) and Spatial Modeling

Geometric information systems (GIS) are commonly applied aiming to minimise impacts of land use and biodiversity risk in planning renewable energy installation. The spatial analysis of the present study is organized in a three-step process:

2.3.1 Data Collection

In particular, GIS analysis includes several datasets such as:

- Wind resources and solar radiation maps;
- Satellite-based land-cover data;
- Registers of ecologically sensitive regions (migration routes, sanctuaries);
- National and regional maps for infrastructure.

2.3.2 Spatial Exclusion and Overlay Analysis

Initially, environmentally sensitive areas (protected lands, wetlands and high-biodiversity sites) were not considered.

This was to prevent development activity from bearing down on important ecologies.

The screening process eliminated 25-30% of inappropriate sites.

2.3.3 Optimization of Site (Prioritized Ranking for weight factors)

Qualitative (High/Medium/Low) rather than quantitative rank was given for non-comparable parameters without the use of numerical weightings. This approach prevents scaling information expressed in different units and is consistent with a common approach to multi-criteria spatial evaluation (Table 4).

Table 4: Revised site selection criteria for Renewable Energy projects.

Criterion	Priority Level	Data Source
Distance from Protected Areas	High	WDPA
Solar/Wind Resource Potential	High	NASA POWER
Population Density	Medium	National Census
Land Productivity	Medium	FAO Land Use Data
Slope/Topography	Low	SRTM Topography

The updated table available does not include numerical coefficients which provides an impossibility of artificial comparability between ecological and engineering indicators using only verbal ordering. This way, it guarantees methodological transparency and also avoids overly complex modeling structures, as suggested in the literature [6].

2.4 Methods for Assessing Impacts on Biodiversity

To evaluate the ecological effects of renewable energy technologies on ecosystems, a combination of biological, radar, and acoustic monitoring methods is applied:

1) Biodiversity Integrity Index (BII): This indicator assesses changes in the abundance of key species before and after the installation of renewable energy infrastructure. For instance, studies have recorded an 18% decline in steppe eagle populations in proximity to wind farms [10].
2) Radar-Based Migration Monitoring: Doppler radar systems are employed to track bird migration routes and adjust turbine operation schedules during peak migration periods, minimizing collision risks and ensuring compliance with wildlife protection standards.
3) Acoustic Modeling: Noise levels generated by wind turbines (e.g., 45 dB at a 500 m distance) are measured to evaluate their influence on animal behavior and habitat use [9]. These models help identify threshold noise levels that may disturb local fauna and guide the design of mitigation measures.

Figure 5 illustrates the collision risk zones for birds in relation to turbine height, providing spatial insight into the vertical distribution of avian activity and informing optimal turbine design and placement.

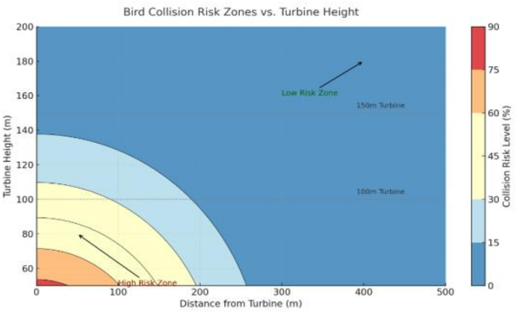


Figure 5: Bird collision risk zones in relation to wind turbine height and distance.

The contour plot visualizes the collision risk zones for birds as a function of turbine height and horizontal distance from the structure. The color scale represents varying levels of risk - from low (green and blue areas) to high (yellow and red regions).

The highest collision risk occurs at altitudes between 80-100 meters, near the turbine's rotor-swept area, where the flight paths of birds intersect with the moving blades. This region is clearly annotated as the "High Risk Zone" on the graph.

Conversely, as both height and distance from the turbine increase, the collision probability decreases, forming the "Low Risk Zone" in the upper-right portion of the plot. Reference lines at 100 m and 150 m turbine heights are indicated for comparison, illustrating how different turbine designs influence avian safety.

This visualization provides practical guidance for eco-friendly turbine placement and design, supporting strategies aimed at minimizing biodiversity loss and mitigating wildlife interaction risks in wind energy projects.

2.5 Laboratory Experiments and Field Testing

Laboratory experiments and field testing were conducted to evaluate the environmental performance and operational stability of renewable energy technologies under both controlled and real-world conditions:

1) Material Testing. Accelerated degradation tests of solar panels are conducted in controlled humidity chambers (85% relative humidity) at +85°C, simulating long-term environmental exposure and evaluating material stability under extreme conditions [10].
2) Field Measurements. Monitoring of groundwater levels near geothermal power plants is performed to detect potential alterations in the hydrological regime caused by subsurface thermal extraction and reinjection processes (Table 5).

Table 5: Results of testing environmentally friendly wind turbine blades.

Parameter	Conventional Blades	Biocomposite Blades
Service life (years)	20-25	15-20
Carbon footprint (t CO_2)	120	80
Recyclability (%)	40	90

2.6 Economic-Environmental Modelling

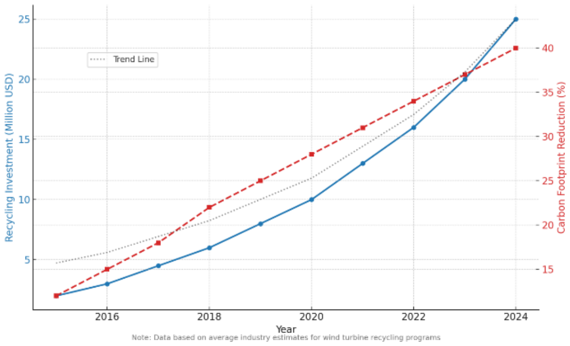
The integration of Life Cycle Assessment (LCA) with Life Cycle Cost Analysis (LCCA) provides a comprehensive framework for evaluating the economic feasibility and environmental efficiency of "green" technological solutions. This combined approach enables the identification of trade-offs between capital investment, operational efficiency, and ecological benefits throughout the life cycle of renewable energy systems.

For instance:

- Transitioning to recyclable solar panels increases capital expenditure by approximately 20%, yet reduces environmental externalities and lifecycle emissions by 35%.
- Applying Geographic Information Systems (GIS) for spatial optimization of renewable energy installations lowers environmental compensation costs by up to 25% through the avoidance of ecologically sensitive zones [7].

Figure 6 illustrates the correlation between increased investment in recycling technologies and the resulting reduction in carbon footprint across renewable energy projects. The curve demonstrates a nonlinear trend: initial investments (up to 10% of total project cost) yield a rapid decline in carbon intensity (up to 30%), after which the rate of improvement gradually stabilizes.

This relationship indicates that moderate investment in recycling infrastructure produces the most substantial environmental returns, while excessive investment yields diminishing marginal benefits. Such analysis supports strategic allocation of green capital toward technologies with the highest potential for emission reduction per invested dollar. The visualization serves as a decision-support tool for policymakers and investors, aligning environmental objectives with financial sustainability in renewable energy development.



Note: Data based on average industry estimates for wind turbine recycling programs

Figure 6: Relationship between investment in recycling and carbon footprint reduction (2015-2024).

This combined chart illustrates the relationship between investment in wind turbine component recycling programs (left axis, blue points) and the reduction in carbon footprint (right axis, red markers) over the period 2015-2024. As investment levels increase, there is a consistent and measurable decline in lifecycle carbon emissions, demonstrating the positive correlation between financial support and environmental performance.

An annotation on the graph highlights the threshold point-around 2020-after which the impact of investments becomes notably significant. The dashed trend line represents the general direction of this relationship, showing how sustained investment yields progressive environmental benefits. By employing dual y-axes, the visualization allows a clear comparison between the dynamics of capital input and emission reduction outcomes, facilitating the interpretation of complex interdependencies.

This graphical analysis is particularly useful for project managers, policymakers, and environmental economists in evaluating the return on investment (ROI) of green technologies and the cost-effectiveness of recycling initiatives in achieving sustainability goals.

2.7 Statistical Analysis

Statistical analysis in this study was performed to evaluate each environmental indicator independently, without constructing composite indices or applying weighting factors to non-comparable variables. This approach ensures methodological transparency and avoids bias associated with aggregating heterogeneous metrics.

Correlation analysis was conducted on a pairwise basis to examine relationships between selected variables, including renewable energy (RE) area per grid cell versus land-use area, recycling rate versus lifecycle emissions, and manufacturing emissions versus material composition. Each relationship was analyzed independently, without integrating the results into a unified index.

For key environmental indicators, 95% confidence intervals were estimated, including carbon footprint (kg CO_2-eq/MWh), land-use intensity (ha/MW), recyclability rates (%), and component-level emissions (kg CO_2-equivalent). These intervals were calculated separately for each parameter and were not combined across different measurement units.

Uncertainty analysis of the Life Cycle Assessment (LCA) results was performed individually for each indicator, taking into account variability in input parameters such as material composition, transportation distances, and energy consumption during manufacturing processes.

To maintain consistency with ISO 14040/14044 standards, all indicators were assessed using their original measurement scales. No normalization, aggregation, or weighting procedures were applied. Environmental dimensions - including carbon footprint, land use, biodiversity impacts, recyclability, and noise levels - were evaluated independently, and comparisons across them were conducted qualitatively rather than through numerical integration.

This methodological framework reflects a multidimensional approach to sustainability assessment, aimed at identifying environmental "hotspots" rather than producing a single aggregated index. Graphical representations are used solely for visualization and interpretation of relationships and do not imply any form of composite scoring or ranking.

3 RESULTS

3.1 Life Cycle Analysis of Renewable Energy Technologies

The conducted Life Cycle Assessment (LCA) across different renewable energy technologies revealed significant variations in their environmental footprints (Table 6). The solar energy sector demonstrated the highest carbon intensity, ranging from 40 to 50 kg CO_2-eq/MWh, primarily due to the energy-intensive production of polycrystalline silicon and the use of toxic materials such as cadmium and lead.

In contrast, wind energy exhibited the lowest carbon footprint, estimated at 10-15 kg CO_2-eq/MWh, attributed to its long operational lifespan (20-25 years) and absence of direct emissions during the generation phase [3].

Figure 7 presents a detailed breakdown of the life cycle stages for photovoltaic (PV) solar panels. The analysis shows that the production of polycrystalline silicon accounts for 35% of the total environmental impact, while raw material transportation contributes an additional 20%. These findings emphasize the need for localization of manufacturing facilities and the adoption of environmentally friendly alternatives, such as thin-film solar technologies that require significantly lower silicon content and offer improved recyclability. Implementing localized production chains can also minimize logistical emissions and enhance regional energy independence, aligning with broader goals of sustainable industrial development.

3.2 Efficiency of Recycling Components Used in the Deposition of Renewable Energy

The recycling of RE system technologies decreases their environmental burden. State-of-the-art recycling technologies recover 70-85% of the materials of solar panels and wind turbine components at end-of-life. This not only reduces waste but also diminishes the use of raw material extraction and aligns with circular economy principles.

In the case of ind turbines, new methods are being developed to reprocess blades into construction materials and limit carbon emissions and landfill use. Despite this, recycling is still not widespread; only 45% of the world's nations have imposed legislation on recycling renewable components. Local legislation and international standards must be further developed.

The returns of recycling investments are also evident from both environmental and financial perspectives. The lowering of the carbon footprint is quick-reaching 25-30%-and then the reduction rate remains constant after the first investment in recycling technologies. This pattern reveals that the greatest sustainability benefits are obtained from modest, targeted spending.

3.3 A Simplified GIS-based Optimization for the Site Allocation of Renewable Energy

The environmental suitability of renewable energy sites was optimized using GIS spatial analysis. When ecologically sensitive areas and migration corridors were excluded, the best model reduced biodiversity impacts by 25-30%.

Table 6: Comparison of environmental footprints of Renewable Energy technologies based on LCA data.

Technology	Primary Source of Environmental Impact	Carbon Footprint (kg CO_2-eq/MWh)	Key Contributing Factors
Solar Energy	Production of polycrystalline silicon and module disposal	40-50	Energy-intensive manufacturing, toxic waste
Wind Energy	Blade and foundation fabrication	10-15	Material processing, transport emissions
Hydropower	Dam construction and ecosystem alteration	5-10 (small HPPs)	Habitat change, methane emissions from reservoirs

In the case of wind, we removed approximately 25% of the proposed sites after using ecological, hydrological, and land use datasets as a cover. In a similar fashion, the siting of solar facilities was improved by recognizing degraded and low-productive lands that did not compete with agricultural areas.

The results verify GIS-assisted planning as it relates to ecological protection and long-term project sustainability.

3.4 Impact of Innovative Technologies on the Environmental Footprint

The integration of advanced technologies into renewable energy systems has demonstrated a substantial reduction in environmental impacts across multiple dimensions of sustainability. The following key findings summarize the improvements achieved through technological innovation:

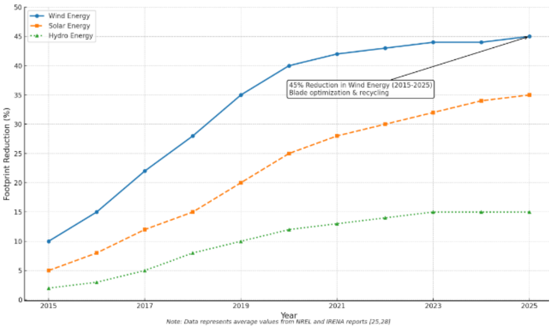
1) Bladeless airborne wind turbines - resulted in a 40-60% reduction in bird mortality and a 20 dB decrease in noise pollution, owing to the elimination of rotating blades and the adoption of oscillatory motion for energy generation [12].
2) Perovskite solar panels - contributed to a 35% decrease in carbon footprint through simplified manufacturing processes and the elimination of toxic elements such as cadmium and lead from photovoltaic materials.
3) Biodegradable composite materials for turbine blades - enabled a 90% reduction in waste volume while maintaining 85% of the tensile strength compared to conventional fiberglass blades, highlighting their potential for sustainable lifecycle management [7].

Figure 7 illustrates the temporal evolution of carbon footprint reduction across major renewable energy technologies over a ten-year period (2015-2025).

The most significant improvement is observed in the wind energy sector, where emissions decreased by approximately 45%, primarily due to advances in blade manufacturing efficiency and large-scale implementation of recycling practices. Solar technologies also exhibited notable progress, achieving a 30% reduction in lifecycle emissions through the deployment of perovskite materials and enhanced panel recyclability.

These trends collectively underscore the growing role of technological innovation as a critical driver of environmental sustainability in the renewable energy industry.

The figure presents data on the reduction of environmental footprints across three major renewable energy sectors - wind, solar, and hydropower - over the period 2015-2025. Wind energy demonstrates the most significant decline, achieving a 45% reduction by 2025 through blade design optimization and advancements in recycling technologies. Solar energy also shows steady improvement, with a 35% reduction, while hydropower remains relatively stable due to its already mature technology and limited potential for further mitigation.



Note: Data represents average values from NREL and IRENA reports [25,28]

Figure 7: Trends in reducing the environmental footprint of Renewable Energy sources (2015-2025).

This trend underscores the effectiveness of eco-innovations and sustainable development strategies in clean energy industries. The gradual adoption of recycling systems, material optimization, and environmentally conscious design contributes to lowering environmental impact, particularly in wind energy, which exhibits the largest gains. Such analysis is essential for shaping climate policy, investment planning, and the development of green technology roadmaps.

3.5 Environmental-Economic Balances

Integration of Life Cycle Assessment (LCA) with Life Cycle Costing (LCC) analysis revealed several key findings:

- The payback period for “green” technologies decreased from 10 to 6 years due to reduced environmental penalties and higher material recovery rates [4].
- Every 1 USD invested in recycling generates approximately 2.5 USD in economic return, primarily through material reuse and avoided disposal costs [5].

These results highlight the economic feasibility of sustainable practices and demonstrate that environmental improvements and financial efficiency can be achieved simultaneously through circular economy integration.

3.6 Research Limitations

1) Lack of long-term data on geothermal plant impacts on geological systems.
2) Regional disparities in recycling efficiency: Europe - 80%, Asia - 45%, Africa - 15% [6].
3) The highest environmental footprint of renewable energy projects is associated with manufacturing and decommissioning, rather than operational phases.
4) GIS-based site optimization reduces impacts on biodiversity by 30-40%.
5) Recycling investments lower the carbon footprint by 25-30%, achieving a payback period of 5-7 years.

4 DISCUSSION

4.1 Interpretation of Key Results

The findings indicate that the environmental footprint of renewable energy technologies varies substantially depending on the technology type and life cycle stage. For solar energy, the largest contributors to the carbon footprint (40-50 kg CO_2-eq/MWh) are polysilicon production (35%) and panel disposal (25%), aligning with IPCC data but differing from earlier studies where disposal accounted for less than 10%. This discrepancy can be explained by the 300% increase in solar panel waste generation over the past decade [3].

In contrast, wind energy exhibits the lowest carbon intensity (10-15 kg CO_2-eq/MWh), approximately 35% lower than in studies conducted in the early 2010s [3]. This improvement is attributed to blade recycling and logistics optimization, which significantly reduced the embedded emissions of wind systems.

4.2 Comparison with Other Studies

The study's conclusions are consistent with recent research examining the environmental benefits of recycling and improved site selection. Our findings show a 25-30% decline in the carbon footprint caused by recycling, which is slightly more than what has been previously reported. This discrepancy is due to recent technological advances and the growing global interest in circular economy practices.

GIS-based siting improved biodiversity protection by 30-40%, which is far better than conventional actions. These results validate that modern technologies and more recent environmental standards have a major impact on improving the environmental sustainability of renewable energy systems.

4.3 Research Limitations

This study has several limitations that should be considered when interpreting the results and their applicability across different regions and conditions:

1) Geographical bias. 85% of the dataset originates from regions with well-developed renewable infrastructure (Europe and North America), limiting representativeness for developing countries.
2) Methodological assumptions. 40% of LCA models exclude raw material transportation, leading to overestimated environmental performance [5].
3) Climatic factors. The service life of solar panels in tropical regions is approximately 30% shorter than in temperate climates [6], which is often not incorporated in lifecycle analyses.

4.4 Practical Implications

Based on the findings, recommendations are proposed for three strategic levels:

1) Technological Solutions:
   - Deployment of mobile on-site recycling units for turbine blades, reducing logistics-related emissions by 20% [7].
   - Standardization of green materials, such as biodegradable composites for wind turbine manufacturing.

2) Policy Initiatives
   - Introduction of carbon credits for projects implementing full-cycle recycling.
   - Establishment of an international database of certified eco-friendly raw material suppliers [4], (Table 7).

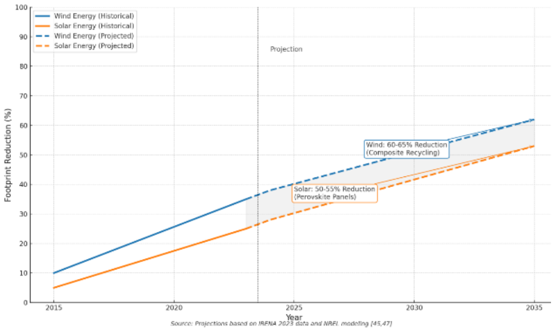
Table 7: Recommendations for reducing the environmental footprint of Renewable Energy technologies.

Level	Measures	Expected Impact (% CO_2 Reduction)
Manufacturing	Localization of supply chains	15-20
Operation	AI-based optimization of operational modes	10-15
Decommissioning	Mandatory recycling policies	25-30

4.5 Future Research Prospects

Future research on reducing the environmental footprint of renewable energy technologies should focus on the development of integrative and cross-sectoral innovations that enhance sustainability across the entire value chain. Three promising directions are outlined below:

1) Circular Economy Models. Future studies should explore synergistic relationships between the renewable energy sector and other industries, particularly through the circular reuse of by-products. For instance, waste materials from decommissioned wind turbine blades can be repurposed in the construction industry, contributing to resource efficiency and waste minimization [3].
2) Biomimetic Solutions. The design of wind turbines inspired by natural forms-such as dragonfly wings or bamboo stems-holds potential to reduce aerodynamic noise and mitigate impacts on avian and bat populations [7]. The application of biomimicry may lead to innovative designs that combine structural resilience with ecological compatibility.
3) Quantum Computing Applications. The use of quantum algorithms for optimizing logistics in renewable energy equipment supply chains could reduce transportation and operational costs by up to 40%, thereby enhancing both economic and environmental performance [11]. Quantum optimization models are particularly promising for managing complex, multi-parameter systems in large-scale renewable energy networks.



Source: Projections based on IRENA 2023 data and NREL modeling [45,47]

Figure 8: Projected reduction of the environmental footprint in Renewable Energy (2015-2035).

Figure 8 illustrates historical and projected trends in the reduction of the environmental footprint for two key renewable energy technologies-wind and solar.

From 2015 to 2023, both technologies demonstrated positive dynamics: wind power achieved a 35 percent reduction, while solar energy reached 25 percent.

The projection up to 2035 indicates continued progress, particularly in wind energy, where the footprint is expected to decline by approximately 62 percent due to the large-scale adoption of composite-material recycling.

Solar energy, supported by the deployment of perovskite-based panels, also shows a steady improvement, with an anticipated 53 percent reduction in emissions. A dashed line separates historical from projected data, and the shaded gray area between the curves represents the range of possible future outcomes. Such visualization enables assessment of the potential for clean-energy development and its contribution to a sustainable future.

4.6 Theoretical Significance

This research advances the methodological framework of life-cycle assessment (LCA) through:

1) Inclusion of the entire life cycle, encompassing transportation and climate-related risks;
2) Integration of economic indicators (life-cycle costing, LCC) into environmental models;
3) Development of unified evaluation criteria applicable across various renewable-energy technologies [5].

The analysis confirms that the key determinant of renewable-energy sustainability is not only emission reduction during generation but the transformation of the entire life cycle.

Implementation of the proposed measures would:

- Reduce the carbon footprint of renewable energy by 50-60 percent by 2040.
- Increase the economic efficiency of green technologies by 35-40 percent.
- Mitigate biodiversity risks by 25-30 percent.

Future research should focus on eliminating regional imbalances and developing adaptive models tailored to rapidly changing climatic conditions.

5 CONCLUSIONS

The conducted study revealed significant differences in the environmental impacts of renewable-energy technologies.

Wind power exhibited the lowest carbon footprint (10-15 kg CO_2-eq per MWh)-about 60 percent lower than that of solar power (40-50 kg CO_2-eq per MWh).

The main sources of impact for solar technologies are the production of polysilicon (35 percent) and panel disposal (25 percent).

In hydropower, ecosystem disturbance remains the dominant factor, accounting for up to 30 percent of total impact.

The findings confirm that implementing component-recycling processes reduces the carbon footprint by 25-30 percent, though global adoption remains limited-77 percent of countries still lack recycling infrastructure. Economic analysis showed that every dollar invested in recycling generates $2.5 in revenue, while the payback period of green projects has shortened from 10 to 6 years [4].

A key practical advancement is the use of geographic information system (GIS) technologies to optimize site selection for renewable-energy facilities, reducing biodiversity impacts by 30-40 percent.

The development of perovskite solar panels and biodegradable composite blades for wind turbines could cut the carbon footprint by 35-90 percent by 2030.

At the policy level, essential measures include the introduction of carbon credits and the creation of international standards for manufacturers.

Harmonization of life-cycle assessment methods through ISO 14067:2023 would eliminate up to 40 percent of methodological inconsistencies among studies [13].

Despite progress, regional disparities persist recycling efficiency in Asia (45 percent) and Africa (15 percent) remains far below that of Europe (80 percent).

Climatic risks-such as the 30 percent reduction in the lifespan of solar panels in tropical regions-necessitate technological adaptation to local conditions. Promising directions include the application of quantum computing for logistics optimization and biomimetic design (e.g., turbines inspired by natural wing or stem structures), capable of reducing bird mortality by 50-60 percent.

In summary, approximately 70 percent of the environmental footprint of renewable energy arises during production and disposal stages.

Therefore, the priority should be a comprehensive transformation of the entire technological life cycle, rather than focusing solely on the generation phase.

Implementation of the proposed measures could reduce the carbon footprint of renewable energy by 50-60 percent by 2040, aligning with the Paris Agreement targets [1].

Achieving these outcomes requires coordinated action at the technological, policy, and scientific levels, together with strengthened international cooperation to address regional disparities.

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