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# ECOLOGICAL IMPACTS OF RENEWABLE ENERGY PROJECTS AND TECHNOLOGICAL INNOVATIONS FOR THEIR MITIGATION

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**Abstract:** The accelerated development of renewable energy projects is a key component of the energy transition and carbon emissions reduction. However, these technologies generate a range of ecological impacts that require proper assessment and management. This study analyzes the main categories of environmental pressures associated with renewable energy production, including extensive land use for solar, wind, and biomass farms, degradation caused by the extraction of rare minerals used in equipment, and risks to biodiversity, particularly birds, bats, and migratory fish species. In the second part, the study presents innovative solutions aimed at mitigating these impacts, such as agrivoltaics and floating solar panels, the use of recyclable materials, vertical–axis wind turbines, sustainable mining practices and urban mining, wildlife protection technologies, battery recycling and reuse, nature–based solutions for habitat restoration, smart microgrids, eco–friendly hydropower, and biomass carbon capture systems. The analysis highlights the potential of these innovations to transform the energy transition into a far more sustainable process, significantly reducing the sector's ecological footprint and contributing to the protection of ecosystems.
**Keywords:** renewable energy, ecological impacts, biodiversity, life cycle assessment, sustainable materials

## INTRODUCTION

The shift to renewable energy is seen as essential for limiting climate change and meeting sustainable development goals, especially by cutting the greenhouse gas emissions linked to fossil fuels.[1] Many studies show that long–term decarbonization plans depend on a growing share of wind, solar, hydro, and biomass energy in the global energy mix.[2,3] However, as renewable energy infrastructure expands at regional and global scales, a number of environmental side effects are becoming increasingly apparent, which cannot be ignored in a comprehensive assessment of sustainability. The literature highlights that, although renewable technologies have a net positive climate impact, they create significant pressures on land use, mineral resources, water, and biodiversity, as well as issues related to end–of–life waste.[4,5]

Large–scale solar and wind farms occupy extensive areas, which can result in the loss or fragmentation of natural habitats and cause land–use conflicts, particularly in ecologically valuable regions or on productive agricultural land.[6,7] Similarly, the expansion of biomass–based technologies can lead to land–use changes that impact soil health, water cycles, and ecosystem services.[8] In addition to land–use pressures, the production of renewable energy equipment—such as solar panels, wind turbines, and storage batteries—relies on the intensive extraction of critical minerals (e.g., lithium, cobalt, nickel, rare earth metals), whose supply chains are associated with significant environmental and social impacts, including habitat degradation, water pollution, and human rights risks in certain regions.[9,10] Moreover, the water consumption of certain technologies, such as conventional hydropower and concentrated solar systems, can alter hydrological regimes, water quality, and the structure of aquatic ecosystems, affecting migratory fish species and human communities that depend on water resources. [2,11]

Another critical area is biodiversity. Numerous assessments highlight the vulnerability of certain bird and bat species to collisions with wind turbines, as well as the barrier and fragmentation effects caused by energy infrastructure. [12,13] In the case of hydropower plants, dams can disrupt fish migration routes and alter the structure and functioning of river ecosystems. At the same time, the issue of waste generated by photovoltaic panels, wind turbine blades, and batteries is beginning to take on systemic proportions, as the first generation of installations approaches the end of its lifespan and the volume of end–of–life equipment continues to grow. [14,15]

In this context, an approach that goes beyond the 'low–carbon emissions' paradigm becomes necessary—one that integrates a life–cycle analysis for renewable technologies, taking into account the entire value chain, from resource extraction and equipment manufacturing to operation, decommissioning, and recycling. [3,10] At the same time, recent literature proposes a range of innovative solutions for reducing the environmental footprint of renewable energy projects, such as dual land use through agrivoltaic systems, integrating floating solar panels on water reservoirs, developing wildlife–friendly wind turbine designs, advanced recycling technologies for panels and blades, as well as the implementation of microgrids and smart demand–management systems [11,16].

The present article aims to synthesize the main types of environmental impact associated with renewable energy production projects, with a focus on land use, resource extraction, water consumption, waste generation, and biodiversity risks, while also presenting a set of technological and management solutions that can help reduce these impacts. The structure of the study follows, in the first part, a detailed examination of the main impact categories for different technologies (solar, wind, hydro, biomass), and in the second part, an analysis of innovative solutions such as agrivoltaics, floating solar panels, the 'second–life' concept for batteries, materials recycling, and nature–based solutions for ecosystem restoration. In this way, the paper seeks to contribute to laying the groundwork for an energy transition that is not only decarbonized, but also environmentally responsible.

## IMPACTS, TRADE–OFFS, AND SOLUTIONS IN THE RENEWABLE ENERGY TRANSITION

Although renewable energy projects are essential in the transition to a low–emission energy system, they generate a series of ecological impacts that must be carefully assessed and managed. Studies outline a complex picture in which the climate benefits of renewable sources coexist with pressures on land, natural resources, biodiversity, and aquatic ecosystems (Figure 1).

At the same time, the literature (figure 2) emphasizes that some of these impacts become visible only when analyzed across the entire life cycle of the infrastructure, including the phases of material extraction, operation, and decommissioning.

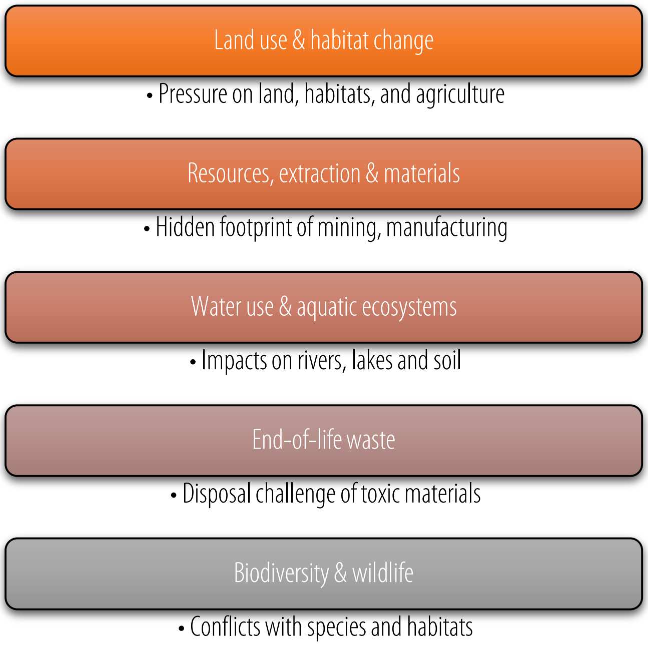


Figure 1. Environmental Impacts Overview

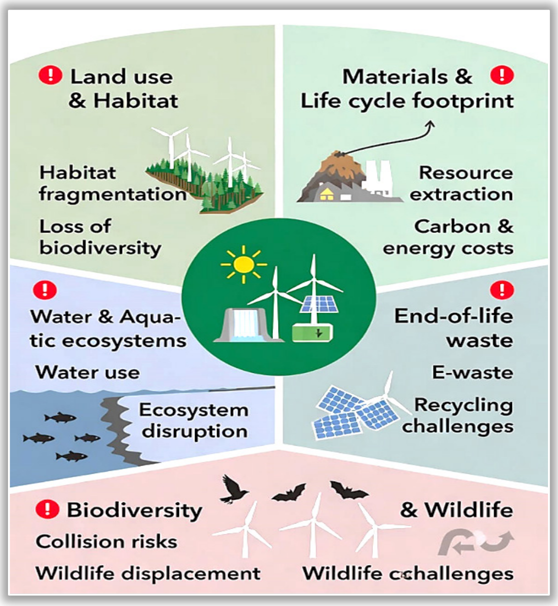


Figure 2. Environmental impacts and trade–offs of the renewable energy transition: key ecological challenges across the life cycle and pathways toward nature–compatible deployment.

The following sections present the main categories of impact identified in current research, as well as the relevant discussions for understanding the relationship between renewable technologies and the natural environment.

### Land use and habitat alterations

Renewable energy projects, particularly large–scale photovoltaic and wind farms, can exert considerable pressure on land use, natural habitats, and agriculture. A recent study [3,17] highlights that the transition to renewable energy involves both opportunities and ecological trade–offs: while it provides significant low–emission benefits, the expansion of the required infrastructure can lead to habitat loss or fragmentation. Another study [18] highlights that solar farms and wind parks require large land areas to be economically viable, which generates significant effects on land cover, soil, and the landscape.

This shift in land use—from natural or agricultural ecosystems to energy infrastructure—represents a significant ecological trade–off, and the analysis indicates that its impacts are often underestimated during the planning process. The key observation is that land–use pressure does not stem solely from the physical footprint of the installations, but also from secondary territorial effects such as habitat fragmentation, altered ecological connectivity, changes in radiative balance and soil–level temperature, or shifts in agricultural practices. [19]

In areas with high biodiversity, the placement of solar and wind projects can lead to the isolation of wildlife populations, reduced continuity of ecological corridors, and decreased ecosystem resilience. Regarding agricultural land, the loss or reduction of productivity is a real risk where energy infrastructure is not integrated in a way that remains compatible with farming activities. [20]

Thus, the results of the analysis highlight the need for more rigorous spatial planning, in which site selection is based not only on energy potential but also on ecological and functional criteria—such as habitat connectivity, the agronomic value of the land, and the sensitivity of local ecosystems. From this perspective, solutions such as using degraded land, integrating agrivoltaic technologies, or developing GIS tools for cumulative–impact assessments become essential for reducing conflicts between the energy transition and environmental protection.

### Resources, extraction, and materials – the hidden footprint

The implementation of renewable technologies requires the extraction of raw materials for manufacturing solar panels, wind turbines, and storage systems. This aspect, often underestimated, involves ecological costs: mining for critical materials, the energy consumed during production, and the use of potentially toxic or hard–to–recycle substances all contribute to an environmental footprint that must be evaluated across the entire life cycle of the infrastructure.

An integrated approach shows that for different renewable sources (hydro, solar, wind, biomass), the project–sizing variables are closely linked to their potential environmental impacts, demonstrating that design decisions (capacity, scale, type) play a critical role in minimizing negative effects [2]. Therefore, achieving energy decarbonization alone is insufficient; it is essential to conduct a comprehensive life–cycle assessment (LCA) that encompasses the extraction of raw materials, manufacturing processes, operational phase, and end–of–life decommissioning of the equipment. [21] By integrating these stages, the true ecological footprint of renewable technologies can be fully understood. For example, while the operational phase of solar panels or wind turbines generates almost negligible emissions, their manufacturing and transportation involve significant consumption of mineral resources, energy, and water, as well as emissions associated with industrial processes. Moreover, the decommissioning of infrastructure at the end of its life raises challenges related to waste management and the recovery of critical materials, particularly for hard–to–recycle components such as the composites used in wind turbine blades or certain types of photovoltaic panels.

Adopting a life–cycle perspective thus provides a far more realistic view of the sustainability of these technologies, enabling the identification of stages with major impacts and guiding investments toward cleaner production processes, alternative materials, and advanced recycling technologies. This approach is also essential when evaluating future scenarios for the expansion of renewable capacity, as large–scale growth of current infrastructure, without improvements in the supply chain, could generate significant cumulative ecological effects.

### Water use and impacts on aquatic environments

Renewable technologies are not without impacts on water resources and aquatic ecosystems. In the case of hydropower, which is frequently used in the renewable energy mix, the construction of dams and reservoirs can alter the natural flow regimes of rivers, affect fish migration, reorganize sediment dynamics, change water quality, and consequently reduce aquatic biodiversity. Moreover, even in the case of solar energy, large–scale installations can influence soil structure and local hydrology, affecting water infiltration and groundwater dynamics [22]. These observations support the idea that the sustainable design of energy infrastructure must include criteria for the protection of water resources and aquatic ecosystems. The analysis indicates that impacts on hydrological systems are not merely local but can cause long–term imbalances in the dynamics of riverine and lacustrine ecosystems, affecting both the hydromorphology and the ecological functions of these habitats.

In the case of hydropower plants, alterations to natural flow regimes, sediment retention, and disruptions to longitudinal connectivity can reduce the capacity of ecosystems to support healthy populations of fish and macroinvertebrates, which are fundamental components of aquatic food webs. [23] Studies also indicate that large–scale photovoltaic systems can modify infiltration and evaporation, influencing the soil water balance and, consequently, the potential for groundwater recharge. [24]

For these reasons, environmental assessments conducted prior to project authorization should not be limited to a site–specific analysis but must also consider cumulative effects on watersheds and regional hydrological flows. The implementation of adaptive management measures—such as maintaining minimum ecological flows, employing technologies that facilitate fish migration, avoiding the placement of solar installations in areas with high hydrogeological vulnerability, or restoring affected aquatic habitats—can significantly reduce pressures on water resources.

Thus, integrating hydrological and ecological criteria into infrastructure design becomes an essential condition for ensuring the long–term compatibility of energy development with the conservation of aquatic ecosystems.

### End–of–life waste and recycling challenges

As the first generations of installations—solar panels, wind turbines, and batteries—reach the end of their service life, the issue of waste emerges. Solar installations may contain hazardous materials, while wind turbine blades, often made from hard–to–recycle composite materials, present a major recycling challenge. This creates a risk of waste accumulation if effective recycling and reuse strategies are not implemented. The literature identifies this as one of the main weaknesses of the energy transition [25,26]. Furthermore, battery–based storage systems (e.g., lithium–ion batteries) can generate toxic waste if not properly managed, adding a hidden ecological impact throughout the life cycle, from material extraction to disposal [27]. This underscores the importance of incorporating "second–life" and recycling strategies from the design phase onward.

### Biodiversity and wildlife – tangible ecological conflicts

One of the most sensitive dimensions of the environmental impact of renewable energy projects is related to biodiversity. Gasparos et al. [28] highlight that the main renewable technologies (solar, wind, hydro, biomass) can contribute, directly or indirectly, to habitat loss, pollution, ecosystem fragmentation, and the degradation of ecosystem services.

For wind energy, recent projects indicate that land–use changes associated with wind farms contribute to biodiversity decline when they affect natural habitats of conservation interest. Similarly, recent analyses show that solar farms can induce habitat fragmentation and behavioral changes among birds and bats, while wind turbines are associated with increased mortality of flying species. Hydropower plants, on the other hand, can disrupt fish migration and the quality of aquatic habitats. [29]

These findings confirm that the energy transition, if not carefully planned and implemented, can impose significant costs on biodiversity, contrary to the common perception of renewable energy projects as ecologically "neutral." The analysis suggests that many of these effects are not immediately visible, which means that traditional environmental assessments often underestimate the real risks to species and habitats. For example, bird and bat mortality caused by wind turbines can be difficult to quantify in the short term, yet the cumulative consequences for populations can become significant, especially in migration corridors. [12] Similarly, habitat fragmentation caused by ground–mounted solar farms can alter the feeding, breeding, and movement behaviors of sensitive species, even if these changes do not immediately lead to noticeable population declines. [30]

The results highlight the need for a far more proactive approach, in which project planning is accompanied by detailed spatial analyses, ecological modeling, and continuous monitoring. Siting infrastructure outside areas of high sensitivity, avoiding migration corridors, applying collision–reduction technologies, and implementing compensatory measures are essential tools for preventing significant impacts. It is also important that the energy transition incorporates principles of landscape ecology so that technological development does not compromise ecosystem functioning. This perspective confirms that, although renewable energy plays a decisive role in reducing carbon emissions, the true sustainability of the transition depends on how biodiversity impacts are managed and on society's ability to adopt solutions compatible with nature conservation.

**INTEGRATED APPROACHES FOR REDUCING IMPACT AND OPTIMIZING THE ENERGY TRANSITION**

Maximizing the benefits of renewable energy while reducing its negative environmental impacts requires an integrated approach (figure 3) that combines the use of energy technologies with principles of sustainable planning, effective recycling strategies, ecological design solutions, and adaptive project management mechanisms. [31]

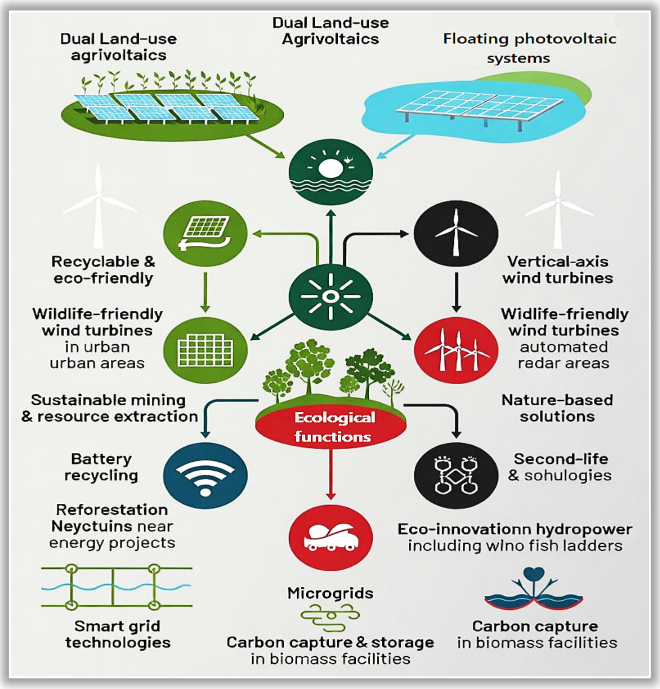


Figure 3. Integrated approaches and innovative solutions for minimizing the environmental impact of renewable energy infrastructure while maximizing climate and socio–economic benefits

In parallel with identifying the ecological impacts of renewable technologies, a growing number of studies propose innovative solutions aimed at reducing environmental pressures and increasing the sustainability of the energy transition process. These solutions focus on optimizing land use, reducing resource consumption, improving material recycling, protecting biodiversity, and intelligently integrating energy infrastructure into natural and socio–economic systems. They reflect a paradigm shift, moving away from the assumption that renewable energy is inherently "environmentally friendly" toward an approach that emphasizes the compatibility of technologies with the surrounding environment throughout their entire life cycle.

**Dual land–use practices (Agrivoltaics)**

Analysis of emerging solutions shows that agrivoltaics represents one of the most effective approaches for reducing the conflict between land requirements for energy production and the need to maintain agricultural activities. Agrivoltaic systems allow solar panels to be mounted at an optimized height so that crops continue to receive sufficient light while the photovoltaic system generates energy. Recent studies indicate that in arid and semi–arid regions, the partial shading provided by the panels can increase crop yields, reduce evapotranspiration, and improve the agricultural microclimate. [32]

Thus, the social and economic benefits of these systems are maximized by reducing tensions related to the occupation of agricultural land by energy infrastructure and by enabling farmers to become energy producers. This dual land use contributes to the diversification of income sources in rural communities, enhancing the economic resilience of farms in the context of climate variability and fluctuations in agricultural markets. At the same time, agrivoltaics provides a favorable framework for cooperation between the agricultural and energy sectors, transforming potential territorial conflicts into opportunities for functional integration. By generating renewable energy directly at the farm level, dependence on centralized grids is reduced, which can contribute to local energy stability and lower operational costs for farmers. Overall, this approach demonstrates that the energy transition can be designed in a way that delivers mutual benefits for the environment, the rural economy, and energy security.

**Floating solar panels (Floating PV / FPV)**

Floating photovoltaic systems (FPV) represent a promising solution for regions where land is limited, expensive, or environmentally sensitive. Installing panels on artificial lakes, reservoirs, or dams helps reduce pressure on terrestrial land resources while simultaneously minimizing land–use conflicts. The literature shows that FPV systems can achieve higher efficiency compared to ground–mounted installations due to the natural cooling effect provided by water, which lowers panel temperature and can increase electrical performance by up to 10–15% under certain conditions. [33] Floating photovoltaic systems provide another major benefit by reducing water evaporation, a critical aspect for drought–prone regions or water–storage infrastructures. By partially covering water surfaces, FPV installations limit direct exposure to solar radiation, thereby decreasing water losses and contributing to a more efficient management of water resources, particularly in areas experiencing high hydric stress. This function becomes essential in the context of climate change, which amplifies the frequency and severity of drought periods. In addition, FPV systems can help prevent excessive algal growth on water surfaces, thus contributing to better water quality. By reducing the amount of light penetrating the water column, they limit the proliferation of algae, especially species that may lead to eutrophication or to the degradation of aquatic ecosystems. This indirect effect has positive implications for aquatic biodiversity, for the quality of water used for agricultural or industrial purposes, and for reducing the costs associated with water treatment.

- **Recyclable and eco–friendly materials in the renewable energy industry**

One of the main findings from the literature review is the rapidly growing interest in developing robust recycling chains for solar panels and wind turbines. Current research focuses on the efficient extraction of silicon, silver, and rare metals from photovoltaic panels through the use of improved pyrometallurgical or hydrometallurgical processes. Recent studies report considerable progress in material recovery, with efficiencies exceeding 95% for silicon and glass. [34] In the case of wind turbine blades, glass– or carbon–fiber–based composites pose major challenges because they are difficult to degrade. An emerging approach involves grinding and reintegrating the material into the cement industry, a process that can significantly reduce the carbon footprint of cement. [34]

In the case of wind turbine blades, glass– or carbon–fiber–based composites pose major challenges because they are difficult to degrade. An emerging approach involves grinding and reintegrating the material into the cement industry, a process that can significantly reduce the carbon footprint of cement. [35] At the same time, manufacturers are testing biodegradable blades and innovative resins that could fundamentally transform wind turbine waste management. These new materials are designed to facilitate the decomposition or reuse of components at the end of a turbine's life, thereby reducing dependence on landfilling and costly industrial grinding processes. The use of thermoplastic resins or biodegradable compounds opens the possibility of establishing closed–loop production cycles, in which used blades can be reprocessed to create new components, reducing the consumption of primary resources. This technological innovation represents an important step toward a circular economy in the wind energy sector, addressing both environmental challenges and the economic issues associated with the increasing volume of waste generated by the global expansion of wind capacity.

- **Vertical–axis wind turbines (VAWTs)**

Vertical–axis wind turbines (VAWTs) offer alternatives in areas where conventional horizontal–axis wind turbines (HAWTs) are difficult to install. These systems are well–suited for urban, industrial, or peri–urban spaces, where wind turbulence reduces the efficiency of horizontal systems. VAWTs generate lower noise levels and operate at slower rotational speeds, which decreases risks to bird populations, an aspect highlighted in numerous ecological assessments. Another major advantage is their reduced spatial footprint, allowing the use of existing structures (rooftops, industrial infrastructure) without occupying additional natural land.

- **Sustainable mining and resource extraction**

The high demand for materials for batteries and energy equipment, particularly lithium, cobalt, and rare metals, makes sustainable extraction essential. It is necessary to develop more efficient practices, such as water–efficient mining, minimizing toxic discharges, and low–impact metal recovery technologies. At the same time, "urban mining," such as the recovery of critical materials from electronic waste, is emerging as a strategic solution to reduce pressure on ecosystems affected by traditional mining activities.

- **Wildlife–friendly wind turbines**

To reduce bird and bat mortality in wind farms, recent technologies include automated radar systems that detect flying wildlife and temporarily stop the turbines. Field studies indicate that the implementation of these systems can reduce mortality by up to 70% in certain critical areas. [36] Additionally, sites located outside migration corridors or in offshore areas have a considerably lower impact on flying biodiversity. Relocating wind infrastructure to such areas avoids direct interactions with migratory bird routes and reduces the likelihood of collisions, one of the most well–documented impacts of onshore wind farms.

In offshore environments, the distribution of sensitive species often differs, and bird densities may be lower compared to continental areas heavily used for feeding, breeding, or migration. Moreover, modern technologies allow the identification of low–risk areas through spatial analyses, ecological modeling, and long–term monitoring, ensuring that final siting is optimized according to the needs of local species. By adopting these strategies, wind projects can be integrated into the landscape in a way that is more compatible with biodiversity conservation, significantly reducing cumulative risks to flying wildlife.

- **Battery recycling and "second–life" solutions**

The development of lithium–ion batteries, as global production increases, raises growing concerns regarding waste, toxicity, and the limited availability of resources. Recent advances in recycling enable the efficient recovery of valuable materials (Ni, Co, Li) using advanced processes. "Second–life" solutions represent a promising approach, as batteries retired from electric vehicles can still be used for 5–10 years in stationary applications, reducing pressure on the extraction of rare materials. Industrial studies show that second–life systems can significantly contribute to grid stabilization or supply microgrids in isolated communities.

- **Nature–based solutions for mitigating the impacts of renewable energy**

In the case of solar, wind, or hydropower projects, nature–based solutions can compensate for a significant portion of the impacts on landscapes and biodiversity. Reforestation, habitat restoration, and wetland reconstruction near energy infrastructure are highlighted in the literature as effective strategies for rehabilitating degraded ecosystems. Such measures can restore ecological connectivity and support the ecosystem services affected by energy projects.

- **Technologies for smart grids**

The implementation of decentralized microgrids reduces the need for large centralized infrastructure and minimizes land–use impacts. Microgrids are particularly useful in areas with variable resources, providing resilience, flexibility, and the ability to integrate diverse renewable energy sources. Recent studies indicate that microgrids reduce grid vulnerability and optimize energy use through local storage and advanced control systems. [37] Demand response systems can balance consumption and production in real time, reducing the need for excessive storage and increasing overall energy efficiency.

- **Eco–innovations in hydropower generation**

For hydropower projects, the development of wildlife–friendly dams—including fish ladders, slow–rotating turbines, or specially designed turbines to reduce mortality—reduces impacts on riverine ecosystems. The literature shows that run–of–river systems have a much smaller ecological footprint than conventional dams, as they do not require the flooding of large areas and maintain the natural flow of rivers.

- **Carbon capture and storage in biomass facilities**

The integration of carbon capture and storage (CCS) technologies in biomass power plants represents an emerging option for achieving nearly zero or even negative emissions. Recent studies show that biomass combined with CCS (Bioenergy with Carbon Capture and Storage – BECCS) can become one of the most effective solutions for reducing atmospheric $CO_2$ concentrations in global energy transition scenarios. [38]

## CONCLUSIONS

The analysis highlights that renewable energy projects, although essential for decarbonizing the energy system and reducing greenhouse gas emissions, are not without ecological costs. Impacts on land use, mineral resources, hydrological regimes, waste generation, and biodiversity indicate that the energy transition cannot be considered ecologically "neutral" if assessed solely from a carbon emissions perspective. Integrating a life–cycle perspective (LCA), combined with rigorous spatial planning and cumulative impact assessment, is therefore essential to fully understand the environmental footprint of renewable technologies.

On the other hand, there is already a substantial portfolio of solutions capable of mitigating these impacts: dual land–use through agrivoltaic systems, floating solar panels, recyclable materials and innovative wind turbine blades, wildlife–friendly turbines, battery recycling and second–life strategies, nature–based solutions, microgrids, and BECCS technologies. When implemented coherently, these approaches can transform the energy transition into a process that is not only low in emissions but also ecologically responsible, ensuring that energy production is compatible with ecosystem protection and the long–term maintenance of their functions. The study thus emphasizes the need for an energy transition designed within the framework of integrated sustainability, where climate, ecological, and socio–economic objectives are harmonized from the early stages of planning and project development.

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