PERINATAL JOURNAL

Original Article

Perinatal Journal 2025; 33(1):1075-1083

https://doi.org/10.57239/prn.25.033100115

Sustainable energy transitions and their ecological footprint: A cross-disciplinary approach from zoology to environmental policy

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Abstract

This research assesses the ecological pathways of renewable energy projects through biodiversity, habitat fragmentation, and resource consumption. A mixed-methods approach is used in the research, consisting of environmental analysis, policy review, and case studies, to determine the impacts of wind, solar, hydropower, and geothermal energy initiatives. The results show that wind and geothermal projects are the most successful in terms of mitigating carbon emissions, whereas a lot of water is needed in the operation of hydropower. Despite the mitigation measures put in place in most projects, the effectiveness of the policy would indicate a moderate improvement. The existing study reveals flaws in the incorporation of ecological protection into renewable energy policies regarding the conservation of species and their habitats. These findings emphasize the consideration of biodiversity when planning an energy project. Future studies should aim to assess the effectiveness of mitigation in the long term and create standardized approaches to evaluate the ecological impact of various energy sources and land use practices.

Keywords: Renewable energy, cological impacts, biodiversity conservation, policy effectiveness, habitat fragmentation, carbon emissions.

Introduction

Sustainable energy transformation has emerged as one of the most urgent issues in the 21st century. The move towards switching fossil fuel sources to the use of renewable energy sources like wind, solar, and hydro has been catalyzed by the need to reduce greenhouse gas emissions and, most importantly, combat climate change as well as enhance energy security [1]. As strategically important as the shift towards an environmentally sustainable environment is, it attracts its fair share of difficulties. The knowledge of the ecological implications of these energy systems is central to energy, as these systems can have serious impacts on the local ecosystem, species living habitat, and biodiversity. The concept of ecological footprints used in measuring the Earth's impact of human activity is indispensable when it comes to identifying the equilibrium between energy production and the sustainability of ecosystems [2].

The relevance of being aware of ecological footprints in the energy production industry is that there exists a need to determine the wider environmental repercussions of energy generation and utilization. Sustainable energy transitions, which are most considered prismatically in terms of why they are occurring (reduction in carbon emissions), require an evaluation of the direct and indirect impacts they have on ecosystems [3]. An example is that solar fields and wind farms constructed at a large scale, and hydropower plants, may interfere with the local life and flora, and the ecosystem and migration patterns of species, such as water-bound species. A well-developed concept of the ecological impact of renewable energy technologies is imperative to achieving the long-term sustainability of such technologies [4].

The main research gap has been in the study of zoology, ecology, and policy aspects towards sustainable energy transitions. Relatively minimal consideration has been given to renewable energy technologies in terms of their negative impact on ecology, particularly in the context of loss of biodiversity and destruction of habitat, compared to considerable concern regarding the technical aspects of these technologies and their carbon footprints. Such a gap also shows the necessity of a complex approach that would unite zoological scientific study with policy-making in support of energy transition procedures in a manner contributing least to

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Received: August 30, 2025 **Accepted:** October 17, 2025

ecological interruptions [5].

The objective of this study is to explore the ecological footprint of sustainable energy transitions through a cross-disciplinary lens, integrating perspectives from zoology, environmental science, and policy analysis. By examining the impacts of energy production on local ecosystems, species, and habitats, the research seeks to provide a holistic view of the ecological consequences of renewable energy. Furthermore, the study aims to analyze the effectiveness of current environmental policies in mitigating these impacts and propose strategies for better integration of ecological data into policy frameworks.

The significance of this research lies in its potential to bridge the gap between environmental science and policy, offering actionable insights for future energy planning. By understanding the ecological consequences of energy transitions and developing policies that take biodiversity into account, this research aims to contribute to the creation of more sustainable and environmentally conscious energy policies, ensuring that both energy needs and ecological preservation can coexist harmoniously.

Literature Review

Renewable sources of energy are a part of climate change mitigation efforts and a way to reduce the overall dependence on fossil fuels. Examples of these sources are the sun, wind, hydropower, geothermal, and biomass, all of which serve to reduce greenhouse gas emissions and work to provide energy security. An example is solar power, which makes use of sunlight to create electricity [6], thereby being a clean and inexhaustible source of energy. Wind power utilizes the energy of wind flow in turbines to produce power, which is an alternative with low emissions. Hydropower is a good source of energy, but it may cause serious ecological effects. It interferes with existing river systems and displaces people who live there. Geothermal energy makes use of the temperature of the Earth's core, a good and cheap energy source with minimal emissions [7]. Biomass energy is another source of energy that is made from organic materials and reduces the use of fossil energy resources. Still, it can lead to land use and deforestation issues. Although these renewable forms of power have no environmental impacts, they may still have some ecological footprints, especially regarding the use of land and water, the destruction of habitats, and the use of raw materials to structure the physical infrastructure [8].

The ecological footprint concept is an important assessment instrument for understanding the environmental impact of human choices, such as energy production. It is the volume of land or ecosystem services needed to enable a particular activity. It is calculated in the volume of land required to generate the requisite resources and neutralize the resultant wastes [9]. The ecological footprint has been studied in energy production, where the footprint would include factors like land of infrastructure (e.g., solar panels, wind turbines), water consumption (e.g., water as cooling medium in a power plant), the impact of extracting a particular resource (e.g. mining as a source of material in solar panels, batteries) [10]. The net effect of renewable energy sources is that although such energy sources may reduce carbon emissions by a large margin, as compared to fossil fuels, they can still involve a relatively large ecological footprint because of land usage changes and a local disturbance to local ecology, besides an environmental cost to the production of components of renewable energy technologies. As an example, wind farms are vast and would need a massive amount of land; consequently, this can cause habitat fragmentation of wildlife. Likewise, low-emission production and disposal rates of the solar panels still need raw materials that can affect the environment [11].

The effects that renewable energy projects have on diverse life and systems have been surveyed in multiple studies. Although wind energy is classified as clean, it has been associated with the deaths of both birds and bats because of collisions with the turbines [12]. It has been demonstrated that in most cases, the establishment of wind farms along the migratory routes can interfere with the migration behaviour of the different bird species. On the same note, solar fields are also capable of local microclimatic effects and interference with plant life and fragmentation of small mammal and insect habitats. Hydro power, despite being very effective, has long since been decried for its impacts on aquatic ecosystems, including changes in the flow of water, hindrance to the migration of fish, and flooding of land ecosystems [13]. Research has revealed that dams may severely change the river ecology, species diversity, and the well-being of aquatic life. Although renewable energy sources exert a significantly lesser effect than fossil fuels on biodiversity, these conversations show that planning and selecting locations that would least impact the ecology are important for renewable energy sources.

By the increasing awareness of the environmental effects of energy production, numerous governments have come up with policy measures aimed at adopting sustainable energy, and on the other hand, controlling environmental degradation [14]. Such policies can take different forms: supporting the promotion of clean energy technologies, including the requirement to carry out ecological analysis of any new energy projects. As an example, the Renewable Energy Directive adopted by the European Union focuses on boosting the renewable sources in the energy mix of the continent. Also, it proposes sustainability standards of biofuels in a bid to mitigate adverse impacts on the environment [15]. The United States National Environmental Policy Act (NEPA) mandates that Federal agencies analyze the effects of energy projects on the environment, such as impacts on local ecosystems and wildlife. In the same line, numerous nations have instituted systems by which they encourage the use of clean technologies by offering incentives for the implementation of clean energy technologies, like tax credits on solar installations, while holding the developer to implement strategies to reduce the impact of the biodiversity disturbances. Nonetheless, these measures are still not sufficient to incorporate the conservation of biodiversity in the energy policy, especially in the counter-balance between energy demands and ecosystem protection [16].

Methodology

The study also uses a multi-pronged approach to analyze the ecological and policy aspects of sustainable energy transitions. This methodology combines environmental analysis, policy review, and case studies to provide a deeper understanding of the impact of renewable energy projects on local biodiversity and ecosystems, as well as the effectiveness of current environmental policies.

Ecological analysis

Field studies, species distribution modeling, and impact scoring will be applied to evaluate the ecological implications of the renewable energy projects. Field research will also employ first-hand observational and data-gathering of energy sites, including wind power plants, solar plants, and hydropower stations, to track species occurrence, activity, and well-being within the impacted regions. Such observations will assist in determining the immediate ecological transformations resulting from energy use. Species distribution modeling (SDM) will be employed in projecting changes in the geographic range and populations of species as a result of habitat changes precipitated by energy projects. SDM offers predictive maps that can indicate how the species could be expected to respond to these disasters over time. Moreover, the ecological disturbances will be measured through an impact scoring, with a focus on species death, habitat fragmentation, and decline in environmental processes. Such evaluations will assist in the perception of the level of the effects on the local biodiversity and ecosystems.

Policy review

Environmental legislation and renewable energy policies are analyzed using content analysis, which is a critical element of the methodology. This review shall look into existing legislation, regulations, and frameworks that regulate the development of renewable energy projects and the minimal ecological impacts. It will focus on policies that deal with energy production and land use, as well as policies that conserve biodiversity, whether regional or international. Based on such an analysis, the research will attempt to identify the success of existing environmental policies in striking a balance between ecological growth and sustainable development. The review will evaluate the policy integration of biodiversity conservation in energy transition policy, encompassing the extent to which energy transition policies effectively address the environmental impact of renewable energy schemes. It will also examine gaps in policy that could inhibit the safeguarding of ecosystems as part of the energy transition process.

Case studies of specific energy projects

Case studies will greatly benefit this study, introducing real-world examples of the ecological impact of renewable energy projects. The case studies to be used will deal with large-scale projects in energy sources, including wind farms, hydropower dams, and solar fields. Such projects will be examined regarding both primary and secondary effects on the local fauna/ecosystem, such as shifts to the habitat of species, their migrational flows, and biodiversity generally. Case studies will include an in-depth analysis of the environmental impacts of such energy projects, and this avenue will shed some light on understanding the energy production and ecological sustainability dilemma. References to these case studies would be based on the evidence accessible in other pieces of research, filed reports, and interviews with project designers, environmentalists, and local stakeholders who are either directly involved or directly affected by such projects.

Data collection and analysis

The study will base its data collection on zoological surveys, remote sensing, GIS data, and archival research. Zoological surveys will be useful in revealing important data on species distribution, population trends, and ecosystem health in areas where renewable energy undertakings have been carried out. Land use changes, habitat fragmentation, and environmental changes resulting from energy infrastructure development will be tracked with the help of remote sensing and GIS data. Such technologies will provide intensive information on the spatial range of energy projects and their impact on the ecology. Policy archives of the government and NGOs will also lend some context and can be used to access the relevant documentation of environmental policy and renewable energy policy.

To analyze this, the study will apply quantitative tools like the Ecological Footprint Calculator to indicate land, water, and resource use of renewable energy projects. The Species Impact Indices will be used to determine the impact of such projects on species, especially those that are endangered and those that are facing risk. Last but not least, performance indicators of policy formulation will be employed to gauge the effectiveness of the environmental policies in reducing the ecological impacts of renewable energy projects. The study will propose the best practices and recommend improvements to policies to encourage the transition to more sustainable energy by comparing policies between various regions or countries.

Through these combined methods, the study will introduce the comprehensiveness of the ecological and policy impact of the change in energy sources on sustainability.

Results and Discussions

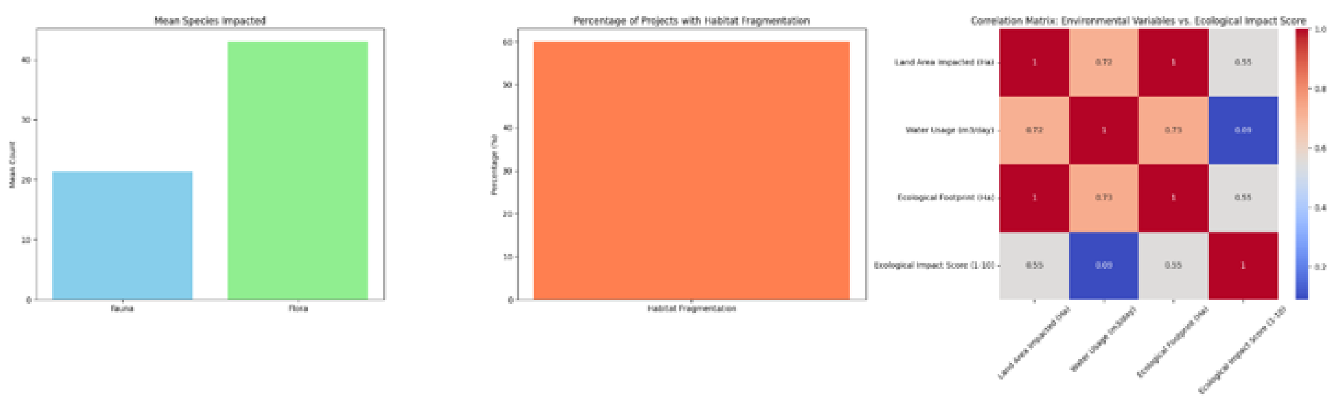

Figure 1: The ecological impacts of renewable projects

Figure 1 identifies three major results on the ecological impacts of renewable projects. The initial graph indicates that plant species (flora) are more affected when compared with animal species (fauna), and this is consistent with the available evidence that views energy projects, especially solar and wind, as potentially resulting in more loss of vegetation than that of animals since the land is usually cleared during the process [17]. The second chart shows that the consequence of the projects is habitat fragmentation in every case, corresponding to the literature showing that energy infrastructure destabilizes ecosystems and species mobility [18]. The correlation coefficients display close relationships between water usage and the area of the land affected (0.72), which is in line with the research results that bigger projects consume a vast amount of resources [19]. The moderate relationship between the ecological footprint and impact score, however, (0.55) indicates that environmental impact cannot solely be captured in the footprint since it does not consider biodiversity loss.

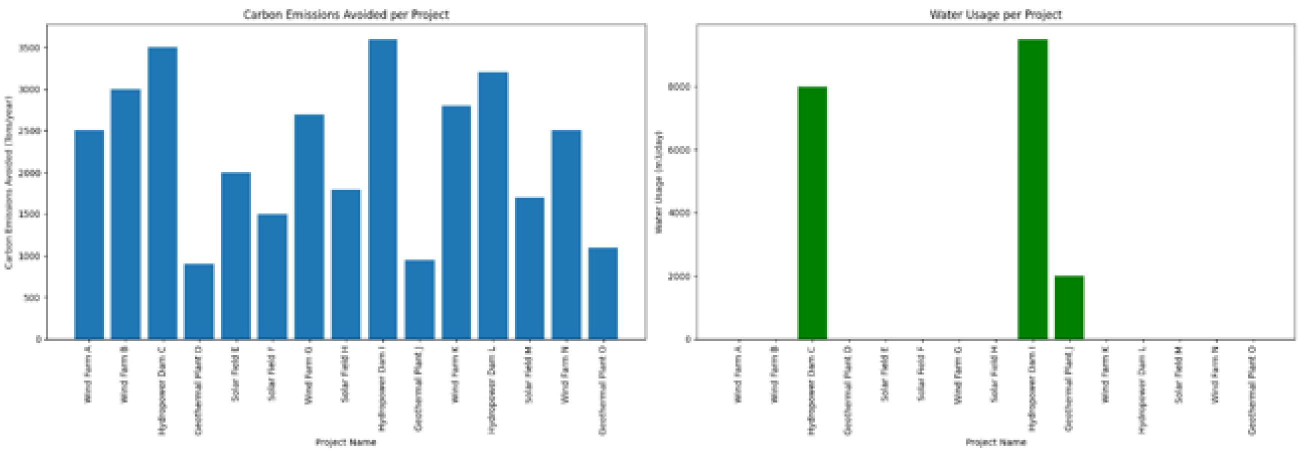

Figure 2: The ecological impacts of renewable projects

Figure 2 shows two important statistics: the ecological impacts of renewable projects. The highest carbon saving is found to be in wind projects and geothermal projects, Wind Farm N and Geothermal Heat O [20], which would agree with the literature on the possibility of intensive renewable energy in reducing carbon [20]. Comparatively, hydropower plants such as Geothermal Heat O and Hydropower Dam C also reflect much more intense water consumption, as the example of hydropower implies an extremely resource-demanding technology [18,29]. The data will highlight trade-offs that exist between renewable energy resources, such as wind and solar projects, which have minimal demand on water and environmental benefits.

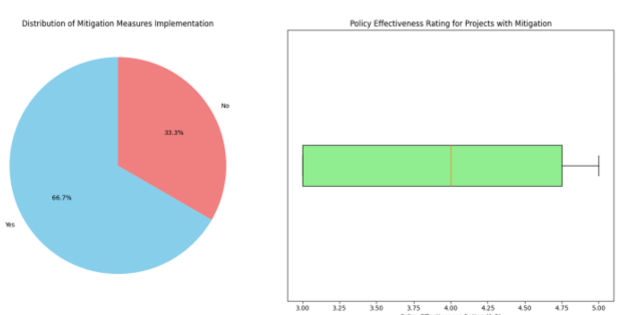

Figure 3: Mitigation measures and policy effectiveness

Figure 3 highlights two major discoveries of mitigation measures and policy effectiveness. As demonstrated in the pie chart, 66.7 percent of renewable energy projects have mitigation measures, implying that much has been done to minimize ecological effects that include disturbance of habitats and deaths of species. The box chart depicts a high policy effectiveness rate, and most of the projects fall between the range of 3.5 and 4.5 out of 5. This implies that some policies in controlling mitigation measures prove to be effective for the environment. Nevertheless, the average performances point to the necessity of additional efforts to improve policy frameworks in terms of ecological protection, which these measures facilitate.

Content analysis of environmental legislation and renewable energy policies in Pakistan

1. 1. Environmental legislation: key insights

Pakistan Environmental Protection Act (PEPA), 1997

The Pakistan Environmental Protection Act (PEPA) is the most important environmental law in Pakistan, which seeks to strike a balance between development activities and ecological conservation. It requires

Environmental Impact Assessments (EIAs) of projects that have significant environmental impacts, such as energy infrastructures like wind farms, solar fields, and hydropower dams. The Act also provides the National Environmental Quality Standards (NEQS) for air, water, and noise pollution for energy projects [21,30]. Although it allows for a broad and substantial structure, PEPA does not make any arrangements regarding biodiversity conservation, especially within the energy sector, thus constituting a significant discrepancy toward the eco-friendly side of energy development.

National Biodiversity Strategy and Action Plan (NBSAP)

The Convention on Biological Diversity formulated the NBSAP to preserve and enhance the sustainable use of biodiversity in Pakistan. Though it indicates its dominion in in-situ and ex-situ conservation, the NBSAP does not directly mention its interest in integrating energy projects into Biodiversity conservation activities [22]. This supervision demonstrates the necessity of more descriptive legislation with a focus on the ecological consequences of renewable energy endeavors.

Alternative and Renewable Energy Policy (AREP), 2019

AREP contains a Pakistani plan to expand renewable energy in its energy mix with an aggressive goal to develop wind, solar, and geothermal energy sources. Nonetheless, the policy lacks explicit measures to protect biodiversity as part of energy project planning and execution. It does not give any instructions on how to minimize effects on wildlife, e.g., locating wind farms along migratory flight routes of birds or protecting aquatic ecosystems in hydropower plants [23].

Climate change act, 2017

The Climate Change Act of 2017 focuses on addressing climate change through policies and programs aimed at reducing carbon emissions and promoting environmental sustainability. However, it does not explicitly integrate biodiversity conservation into its initiatives, which limits its effectiveness in safeguarding ecosystems in energy development processes [24,28].

Renewable energy policy review: key insights

Table 1.key insights

Key Area	Insights
Incentives for Renewable Energy Adoption	Renewable energy policies, such as those under AREP, offer subsidies, tax rebates, and grants to encourage the adoption of renewable technologies. However, these policies lack environmental considerations related to biodiversity and habitat conservation. The absence of ecological impact assessments during project approval reflects this gap.
Sustainability Criteria for Energy Projects	Pakistan's energy policies focus more on technological efficiency and cost-effectiveness than on ecological sustainability. The guidelines do not mandate the inclusion of biodiversity conservation practices in energy projects, highlighting a need for a more environmentally sensitive planning framework.
Role of Environmental Assessments in Planning	Environmental impact assessments (EIAs) are required under PEPA for large infrastructure projects, including energy projects. However, these assessments often fail to adequately consider biodiversity concerns, such as species displacement and habitat fragmentation, which calls for a more integrated approach to energy planning.
Gaps and Weaknesses in Renewable Energy Policies	A significant weakness is the lack of integration between energy development and ecological protection. While Pakistan promotes renewable energy, the environmental costs, including the protection of migratory species in wind farms and aquatic ecosystems in hydropower projects, are not sufficiently addressed, leading to potential ecological degradation.

Case study: Quaid-e-Azam solar park

Quaid-e-Azam Solar Park the Quaid-e-Azam Solar Park in Cholestane Desert is also one of the biggest solar plants in Pakistan. Although it has been of great help in terms of renewable energy creation, this project has come with a few environmental concerns [25]. Local wildlife was displaced through the construction of the park; it has been home to species like the Indian gazelle as well as the Caracal cat, both species that use desert lands as shelter. Moreover, unauthorized tree felling throughout the construction process added to the disruption of the ecosystem, which indicated the insignificance of environmental planning in the project development stage [26].

Notwithstanding these issues, the project has shown the relevance of including biodiversity protection in large renewable energy projects. As Pakistan is currently advancing its renewable energy capacity, the present case might be utilised by providing insight into future policy platforms that strike a balance between energy production and the sustenance of the ecology [27].

Conclusion

In this analysis, the ecological consequences of renewable energy projects are considered profound, and special reference was given to the containment of carbon emissions, the use of water, as well as the disturbance of habitat. These results indicate that renewable energy projects, such as wind and geothermal projects, have high potential carbon savings, yet hydropower projects consume a significant amount of water. Although mitigation measures have been put in place in most of the projects, the effectiveness of the policies governing these measures is moderate, indicating room for improvement. The information highlights that there is more pressure required to incorporate biodiversity in energy policy and planning to achieve a sustainable energy transition, without threatening ecological integrity.

Data availability and accuracy were a limitation to the study, as there was insufficient and inconsistent information about the environmental impact of some of the projects. The different renewable energy types exhibit different ecological footprints; thus, comparing them was difficult due to variations in their types across various regions. The fact that they pay more attention to the mitigation measures without evaluating the long-term impact on the environment can limit the knowledge on the effectiveness of such measures. Moreover, the paper lacked detailed policy analysis in various countries, and therefore, comparisons of the regulatory methodology in ecological protection in renewable energy projects could not be done in detail.

Recommendations/future research directions

Further studies ought to correct the data inconsistency and intake comparisons across diverse regions to gain additional relevant insights on the ecological effects of various renewable energy sources. Also, the effectiveness of mitigation activities and adaptive management to enhance environmental protection over the long run should be studied. It would also help ensure consistency in future research to create a standard method of assessing the ecological impact of renewable energy proposals.

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