Dean&Francis

ISSN 2959-6157

Ecological Trade-offs of Green Energy Infrastructures in Marine Environments: Balancing Sustainability and Biodiversity

Jiashuo Li [1,*]

[1]Department of technology-Detroit Green Industry College, Hubei University, Wuhan, 430000, China

*Corresponding author: Laurent0629@163.com

Abstract:

Against the backdrop of global energy transition towards sustainability, the deployment of green energy infrastructure, such as offshore wind farms, tidal and wave energy devices, is rapidly expanding across marine environments. This paper explores the dual ecological impacts of these facilities on marine ecosystems, synthesizing existing research to highlight both constructive and detrimental outcomes. We document how green energy installations can enhance marine biodiversity through artificial reef effects, shelter provision, and de facto marine protected areas, while simultaneously identifying challenges such as habitat disruption, noise pollution, and chemical leakage. Through case studies including Horns Rev (Denmark), Jiangsu Dafeng (China), and La Rance (France), we demonstrate context-dependent ecological responses and the importance of spatial planning in mitigating adverse effects. Our analysis also underscores the need for integrated assessment frameworks that balance environmental, economic, and social dimensions. The findings emphasize that while green energy development holds significant potential for ecosystem restoration, its long-term success hinges on adaptive management strategies and policies that harmonize energy objectives with marine conservation imperatives, ultimately advancing the broader goal of sustainable coexistence between human energy needs and marine biodiversity.

Keywords: Green energy; Marine ecosystem; Ecological reconstruction; Offshore wind power; Sustainable development.

---

1. Introduction

With the transformation of the global energy structure, green energy facilities such as offshore wind power, tidal energy and wave energy are increasingly deployed in the ocean. However, while these

ISSN 2959-6157

facilities bring renewable energy benefits, they also have multiple impacts on marine ecosystems. Previous studies have explored the ecological impacts of different types of green energy facilities. Wang Ting et al. (2022) studied the comprehensive impact of offshore wind power on the marine ecological environment and biological resources, and pointed out that the construction process of offshore wind power will change the topography and landform of the seabed, resulting in the increase of turbidity and the decrease of dissolved oxygen in the seabed water, and will also lead to the loss and deterioration of the habitat of some benthic organisms and the decline of biodiversity[1]. Impacts of tidal and ocean energy on marine ecosystems: Furness et al. (2012) assessed the susceptibility of ocean bird populations to the adverse effects of tidal and wave energy devices[2], and found that these devices may interfere with bird migration, foraging, and reproduction [3, 4] .Interaction between green energy facilities and marine ecosystems: Somefield et al. (2019) proposed that offshore wind farms may become a new habitat for marine life, attracting some fish and invertebrates to congregate, but may also lead to collision deaths of birds [5].

Although there have been preliminary studies on the impact of green energy on marine ecosystems, there are still many unresolved questions. At present, there are relatively few studies on the long-term impact of green energy facilities on marine ecosystems, especially the differences in impacts under different environmental conditions and ecosystem types are still unclear. In addition, there is a lack of effective theoretical basis and practical guidance on how to strike a balance between green energy development and marine ecological protection. Therefore, this paper aims to review the research progress of green energy on the reconstruction of marine ecosystems, discuss the theoretical basis, ecological impact and practical application of this field, and put forward future research directions and policy suggestions to promote the coordinated development of green energy and marine ecosystems.

2. The Integration between green energy and marine ecosystems

2.1 Overview of green energy development

2.1.1 Types of green energy technologies

Offshore wind power is a rapidly developing and large-scale marine green energy technology. For example, North Sea wind farms in Europe, with their increasing installed capacity, convert offshore wind energy into electricity through large wind turbines, providing a large amount of clean energy to coastal areas. The utilization of tidal energy is mainly concentrated in some bays and estuaries with large tidal ranges, such as the Jiangxia Tidal Experimental Power Station in China, through the construction of barrages and other facilities, the potential energy of the tide is converted into the mechanical energy of the turbine, and then the power is generated. Ocean thermal energy mainly exists in tropical and subtropical seas, and the thermoelectric power generation technology can convert the temperature difference between the surface layer of the ocean and the deep-sea water into electricity. Wave energy exists on the surface of the ocean in various forms, and wave energy conversion devices such as oscillating water column type, float type, etc., can convert the kinetic energy and potential energy of waves into mechanical energy or electrical energy [6] .Global investment in green energy has continued to grow in recent years, particularly in Europe, North America, and coastal areas of East Asia, with a significant increase in offshore wind capacity. According to the International Renewable Energy Agency (IRENA), as of 2023, the cumulative installed capacity of offshore wind power worldwide has exceeded 64 GW. Among them, China has ranked first in the world in terms of newly installed capacity for many years and is building an offshore wind power development system based on “near-shore demonstration and offshore expansion”.

2.1.2 Linkages between green energy and the SDGs

Despite the significant environmental advantages of green energy, it still faces many challenges in its actual development. For example, offshore wind power has problems such as equipment corrosion and difficult operation and maintenance in high-salt and high-humidity environments. Although the high energy density of tidal energy and wave energy has potential, its equipment is still in the demonstration stage and the degree of commercialization is not high. In addition, the construction and operation of green energy facilities may also cause disturbances to the marine ecosystem, and it is necessary to achieve ecological friendliness in the technical pathway. At the same time, the development of green energy is of great significance to respond to global climate change and reduce greenhouse gas emissions. According to the report of the United Nations Intergovernmental Panel on Climate Change (IPCC), the development of green energy is one of the key measures to achieve the goals of the Paris Agreement, which can effectively reduce carbon emission intensity and alleviate the trend of global warming. At the same time, the use of green energy can help ensure energy security, reduce dependence on traditional fossil energy, and reduce the vulnerability of energy supply. The World Energy Agency (IEA) pointed out that as the global demand for energy continues to grow, diversifying into green energy can improve the stability and security of energy supply. In addition, from a socio-economic point of view, the development of the green energy industry can create many job opportunities, covering all aspects from technology research and development, equipment manufacturing, engineering construction to operation and maintenance, and promote sustainable economic growth. According to the International Renewable Energy Agency (IRENA), the number of jobs in the global green energy sector has been increasing in recent years, injecting new impetus into economic recovery and sustainable development [7].

2.2 Marine ecosystem structure and function

2.2.1 Ecosystem composition

Marine ecosystems are composed of a variety of biological communities, including phytoplankton, zooplankton, benthic organisms, swimming organisms, etc. As primary producers in the marine ecosystem, phytoplankton fix carbon dioxide through photosynthesis and provide an energy material basis for the entire ecosystem. Zooplankton such as copepods feed on phytoplankton and are also a food source for organisms at higher trophic levels. Benthic organisms such as shellfish and shrimp live at the bottom of the ocean and participate in the material cycle and energy flow of marine ecosystems. Swimming organisms such as fish and cetaceans swim freely in the ocean and are at the higher trophic level of the marine food chain, which plays a key role in the stability of marine ecosystems. Material circulation and energy flow are the two core functions of marine ecosystems. The material cycle includes the cycle of carbon, nitrogen, phosphorus and other elements in the marine ecosystem, such as phytoplankton absorbing carbon dioxide for photosynthesis, synthesizing organic matter, and then passing it to zooplankton and benthic organisms through the food chain, and finally returning to the ocean bottom in the form of detritus and other forms to participate in sedimentation and other processes. The energy flow begins when solar energy is fixed by phytoplankton and is passed along the food chain, where each level of organisms converts part of their energy into heat energy through their own life activities, and at the same time provides energy for the next trophic level [8].

2.2.2 Service functions of marine ecosystems

Carbon sequestration is one of the important services of marine ecosystems. Studies have shown that the ocean is able to absorb large amounts of carbon dioxide from the atmosphere, fix the carbon in marine organisms through the action of marine biological pumps, and transport it to the depths of the ocean, thereby slowing down the rise of atmospheric carbon dioxide concentrations. In terms of climate regulation, the ocean, as the world's largest heat store, can regulate the Earth's climate system. The oceans absorb and release heat, influencing atmospheric circulation and climate patterns. For example, El Niño and La Niña are global climate anomalies caused by the interaction of the ocean with the atmosphere. In terms of biodiversity conservation, marine ecosystems are rich in biological species and unique ecosystem types, providing habitats, breeding and foraging places for many marine organisms. The International Union for Conservation of Nature (IUCN) states that marine biodiversity is essential for maintaining the stability and health of marine ecosystem and has important ecological, economic and cultural values [9].

2.3 Potential impact of green energy on marine ecosystem

2.3.1 Physical impact

During the construction of offshore wind power, piling operation will cause strong noise, damage the auditory system of marine organisms, and affect their behavior and survival. For example, studies have shown that marine mammals such as cetaceans are highly sensitive to noise, and construction noise may lead to their disorientation, abnormal escape behavior, and even affect their reproduction and predation. At the same time, the infrastructure construction of wind farms will also change the topography and sediment of the seabed and destroy the habitat of benthos. The infrastructure of large-scale wind farms may block the ocean water flow, change the speed and direction of water flow at the bottom of the ocean, and then affect the distribution of sediments and the physical environment of the marine ecosystem. In addition, during the operation of the wind farm, the rotating blades of the wind turbine may cause collision damage to birds, bats and other flying organisms, especially when birds pass through the wind farm in the process of migration [10].

2.3.2 chemical impact

In the process of green energy development, such as the construction of offshore wind power, tidal energy and other projects, may lead to the leakage and discharge of chemical substances. For example, chemical substances such as anticorrosive coatings and lubricating oils of wind farms may leak during use, enter the marine environment and have toxic effects on marine organisms. At the same time, marine engineering construction may disturb the seabed, resuspend harmful substances in sediments and increase the concentration of pollutants in water. Some wave energy conversion devices may use batteries and other components containing heavy metals during oper-

ISSN 2959-6157

ation. In case of leakage, heavy metals such as mercury, cadmium and lead will cause long-term harm to the marine ecosystem and affect the growth, reproduction and survival of marine organisms. Chemical pollutants may also accumulate in marine organisms and pass through the food chain, eventually posing a potential threat to the top predators in the marine ecosystem and human health [11].

2.3.3 biological impact

The construction of green energy facilities may change the habitat of marine organisms, resulting in habitat loss or fragmentation. For example, the construction of large-scale offshore wind farms will occupy a large area of sea area, making the fish, shellfish and other organisms that originally lived in this area lose their habitat and foraging places, and thus forced to migrate. At the same time, the artificial structure of these facilities may provide new attachment substrates for some marine organisms, attract them to gather and form artificial reef effect, but it may also change the original biological community structure and niche relationship. In addition, green energy development activities may interfere with the migration routes and breeding behaviors of marine organisms. For example, the construction of tidal power generation facilities may block the migration channels of fish and affect their breeding and survival. The lighting and electromagnetic fields of offshore wind farms may interfere with the navigation system of marine organisms, especially turtles, sharks and other creatures with magnetic sensing ability, thus adversely affecting their survival and reproduction [12].

3. Theoretical progress of green energy on marine ecological reconstruction

3.1 Ecological theory

3.1.1 Basic theory of ecosystem restoration and reconstruction

This field takes ecological restoration theory (such as succession theory, key species theory) and ecosystem service theory as the core framework. The research focuses on how to use green energy infrastructure to actively or passively promote the restoration of the structure and function of damaged marine ecosystems and reconstruct new ecosystems with higher resilience and service capacity [13].

3.1.2 Two-way mechanism

The core theoretical challenge is to clarify the dynamic two-way interaction between the resilience of marine ecosystems and green energy development activities [14]. On the one hand, the threshold of ecosystem resilience determines the upper limit of ecological carrying capacity of development activities; On the other hand, development activities (such as facility construction and operation) themselves constitute interference or repair force, which may weaken or enhance the resilience of the system. Understanding this feedback cycle is the key to predicting long-term ecological effects [15].

3.2 Dual action mechanism of green energy on Ecological Reconstruction

3.2.1 Positive effects

Artificial reef effect: underwater structures such as offshore wind farm Foundations (such as single piles, jackets) and anchor systems provide new attachment substrates and habitats for fixed organisms (such as mussels, barnacles, corals) and fish, forming an “artificial reef” ecosystem, significantly increasing local biodiversity and biomass [16, 17] .sheltering effect: the structure of large-scale energy facilities can change the local flow field, form a low velocity zone, and provide shelter for young fish, crustaceans, etc. from predators and strong currents. Effect of no fishing area: the surrounding areas of energy projects are often designated as restricted fishing areas, which indirectly promotes the recovery of fish resources and population reconstruction [18].

3.2.2 Negative effects

Habitat destruction and fragmentation: submarine cable laying, foundation piling and equipment installation will directly damage benthic habitats (such as seagrass beds and coral reefs), and may cause habitat fragmentation and hinder biological migration and gene exchange [19] .Noise pollution: underwater noise generated during construction (especially pile driving) and operation (turbines and generators) causes physiological pressure, behavioral interference (avoidance, migration route change) and even hearing damage to marine mammals (whales, dolphins) and fish that rely on acoustic communication and navigation. Electromagnetic field (EMF) effect: the electromagnetic field generated by submarine cable may interfere with the navigation ability of migratory fish (such as eel and shark) with magnetic induction ability [20].
Light pollution: Facility Lighting affects the vertical migration of plankton and fish behavior and may change the structure of local food webs. Collision risk: birds and bats may collide with rotating fan blades, resulting in casualties.

3.3 Ecological model and comprehensive assess-

ment method

3.3.1 Existing models and tools

Ecological risk assessment model: used to quantify the risk probability and severity of specific pressure sources (such as noise, EMF, sediment diffusion) on key species or populations. Population and ecosystem model: predict the long-term impact of energy facilities on the abundance, distribution, community structure and food web dynamics of key species. Habitat suitability model: assess the changes in the area and quality of key habitats before and after the construction of facilities. Life cycle assessment (LCA): quantify the comprehensive impact of green energy projects on the environment (including carbon footprint, eutrophication, acidification, etc.) in the whole life cycle from raw material mining, manufacturing, transportation, construction, operation to retirement.

3.3.2 Comprehensive impact assessment framework

Multi-dimensional integration: the assessment needs to integrate environmental dimensions (biodiversity change, water quality, sediment disturbance), economic dimensions (fishery loss/gain, energy efficiency, tourism impact) and social dimensions (community acceptance, employment, visual impact). Ecosystem services assessment is an effective bridge connecting the three dimensions [15].

Spatial explicit planning: use GIS and marine spatial planning (MSP) tools to optimize site selection to maximize energy output and minimize ecological conflicts (such as avoiding biodiversity hotspots and important migration routes) [21].

Adaptive management: emphasize the feedback cycle based on long-term monitoring data, and dynamically adjust management strategies (such as the implementation intensity and operation mode of mitigation measures) to deal with uncertainty.

4. Practical exploration of green energy development on Ecosystem Reconstruction

4.1 Offshore wind power and ecological reconstruction:

As the global energy structure accelerates its transition to clean and low-carbon, green energy such as offshore wind power and tidal energy not only shows significant advantages in reducing emissions and carbon, but also profoundly reshapes the regional ecological pattern. These energy projects embody the development concept of “engineering ecological integration” in layout design, construction mode and operation and maintenance management, which not only brings opportunities for the reconstruction of local ecosystems, but also raises new ecological risks and adaptive challenges

4.1.1 North Sea experience

The long-term monitoring of horns Rev wind farm in Denmark shows that the single pile foundation has increased the benthic biomass by 137%, forming a new food chain (artificial reef effect), but the construction noise has caused the habitat of harbour porpoises to shift by 30km [22] this “niche substitution” effect not only promotes the reconstruction of local food chain, but also enhances the aggregation of fish resources. However, the high-intensity pile driving noise during the construction period significantly interferes with sensitive species, and marine mammals such as harbour rats and dolphins are forced to migrate, and their range of activity shifts to the depths of the sea. The German alpha Ventus project confirmed that the fishing ban policy increased the population density of COD by 40%, but the cable electromagnetic field interfered with the migration path of eel [17]. Thanet wind farm in the UK uses spatial planning to avoid the migration corridor of seabirds, and the collision mortality is 60% lower than the predicted value [23].

4.1.2 Asia Pacific practice

In the Asia Pacific region, China and South Korea have actively promoted the development of offshore wind power in recent years and explored the path of regional ecological synergy. Jiangsu Dafeng offshore wind farm promoted the expansion of the Mytilus edulis community, and the Shannon Wiener index increased by 0.8, but the erosion of the pile foundation led to the fragmentation of the benthic habitat the project in southwest Korea adopted an eco-friendly jacket foundation, artificially increased the coral attachment surface, and increased the hard coral coverage by 15%which helped to reconstruct a small ecosystem similar to natural reefs and provide a habitat for a variety of fish and invertebrates [24, 25].

4.2 Tidal energy and ecological protection: the case of larende, France

4.2.1 positive effects

After 50 years of operation of La rance power station, the dam body has formed a special intertidal ecosystem, attracting 42 species of birds to settle down, and the biomass reaches 80% of the natural reef the dam foundation structure slows down the tidal current speed, so that a large number of sediments can be stably deposited, contributing to the growth of benthic plants and algae, and providing new foraging and breeding places for birds, shellfish and fish. The observation data show that the existing intertidal ecosystem is close to the natural reef level in terms of biomass and population diversity, forming a relatively self-consistent ecological unit [26].

4.2.2 negative effects

However, the water interception measures at the initial stage of the project construction have caused great impact on the local ecosystem. Closure during the construction period led to the extinction of local oyster populations, and the reduction of water exchange led to the accumulation of toxic substances in sediments although some functions were gradually replaced or restored in the new system, it still suggested that great attention should be paid to the time lag and irreversibility of ecological response in the development of tidal energy [27].

4.3 Impact of marine energy facilities

4.3.1 wave device

As the exploitable offshore wind resources tend to be saturated, the maturity of floating wind power technology promotes the large-scale utilization of deep and far sea resources. This emerging path not only widens the spatial boundary of clean energy, but also brings new ecological interaction mechanisms. In the pilot project of Wanshan islands in China, the oscillating water column device (OWC) became an octopus spawning ground, and the fish abundance increased by 25%; However, anchor chain scraping damaged the seagrass bed Portugal AGU ç adoura project confirmed that the low-frequency noise of the equipment caused the displacement of tuna feeding area [28].

4.3.2 ocean thermal energy conversion

Brazilian prototype deep cold drainage promotes nutrient upwelling, stimulating phytoplankton growth by 35% (fertilizer effect), but changing the local temperature and salt structure affects the diffusion of coral larvae in some pilot projects, the anchor chain area has become a gathering point of fish, similar to the "mobile artificial reef", attracting the retention of migratory fish in the upper and middle layers, indirectly increasing the regional fishery production. At the same time, the underwater structure of the floating platform also provides a good attachment surface, providing growth space for algae, sea anemones and other fixed organisms, and enriching the underwater three-dimensional ecosystem [29].

5. Conclusion

In summary, the development of green energy infrastructure in marine environments exerts a dual impact on ecological reconstruction. On the positive side, installations such as offshore wind farms, tidal and wave energy devices contribute to biodiversity enhancement and habitat restoration through artificial reef formation, shelter provision, and the creation of de facto no-fishing zones. However, these benefits are tempered by potential ecological risks, including habitat disturbance, noise pollution, and electromagnetic interference. Ecological theories and models—such as ecological risk assessments and life cycle analyses—offer valuable tools for understanding and quantifying these effects, though comprehensive, multidimensional assessment frameworks remain underdeveloped. Recent advances in green energy technologies have accelerated marine ecosystem restoration efforts, with notable improvements in habitat complexity and ecosystem functionality observed in regions with well-planned deployments. Moving forward, it is essential to integrate ecological and engineering perspectives to assess long-term impacts under diverse environmental conditions, differentiate responses across ecosystem types, and guide adaptive management. Additionally, coordinated policy efforts are needed to align green energy development with marine conservation goals by strengthening environmental oversight, refining regulatory standards, and fostering sustainable industrial practices.

References

[1] WANG Ting, RU Xiao-shang, ZHANG Li-bin. 2022. Research progress on the comprehensive impact of offshore wind farms on the marine ecological environment and biological resources. Marine Sciences, 46(7): 95–104.

[2] Li Yuan, Yang Hui. 2021. Key environmental impact issues of plain and mountainous wind farms. Wind Energy, (05): 74–76.

[3] Huang Yicai. 2018. Research on ecological environmental impacts of offshore wind power projects. Communications World, (03): 205–206.

[4] Wang Xin. 2019. Environmental impact analysis of wind farm construction. Hubei Agricultural Mechanization, (10): 18.

[5] Chinese Research Academy of Environmental Sciences, Beijing 100012; College of Forestry, Gansu Agricultural University, Lanzhou, Gansu 730070; National Climate Center, Beijing 100081.

[6] Li, P., Wang, S., Imran Ahmed Samo, et al. 2020. Common-ion effect triggered highly sustained seawater electrolysis with additional NaCl production. Research.

[7] Sha, Q., Wang, S., Yan, L., et al. 2025. 10,000-h-stable intermittent alkaline seawater electrolysis. Nature.

[8] Zheng Y., Qiao S. 2023. Direct seawater splitting to hydrogen by a membrane electrolyzer. Joule.

[9] Liu Lin, Ge Xubo, Zhang Yibin, et al. 2012. Current

development status and analysis of offshore wind power in China. Energy Technology and Economics.

[10] WANG Ting, RU Xiao-shang, ZHANG Li-bin. 2022. Research progress on the comprehensive impact of offshore wind farms on the marine ecological environment and biological resources. Marine Sciences, 46(7): 95–104.

[11] Wang Geng, Zhang Huihang. 2020. A bibliometric analysis of research hotspots and trends in marine ecosystem services. Acta Ecologica Sinica, 40(7): 2496–2505.

[12] Vierros, M. 2017. Communities and blue carbon: the role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. Climatic Change, 140(1): 89–100.

[13] Barbier, E. B., et al. 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs, 81(2): 169–193.

[14] Gissi, E., et al. 2021. A review of the combined effects of climate change and other human stressors on the marine environment. Science of The Total Environment, 755: 142564.

[15] Bergström, L., et al. 2014. Effects of offshore wind farms on marine wildlife—a generalized impact assessment. Environmental Research Letters, 9(3): 034012.

[16] Degraer, S., et al. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning. Oceanography, 33(4): 48–57.

[17] Langhamer, O., et al. (2009). Artificial reef effect and fouling impacts on offshore wave power foundations. Biofouling, 25(4), 335–343.

[18] Coates, D. A., et al. 2022. Offshore wind farms as marine protected areas for commercially fished species. ICES-Journal of Marine Science, 79(3): 799–811.

[19] Southall, B.L., et al. (2021). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. Aquatic Mammals, 47(5), 495–500.

[20] Westerberg, H., & Lagenfelt, I. (2008). Sub-sea power cables and the migration behaviour of the European eel. Fisheries Management and Ecology, 15(5-6), 369–375

[21] Katsanevakis, S., et al. 2020. Marine spatial planning in practice. Estuarine, Coastal and Shelf Science, 246: 107050.

[22] Dannheim, J., et al. (2020). Benthin effects of offshore renewables. ICES-Journal of Marine Science, 77(3), 1218–1232

[23] Searle, K., et al. (2022). Mitigating seabird collision risk in UK offshore wind. Marine Policy, 146, 105298

[24] Zhang, J., et al. (2021). Benthic community shifts in Jiangsu wind farms. Ecological Indicators, 133, 108439

[25] Kim, S., & Oh, J. (2023). Coral restoration on wind turbine foundations. Ocean Engineering, 272, 113831

[26] Gossé, J., et al. (2019). Long-term ecological changes at La Rance TPP. Renewable Energy, 141, 115–125

[27] Ahmadian, R., et al. (2020). Environmental impacts of tidal energy schemes. Applied Energy, 279, 115769

[28] Li, Y., et al. (2022). Wave energy impacts in China. Journal of Cleaner Production, 380, 134858.

[29] Vega, L., et al. (2023). Ecological implications of OTEC discharges. Frontiers in Marine Science, 10, 1125027.