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PAPER • **OPEN ACCESS**

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IOP Conf. Series: Earth and Environmental Science **1552** (2025) 012010 doi:10.1088/1755-1315/1552/1/012010

Environmental Risks and Impacts of Offshore Energy: A Literature Review

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Abstract. Offshore renewable energy will be essential in achieving the European Union's goal of climate neutrality by 2050 and meeting the growing global energy demand. This sector includes wind, wave, and solar energy, each advancing at different stages of development. However, the expected expansion of offshore energy production may lead to significant environmental consequences. Assessing the ecological risks posed by wind-generated electricity to marine ecosystems is both urgent and essential. Offshore wind farms can affect biodiversity, disrupt habitats, and interfere with the migration patterns of marine species. Therefore, comprehensive studies are needed to identify potential risks and develop strategies to mitigate them. Through such assessments, like the ones compiled in the work presented herein, effective environmental management strategies can be implemented to minimize negative impacts. This will help ensure that offshore energy contributes to the transition toward sustainable energy without compromising marine ecosystems. The adoption of sustainable measures will allow the sector to grow responsibly, balancing technological progress with environmental preservation.

1. Introduction

The transition to a low-carbon economy has become a global imperative in the face of escalating climate change, rising energy demand, and the depletion of terrestrial energy resources. As governments and industries seek to diversify energy portfolios and reduce greenhouse gas (GHG) emissions, offshore energy—comprising offshore wind farms, wave and tidal energy, ocean thermal energy conversion (OTEC), and offshore oil and gas extraction—has gained strategic importance. According to the International Energy Agency (IEA), offshore wind alone has the technical potential to generate more than 18 times the current global electricity demand (IEA, 2019).

The marine environment presents unique advantages for energy production, such as higher wind speeds and vast spatial availability, which make offshore installations especially attractive compared to their land-based counterparts (Rodrigues et al., 2015). However, alongside these benefits come significant environmental challenges. Offshore energy infrastructure can disrupt marine ecosystems through physical disturbances during construction, operational noise, electromagnetic fields, pollution, and habitat modification (Gill, 2005; Wilhelmsson et al., 2006). Moreover, oil and gas operations offshore pose additional risks such as catastrophic spills and chronic hydrocarbon pollution, as witnessed in events like the Deepwater Horizon disaster (Zapelini de Melo et al., 2022).

One of the key environmental concerns associated with offshore energy, especially offshore wind and tidal turbines, is underwater noise pollution, which can interfere with the communication, navigation, and reproduction of marine mammals and fish (Popper and Hawkins, 2019; Siddagangaiah et al., 2025). Additionally, the benthic environment—the ecological region at the lowest level of the ocean—can be significantly altered due to seabed anchoring and cable trenching, impacting benthic species and nutrient cycles (Wawrzynkowski et al., 2025).

Despite these concerns, offshore renewable energy is often perceived as an environmentally preferable alternative to fossil fuel-based systems. Studies have suggested that, with proper regulation, spatial planning, and technological innovation, the environmental footprint of offshore energy can be minimized (Noshchenko et al., 2025). The development of marine spatial planning tools and environmental impact assessments has been instrumental in identifying and mitigating potential conflicts between energy development and marine conservation objectives (Galparsoro et al., 2025).

Given the rapid growth of offshore energy, a comprehensive understanding of its ecological implications is essential for sustainable development. This article aims to assess the environmental impacts of various offshore energy technologies, drawing on current research and case studies. It will also explore the effectiveness of mitigation strategies and governance frameworks that seek to balance energy needs with marine ecosystem protection. This paper adopts an integrated perspective on the environmental impacts of offshore energy, highlighting comparative trade-offs, common challenges, and opportunities for shared mitigation measures.

2. Types of Offshore Energy Technologies

Offshore energy encompasses a range of technologies that exploit marine environments to generate electricity or extract fuels. These technologies differ in their operational principles, infrastructure requirements, and associated environmental impacts. This section provides an overview of the principal offshore energy systems: offshore wind energy, tidal and wave energy, ocean thermal energy conversion (OTEC), and offshore oil and gas extraction.

2.1 Offshore Wind Energy

Offshore wind power has emerged as the most mature and widely implemented form of offshore renewable energy, with rapid global expansion driven by technological innovation, falling costs, and policy support. Wind turbines are installed either on fixed-bottom foundations (typically in waters less than 60 meters deep) or floating platforms, which are suitable for deeper regions where fixed structures are not feasible. Europe, China, and the United States are leading the global offshore wind deployment, with numerous projects under construction or in planning stages.

Compared to onshore wind, offshore sites provide access to stronger and more consistent wind resources due to the absence of terrain-induced turbulence, resulting in higher energy production efficiency (Rodrigues et al., 2015). Additionally, offshore wind farms typically encounter fewer land-use constraints, making them suitable for large-scale deployment. However, the development and operation of offshore wind infrastructure can have notable environmental implications. For example, pile driving during the installation of turbine foundations produces intense underwater noise, which has been shown to disturb marine mammals and fish by disrupting communication, navigation, and behaviour (Thomsen et al., 2006). Furthermore, the presence of electromagnetic fields emitted by subsea power cables may influence species that rely on electro- or magneto-reception, such as elasmobranchs, potentially altering their movement or orientation (Gill et al., 2014). These interactions highlight the importance of incorporating ecological considerations into offshore wind energy planning and mitigation strategies. In addition, floating offshore wind farms, while reducing some impacts of seabed fixation, introduce new challenges, such as anchor and mooring impacts and the risk of entanglement for migratory species.

The sector is experiencing exponential growth, with the International Energy Agency (IEA) projecting global installed capacity to rise from 64 GW in 2023 to over 370 GW by 2030, with continued expansion expected through 2050. This rapid expansion necessitates the development of robust environmental assessment frameworks to ensure marine ecosystems are protected while maximizing renewable energy gains.

Table 1. Key contribution on the environmental aspects of offshore wind energy

Focus area	Key contribution	Reference
Life Cycle Assessment of Floating Wind	Evaluated environmental impacts of floating wind farms in deep-sea areas	Yuan et al 2023
Environmental Impacts of Floating Wind	Discussed cumulative impacts and lessons from fixed-bottom wind farms	Rezaei et al 2023
Marine Environment Impact Analysis	Analysed the effects of wind farm construction on marine ecosystems	Łazuga 2024
Environmental Impact Assessment	Provided recommendations for sustainable offshore wind farm development	Rahman & Kumar 2024

Recent literature on offshore wind energy highlights a growing focus on the environmental consequences of floating and fixed-bottom offshore wind farms, Table 1.
Studies by Yuan et al. (2023) and Rezaei et al. (2023) assess the life-cycle environmental footprint and cumulative ecosystem effects, respectively, underscoring the importance of integrated impact assessments in deep-sea and nearshore deployments. Łazuga (2024) provides a quantitative analysis of construction-phase impacts on benthic habitats and marine biodiversity. Rahman and Kumar (2024) propose best practices for environmental impact assessments and policy frameworks to enhance sustainable offshore wind development.

2.2 Tidal and Wave Energy

Tidal and wave energy technologies utilize the kinetic and potential energy of moving seawater to generate electricity. Tidal energy is derived from predictable tidal cycles, either through tidal barrages or tidal stream turbines, while wave energy captures surface oscillations using buoys or oscillating water columns.

Table 2. Findings on Environmental Impacts of Tidal and Wave Energy

Focus area	Key contribution	Reference
Pinniped behavioural response to tidal turbines	Harbour seals showed localized avoidance of operational tidal turbines, suggesting habitat displacement.	Montabaranom et al. 2025
Ecosystem modelling of tidal energy	Predicted impacts on benthic habitats, food webs, and hydrodynamics.	Schuchert et al. 2016
Global environmental effects of marine energy	Synthesized impacts of wave and tidal energy globally, emphasizing mitigation.	Copping et al. 2020
Ecosystem-based management and EU governance	Advocated for integrating Ecosystem-Based Management (EBM) and ecosystem services into EU marine renewable energy policy for coherent and sustainable governance.	O'Hagan et al. 2020

Despite their promise as low-carbon energy sources, tidal and wave technologies present notable environmental challenges that require rigorous management. Recent findings by Montabaranom et al. (2025) demonstrated that harbour seals exhibit localized avoidance behaviour in response to operational tidal turbines, suggesting that such infrastructure may alter spatial use and lead to habitat displacement. In addition to physical presence, acoustic emissions from turbines may contribute to sensory disturbances, potentially affecting the behaviour and navigation of marine animals, especially those reliant on echolocation or acute auditory perception. In addition, habitat modification occurs during the installation and operation of energy devices, often leading to changes in seabed morphology, sediment transport, and water column stratification. Such alterations can affect benthic communities and coastal ecosystems, especially in areas of high ecological sensitivity (Schuchert et al., 2016). The deployment of anchoring systems, foundations, and subsea cables may introduce artificial hard substrates that change species composition and predator-prey dynamics. Furthermore, collision risks are of particular concern for marine animals interacting with moving parts of turbines, especially in high-energy environments where visibility is reduced. Copping et al. (2020) conducted a comprehensive synthesis of environmental effects associated with marine renewable energy, identifying behavioural changes and potential habitat displacement among various marine taxa. The study emphasized that physical presence, operational noise, and electromagnetic fields from tidal and wave energy systems can cause localized avoidance behaviours and stress responses in sensitive species. In addition, acoustic emissions from turbines may impair sensory perception, potentially affecting navigation and predator-prey interactions, particularly for species that rely on sound for orientation and communication.

Although technological innovations—such as quieter turbine designs, real-time environmental monitoring, and adaptive management protocols—are advancing to minimize ecological impacts, there remains a critical need for site-specific environmental impact assessments and long-term ecological research. According to O'Hagan (2020), effective governance of marine renewable energy must integrate Ecosystem-Based Management (EBM) principles and account for ecosystem services to address the inherent uncertainties in ecological responses. Embedding EBM into regulatory frameworks and permitting processes enhances the capacity to balance technological development with environmental protection.

2.3 Offshore oil and gas extraction

Offshore oil and gas extraction involves the exploration and production of hydrocarbons beneath the ocean floor, often at great depths and under extreme environmental conditions. While it plays a major role in global energy supply, this activity raises significant environmental concerns, including the risk of oil spills, chronic pollution from produced water discharge, and disruption to marine habitats due to infrastructure and noise. Advances in technology have improved safety and efficiency, but environmental risks remain, particularly in ecologically sensitive areas such as the Arctic and deep-water regions.

Table 3. Findings on Offshore oil and gas extraction

Focus area	Key contribution	Reference
Deepwater Horizon oil spill	The Deepwater Horizon spill caused widespread contamination of deepwater habitats, affecting deep-sea corals and benthic communities.	Beyer et al. 2016
Produced water discharges	Produced water discharges on the Norwegian continental shelf show mild acute effects on marine organisms, with detectable exposure several kilometres from discharge points	Beyer et al. 2020
Offshore oil spills in Brazil	Expansion of offshore oil exploration in Brazil raises environmental concerns due to potential oil spills and impacts on marine ecosystems	Zacharias et al. 2024
Environmental impacts of offshore activities	Offshore oil and gas activities contribute to marine pollution, with drilling and dredging activities posing significant threats to marine ecosystems	Albeldawi 2023

Recent research, Table 3, has significantly advanced our understanding of the environmental consequences of offshore oil and gas extraction. Beyer et al. (2016) documented the extensive ecological damage caused by the Deepwater Horizon spill, particularly its impact on deep-sea corals and benthic communities, emphasizing the vulnerability of offshore ecosystems to large-scale contamination events. Building on this, Beyer et al. (2020) explored the subtler but chronic effects of produced water discharges, demonstrating that even regulated operational discharges can result in bioaccumulation and toxic exposure for marine organisms at considerable distances from source points. Similarly, Zacharias et al. (2024) highlighted the increasing risks associated with offshore expansion in Brazilian waters, where limited environmental oversight could exacerbate the potential for ecological harm from oil spills. Albeldawi (2023) further expanded this perspective by analyzing how routine activities such as drilling and dredging contribute cumulatively to marine pollution, disrupting benthic habitats and altering sediment composition. Collectively, these studies underscore the need for integrated monitoring, stricter regulatory frameworks, and improved mitigation strategies to minimize both acute and chronic impacts on marine biodiversity.

2.4 Ocean Thermal Energy Conversion (OTEC)

Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that generates electricity by using the temperature difference between warm surface water and cold deep-sea water, typically found in tropical regions. This thermal gradient drives a closed-cycle system in which a working fluid is vaporized, spins a turbine, and is then condensed, producing continuous, base-load energy. While promising, OTEC systems face technical and environmental challenges, including high infrastructure costs and potential ecological disturbances. Recent advancements in OTEC technology reflect growing global interest in harnessing the ocean's thermal gradients as a source of sustainable energy, as presented in Table 4.

Table 4. Findings on Ocean Thermal Energy Conversion

Focus area	Key findings	Reference
Reliability analysis	Monte Carlo simulations used to assess the influence of temperature variability on OTEC reliability	Ghaedi et al., 2024
Experimental study of high-power OTEC platform	Developed a land-based OTEC system using R134a as the working fluid; achieved a maximum output power of 48 kW with a system efficiency of 2%, providing empirical data for system design and performance optimization.	Lu et al., 2024
Integration of OTEC with waste heat recovery from offshore platforms	Analysed four systems integrating OTEC with waste heat recovery; the best-performing system increased net power output by 1569.13% and thermal efficiency by 70.35% compared to standalone OTEC systems, demonstrating significant performance enhancements.	Du et al. 2024
Opportunities and challenges of OTEC technology	Discussed various OTEC cycles (Rankine, Uehara, Kalina), identifying technical challenges such as low thermal efficiency and high initial costs, and emphasized the need for technological advancements to overcome these barriers.	Chen & Huo 2023

Studies such as (Ghaedi et al., 2024) have contributed significant theoretical and simulation-based insights into improving system reliability and thermodynamic efficiency, with novel cycle designs offering up to 40% improvements in performance. Experimental projects, including (Lu et al., 2024) have validated the technical feasibility of medium-scale OTEC platforms, achieving stable power outputs in real-world conditions. Meanwhile, integrative approaches – like those proposed by Du et al. (2024) – combine OTEC with waste heat recovery systems to enhance energy efficiency, pointing to broader application possibilities in offshore infrastructure. Additionally, review paper by Chen and Huo (2023) emphasizes persistent challenges such as low thermal efficiency and high initial costs, but also highlight technological and regulatory pathways for overcoming these barriers.

These studies underscore a transition from theoretical research to applied engineering, suggesting that with continued investment and innovation, OTEC can play a critical role in diversifying the global renewable energy portfolio—especially for tropical island nations and coastal regions.

2.5.Integrative Discussion: Shared Environmental Challenges and Trade-offs

The environmental impacts associated with offshore energy developments present several challenges that are common across technologies yet vary in scale and character depending on the design and operational context. One of the most prominent shared concerns is underwater noise pollution. Offshore wind farms, particularly during the installation phase of fixed-bottom foundations, generate intense low-frequency noise through pile driving, which has been shown to disturb marine mammals and fish by interfering with their communication, navigation, and foraging behaviour (Popper & Hawkins, 2019). Tidal and wave energy devices, though typically quieter during construction, produce continuous operational noise and turbulence that may affect the spatial distribution and behaviour of sensitive species, such as pinnipeds and cetaceans (Copping et al., 2020). Offshore oil and gas operations further compound underwater noise exposure through drilling activities, seismic surveys, and vessel traffic, contributing to chronic acoustic stress in some marine regions (Beyer et al., 2016). In contrast, Ocean Thermal Energy Conversion (OTEC) systems have a comparatively low acoustic footprint, although they may introduce other localised ecological effects through the intake and discharge of seawater (Chen & Huo, 2023).

Benthic habitat disturbance represents another impact pathway that cuts across offshore technologies but manifests in different ways. Fixed-bottom wind turbines and tidal devices anchored to the seabed can alter benthic communities through physical disturbance during installation and the introduction of artificial substrates that may change local species composition. Mooring lines and anchors from floating structures add further interactions with the seabed, potentially affecting sediment composition and nutrient cycles. Offshore oil and gas drilling and dredging operations pose particularly significant risks to benthic habitats, as demonstrated by the long-lasting impacts of large-scale oil spills and routine discharges of drilling waste (Beyer et al., 2016). While OTEC systems are generally less intrusive to the seabed compared to large foundations, their deep-water pipelines may still influence local benthic species and water column stratification (Chen & Huo, 2023).

When viewed comparatively, these impacts highlight the importance of site-specific design choices and technological trade-offs. For example, while floating offshore wind platforms can reduce direct seabed disturbance compared to fixed-bottom foundations, they require extensive mooring systems that may introduce new risks of entanglement or habitat scouring (Copping et al., 2020). Similarly, while tidal and wave technologies promise predictable, low-carbon energy, they involve moving parts that can present collision hazards for marine life. In all cases, cumulative effects must be considered within a broader seascape where multiple activities interact, potentially amplifying noise exposure, habitat fragmentation, or species displacement (Beyer et al., 2016).

These shared challenges reinforce the need for integrated mitigation measures and governance frameworks that move beyond single-sector management. Cross-cutting solutions such as the use of bubble curtains to dampen construction noise (Popper & Hawkins, 2019), real-time monitoring and exclusion zones for sensitive species (Copping et al., 2020), and the adoption of Ecosystem-Based Management principles in Marine Spatial Planning can help balance renewable energy expansion with the preservation of marine ecosystems. A comparative, cross-technology perspective is therefore critical to designing offshore energy systems that are not only technically and economically viable but also environmentally responsible.

3. Mitigation Strategies

The advancement of offshore renewable energy technologies—particularly offshore wind, tidal, and wave energy—has introduced new environmental challenges that require comprehensive mitigation strategies. While these technologies offer substantial benefits in the transition toward low-carbon energy systems, they also pose risks to marine ecosystems that must be carefully managed through science-based and adaptive approaches.

One of the most prominent concerns is the underwater noise generated during the installation of turbine foundations, especially from impact pile driving. This activity produces intense low-frequency sound that can disturb or even harm marine mammals, notably cetaceans and pinnipeds, by affecting their communication, navigation, and foraging behaviours. To address this, several technical solutions have been developed. Among the most widely adopted is the use of bubble curtains, which create a barrier of air bubbles around the pile-driving site, significantly reducing the intensity and propagation of underwater noise. Recent studies have shown that double bubble curtain systems can attenuate sound pressure levels by more than 20 dB, thus mitigating the acoustic impact on sensitive marine species (Peng et al., 2023).

In addition to noise abatement technologies, proactive deterrent systems such as FaunaGuard are increasingly implemented. These systems emit species-specific acoustic signals designed to displace marine mammals and fish temporarily from high-risk areas during construction phases. Evidence from recent projects, such as the CrossWind offshore wind farm in the Netherlands, suggests that combining FaunaGuard with bubble curtains enhances the overall efficacy of mitigation (Elzinga, 2023).

In addition to technology-specific solutions, there is increasing recognition that mitigation strategies can be adapted and shared across different offshore energy technologies. For example, while underwater noise mitigation has primarily focused on offshore wind construction, operational noise and collision risks are also relevant for tidal and wave energy devices, which rely on submerged turbines and moving parts. Knowledge transfer and standardised guidelines for acoustic management could help ensure that lessons learned from mature wind projects inform emerging tidal and wave deployments, reducing duplication of research efforts and promoting best practice across sectors.

Beyond technological interventions, spatial planning and policy instruments are vital components of impact mitigation. Marine Spatial Planning frameworks that incorporate Ecosystem-Based Management principles facilitate the identification of optimal sites for offshore energy development. This involves integrating ecological data, such as the presence of ecologically or biologically significant areas, migratory corridors, and nursery grounds, into spatial decision-making processes. By doing so, developers can avoid ecologically sensitive regions and reduce the risk of cumulative impacts (Fernandes et al., 2017).

An important aspect that deserves greater attention is the potential for cumulative impacts when multiple offshore energy projects operate within the same marine area or in combination with other human activities such as shipping or fisheries. Spatial overlap can amplify noise exposure, habitat fragmentation, or disturbance to migratory routes. Therefore, integrated Marine Spatial Planning (MSP) should explicitly account for multi-use scenarios and identify thresholds for acceptable cumulative pressures. This approach is particularly relevant as offshore energy expansion accelerates, increasing the likelihood of overlapping footprints and stakeholder conflicts.

Another critical dimension of mitigation is the implementation of real-time environmental monitoring and adaptive management. Techniques such as passive acoustic monitoring, aerial drone surveys, and thermal imaging are used to detect the presence of marine fauna in operational areas. These systems enable real-time decision-making, allowing operators to suspend or delay high-impact activities like pile driving if sensitive species are detected within defined exclusion zones. This dynamic approach is aligned with the precautionary principle and allows mitigation strategies to evolve based on site-specific conditions and observed environmental responses (Palmer et al., 2022).

Furthermore, recent interest in nature-inclusive design offers a proactive strategy to not only minimize harm but also enhance marine biodiversity. Examples include ecologically engineered scour protection, artificial reefs, and bio-enhancing turbine foundations that create new habitats for benthic organisms and fish. Although still in early development stages, such measures represent a paradigm shift from minimizing impacts to actively contributing to ecosystem restoration (Thompson et al., 2020).

Effective mitigation also depends on clear governance frameworks and early stakeholder engagement. Involving local communities, fishers, conservation organisations, and other marine users during the planning and permitting stages can help identify site-specific concerns, improve social acceptance, and encourage co-development of solutions that are technically and ecologically feasible. Strengthening cross-border cooperation and harmonising environmental standards at regional levels will be increasingly important as offshore energy infrastructure expands across national boundaries.

Finally, it is essential to recognise that many mitigation measures remain at early stages of implementation and require further research and validation. Long-term monitoring is needed to assess the actual effectiveness of noise reduction techniques, deterrent devices, and nature-inclusive structures under varying environmental conditions. Comparative studies that evaluate cost-effectiveness, ecological outcomes, and scalability will help refine design guidelines and support evidence-based policy decisions for sustainable offshore energy development.

4. Futures Perspectives and Conclusion

The expansion of offshore renewable energy is pivotal in the global transition toward low-carbon energy systems, with technologies such as floating wind turbines, tidal and wave devices, and Ocean Thermal Energy Conversion (OTEC) contributing to a more diverse and resilient energy mix. Recent technological advancements, including improved turbine designs and real-time environmental monitoring, have enhanced the feasibility and efficiency of these systems.

However, their deployment must be carefully managed to mitigate potential impacts on marine ecosystems.

This paper highlights that while each offshore energy technology presents unique environmental interactions, many challenges are shared across sectors. Underwater noise, benthic habitat disturbance, and risks to marine mammals and fish species are common impact pathways that vary in scale but require coordinated assessment and mitigation. Trade-offs, such as the balance between deeper offshore deployment and the increased complexity of mooring systems, underscore the need for integrated design and planning. The adoption of cross-technology mitigation measures, such as noise reduction techniques and nature-inclusive infrastructure, demonstrates how lessons learned in one sector can benefit others.

To address these challenges effectively, it is essential to strengthen the implementation of Ecosystem-Based Management (EBM) within Marine Spatial Planning (MSP) frameworks. This integrated approach facilitates the sustainable coexistence of offshore energy development with conservation priorities. However, knowledge gaps remain. Future research should prioritise long-term monitoring of cumulative and synergistic effects across multiple projects and technologies, the development of innovative solutions that enhance biodiversity around offshore structures, and improved models to predict ecological responses under changing climate conditions. Collaborative studies that link engineering, ecology, and socio-economic impacts will be particularly valuable.

In conclusion, the sustainable expansion of offshore renewable energy depends on a holistic approach that synthesises insights across technologies, acknowledges trade-offs, and proactively addresses shared environmental challenges. By investing in targeted research and adaptive governance, policymakers and stakeholders can ensure that offshore energy contributes meaningfully to climate goals while safeguarding the integrity of marine ecosystems.

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