

## REVIEW ARTICLE OPEN



## Reviewing the ecological impacts of offshore wind farms

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Offshore wind energy is widely regarded as one of the most credible sources for increasing renewable energy production towards a resilient and decarbonised energy supply. However, current expectations for the expansion of energy production from offshore wind may lead to significant environmental impacts. Assessing ecological risks to marine ecosystems from electricity production from wind is both timely and vital. It will support the adoption of management measures that minimize impacts and the environmental sustainability of the offshore wind energy sector.

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## INTRODUCTION

Ocean energy and offshore wind energy (OWE), in particular, have been identified as potential renewable energy sources, with a view to decarbonizing and reducing greenhouse gas emissions<sup>1</sup> and contributing to achieving the United Nations Sustainable Development Goal (SDG) 7, Affordable and Clean Energy<sup>2</sup>. OWE provides local electricity production capacity and reduces the need for oil or gas maritime transportation, preventing the risk of spills<sup>3</sup>. Moreover, the current context of increasing energy prices, supply-side constraints, and dependency on third countries for traditional energy sources are positioning OWE as a strategic renewable energy source to achieve resilience.

In the last decade, electricity production from wind energy has grown exponentially worldwide in the last decade, benefiting from technological advances<sup>4</sup>, declining production costs, and strong subsidies from states and investors<sup>5,6</sup>. In terms of the Levelized Cost of Energy, an almost 55% drop is anticipated from 2018 to 2030<sup>7</sup>, and 37% to 49% declines in production costs by 2050<sup>8</sup>, making the offshore wind sector increasingly competitive with fossil fuels<sup>7</sup>.

Offshore wind farms (OWFs) already accounted for 10% of new wind power installations around the world in 2019<sup>5</sup>, and are expected to contribute more than 20% of the total installed capacity of offshore wind electricity production by 2025<sup>5</sup>. To attain this growth rate, the global installed capacity of offshore wind projects needs to increase almost tenfold by 2030 (to 228 GW) and continue to rise to 1000 GW by 2050<sup>9</sup>. To achieve such expectations, experts predict that by 2035, 11–25% of all new offshore projects globally will feature floating foundations<sup>8</sup>.

In 2018, more than 80% of the global installed offshore wind capacity was located in Europe<sup>1</sup>. However, estimations are that between 240 and 450 GW of offshore wind power production capacity are still needed by 2050 to contribute to the European Union's goal of climate neutrality<sup>10–12</sup>. To achieve such an objective, OWE will need to account for at least 50% of the total energy mix in 2050 and supply 30% of future electricity demand in Europe<sup>10</sup>. Accordingly, the European Offshore Renewable Energy Strategy<sup>11</sup> was published as part of the European Green Deal<sup>10</sup>, which is expected to position the European Union as a global leader in clean technologies<sup>11</sup>.

Renewable energy production growth should not lead to significant environmental harm nor compromise environmental objectives, and new projects must be compatible with biodiversity protection and conservation objectives (e.g., SDG 14, Life Below Water, or the Convention on Biological Diversity' post-2020 targets<sup>13</sup>).

When developing plans for a new industry such as offshore renewables, there may be interactions between devices and marine species or habitats that regulators and stakeholders perceive as risky<sup>14</sup>, as there are still considerable gaps in scientific knowledge about the ecological impacts of wind turbines<sup>15,16</sup>. Previous studies have shown a gap between perceived and actual risks, with the former arising from uncertainty or lack of data about the real environmental impacts of ocean energy devices<sup>3</sup>. Consequently, uncertainties regarding the assessment of impacts resulting from cumulative pressures caused by OWE production devices also lead to substantial delays during the consenting process<sup>14,17,18</sup>.

Consideration of environmental impacts of new OWE projects, together with implications to other maritime sectors (e.g., fisheries, tourism), need to be assessed during strategic planning processes at administrative, regional, national, or even international levels through marine spatial planning (MSP) processes<sup>19</sup>. The adopted plans should apply an ecosystem-based approach, ensuring that the pressures exerted by maritime activities do not compromise the achievement of a healthy ocean and the resilience of marine ecosystems, and their ability to sustainably supply marine goods and services<sup>20</sup>. However, recent reviews have highlighted that environmental impacts and MSP aspects are still poorly addressed in OWE planning<sup>21</sup>. There is thus an urgent need to identify and assess potential environmental impacts associated with offshore energy production in order to prevent or minimize negative effects at a very early stage of the OWE planning process<sup>22</sup>.

In this review, we assess the ecological impacts of OWE devices by mapping the full set of interactions between the latter and marine ecosystem elements (i.e., species, habitats, ecosystem structure and function) useful to planning processes. A systematic literature review was conducted to obtain the most updated scientific findings derived from environmental studies concerning wind energy devices from peer-reviewed literature and selected

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technical reports<sup>23–25</sup>. The quantitative summaries of scientific findings were extracted through a meta-analysis (see Supplementary Sections 1, 2, for the full description of the review process and data analysis).

### SCIENTIFIC KNOWLEDGE ON ENVIRONMENTAL IMPACTS OF WIND ENERGY DEVICES

A total of 867 findings on pressures due to wind energy devices and impacts on ecosystem elements were extracted from 158 publications. This is a relatively small number of articles among the total screened (1353). Half of the analysed publications (51%) presented empirical evidence, while 36% of the studies were based on modelling approaches, including the modelled propagation of underwater noise<sup>26</sup>. Literature reviews accounted for 11% of the publications, and only 1% of the studies were based on expert judgement (Supplementary Section 2).

A continuous increase in the number of publications is identified, especially in the last eight years (74% of the scientific publications), which is in line with the increase of OWFs and installed production capacity<sup>1,5,9</sup>. Studies have been conducted in shallow seas (North Sea, 66% of the publications), during the operational phase (64%), in shallow waters (90% at <30 m depth), close to the coast (56% <20 km offshore), with few turbines (80% with <81), low production capacity (63% with <160 MW), and a small area (67% <70 km<sup>2</sup>).

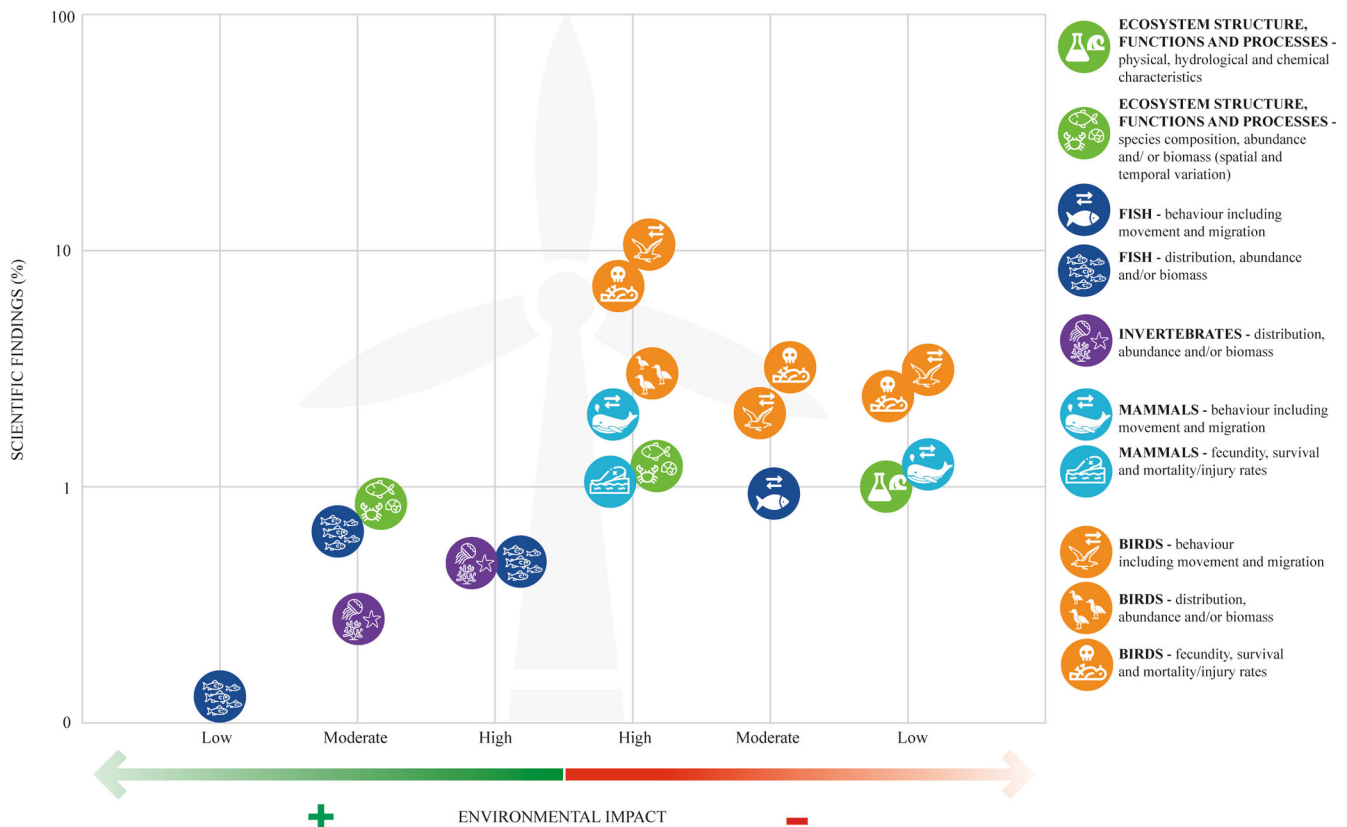
Most studies investigated single pressures, with few papers addressing the interaction of two or more pressures produced by wind energy devices<sup>27–29</sup>. In total, 24 studies investigated more than one pressure, and only about half of them dealt with three or more pressures (one study investigated four pressures and three studies five pressures<sup>30–32</sup>). Among them, three were literature

reviews<sup>30,31,33</sup>. Only 23 studies analysed two or more ecosystem elements simultaneously (most of them being review articles, e.g.,<sup>29,30,33</sup>). Among these, only one study considered five ecosystem elements<sup>33</sup>. This represents a shortcoming in the analysis of wind energy devices impacts, since it is well-known that human activities can produce several co-occurring pressures, which can result in cumulative, synergistic or antagonistic impacts on the ecosystem<sup>34–36</sup>. Investigating multiple interactions between human activities and ecosystem elements is urgent, given that future wind energy developments will add to the cumulative impacts already produced by existing activities and climate change<sup>37</sup>. Additionally, due to the expected increased demand for marine space, multiple ocean uses are likely to take place in the same area as OWE activities and an increase of local cumulative pressures is likely to happen<sup>38,39</sup>.

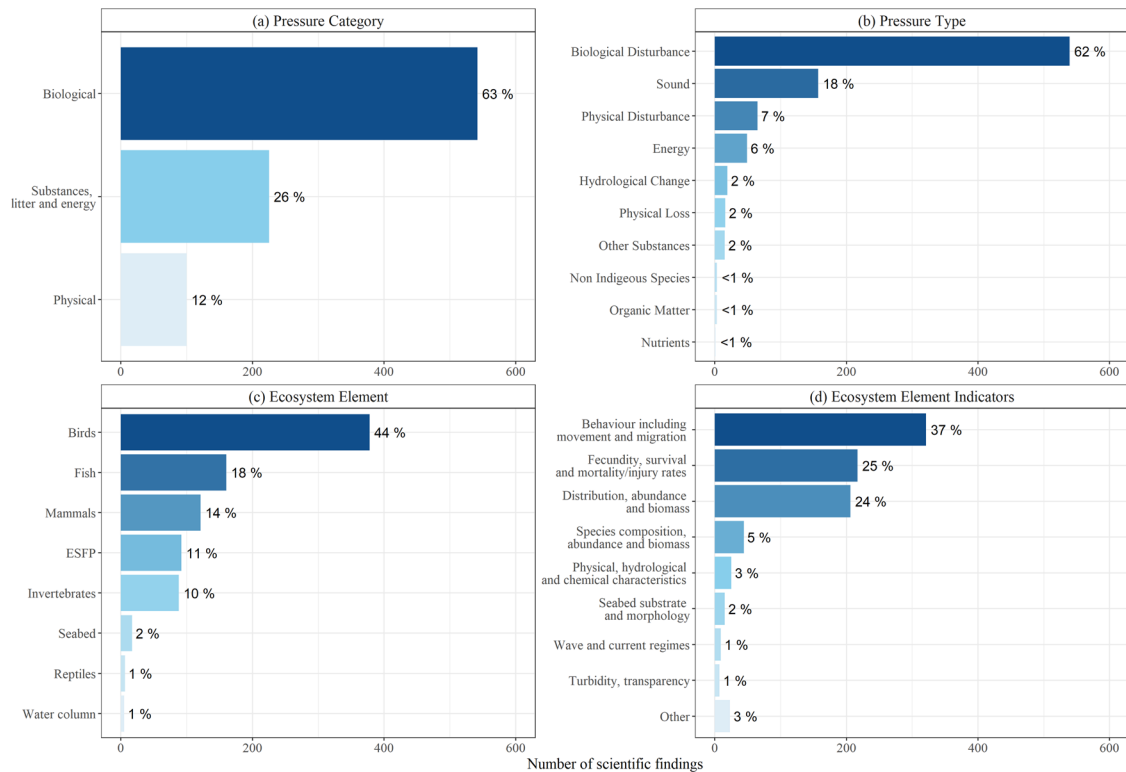
### ENVIRONMENTAL IMPACTS FROM WIND ENERGY PRODUCTION DEVICES ON MARINE ECOSYSTEMS

Offshore energy production can have both positive and negative impacts on marine ecosystems<sup>33,40</sup>. Negative impacts are reported more frequently (up to 10% of the scientific findings) being especially linked to birds, marine mammals, and ecosystem structure. Positive effects are less reported (up to 1% of scientific findings), relating mostly to fish and macroinvertebrates (Fig. 1).

The ecological risks derived from the negative impacts of wind energy devices can vary biogeographically, depending on the environmental characteristics and vulnerability of the affected area (e.g., presence of migrating bird species especially sensitive to wind turbines<sup>41</sup>). The identification of potential significant impacts is, therefore, always case-specific. In particular, the real impact of an OWF on protected species and habitats will show



**Fig. 1** Most frequently reported environmental impacts of wind energy devices on the most representative indicators of ecosystem elements, by type (positive/negative) and magnitude (high to low). See Supplementary Table 5 for the full list of impact types and magnitudes for each ecosystem indicator.



**Fig. 2** Proportions of scientific findings of interactions between offshore wind energy devices and marine ecosystem extracted from the literature review. The information is classified according to studied pressure category (a) and type (b); and for ecosystem elements (c) and indicators assessed (d) in scientific research. ESFP ecosystem structure, functions, and processes.

high spatial variability; it must be carefully assessed with respect to local conservation objectives and the affected species/habitats<sup>41</sup>. Furthermore, environmental impacts will also depend on the initial state and resilience of the area, which can change dramatically for some ecosystem elements<sup>42–44</sup>.

Indirect impacts, which tend not to be fully investigated, must also be considered. Increases in prey species (e.g., pressure tolerant) at OWFs will increase food availability to higher trophic levels (e.g., bird and mammal species), thereby increasing their populations<sup>45–48</sup>. Impacts will thus vary among species within the same ecosystem element (e.g., different seabird species may be affected in different ways by turbines)<sup>49</sup>. In some cases, impacts may be positive (e.g., seabirds have rest areas and more resources for food<sup>50</sup>), while in others, species may suffer significant adverse effects impacting their behavior<sup>51–53</sup>. Impacts may spread far from the OWF area (e.g., lower number of organisms of migratory populations at the final destination), as is the case for land-based wind farms<sup>49</sup>. It is, therefore, fundamental to consider the spatial and temporal distribution of the most sensitive species when determining the risks associated to a given project. For the adoption of such an approach, better data is required on species distribution and abundance over annual cycles and on the migration routes of birds, fish, and marine mammals<sup>15</sup>.

Despite the evident negative impacts of OWFs on ecosystem elements, potential positive impacts must also be highlighted. According to several authors, positive environmental impacts are linked to reserve and reef effects on the area of OWF deployment and mooring structures<sup>30,31,54,55</sup>. These can function as artificial reefs and fish aggregation devices for small demersal fish<sup>45,54,56,57</sup>, attracting more marine life than natural reefs<sup>54</sup>. Evidence suggests that OWFs may enhance diversity in areas with homogeneous seabed<sup>58</sup>. Also, the prohibition of bottom trawling near OWFs for safety reasons eliminates disturbance of fish, benthos, and benthic habitats<sup>59,60</sup>, partially by providing protection from fishing<sup>61</sup>.

Findings suggest that negative impacts on fishing activities can be mitigated by spill-over effects due to increased catches (up to 7%, close to wind farms) and slight modifications in catch composition<sup>61</sup>. Long-term monitoring and additional information on ecological processes influencing fish stock dynamics will further enable the demonstration of whether extra production at population level occurs<sup>62</sup>.

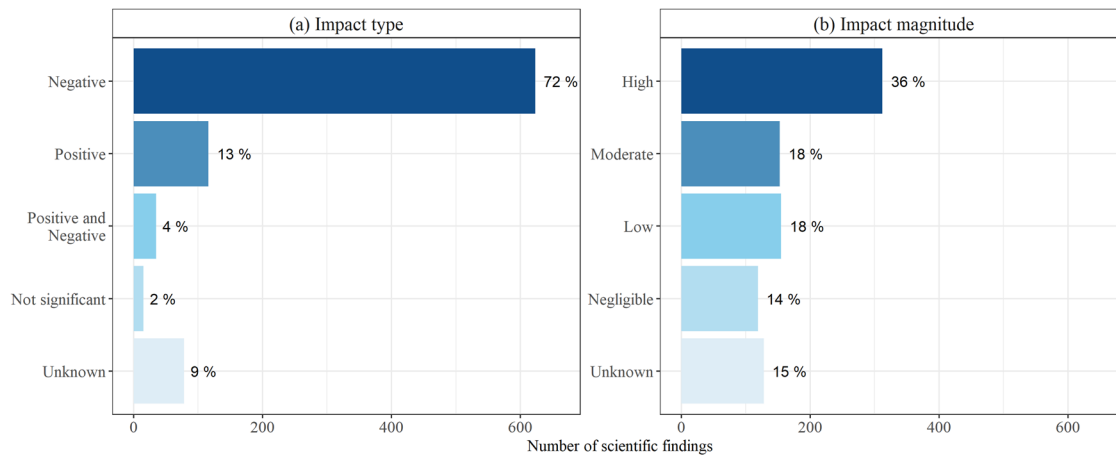
### Pressures on ecosystem elements and their indicators

Of the 867 findings identified, biological pressures correspond to the most-studied pressure category (63%) (Fig. 2a). From 16 pressure types (see Supplementary Table 4 for the full list), 10 pressures were assessed, the most frequent ones being those associated to biological disturbance<sup>63–65</sup> and noise input<sup>66,67</sup> (62% and 18% of the findings, respectively; Fig. 2b). Most findings associated to ecosystem elements were reported for species (87%, especially birds), ecosystem structure, functions, and processes (11%), and habitats (3%) (Fig. 2c). The most studied indicators were behaviour<sup>68,69</sup> (37%), fecundity, survival, and mortality/injury rates<sup>70</sup> (25%), and distribution, abundance and/or biomass<sup>61,71</sup> (24%) (Fig. 2d).

Indicators that are most studies for analysing the effects of the pressures produced by wind turbines on ecosystem elements are identified in Table 1. Despite the relatively high number of species studied, there is a bias toward northern distribution species such as *Phocoena phocoena* (47 findings), *Phoca vitulina* (26 findings), *Uria aalge* (16 findings), or *Gadus morhua* (13 findings)<sup>55,66,72,73</sup>, and a lower number of findings to invertebrates (see Supplementary Tables 7–10). However, with the expected global expansion of OWFs projects to new areas, impacts on temperate, subtropical, and tropical species must be further investigated<sup>74</sup>. While disturbance of high taxonomical levels is important (i.e., mammals, seabirds, fish)<sup>75</sup>, physical loss and physical disturbance of benthic habitats<sup>31</sup> needs to be investigated in detail, as large OWF

**Table 1.** Interactions between pressures from offshore wind devices and ecosystem elements, including species, habitats and ecosystem structure, functions and processes.

Indicators for:	Ecosystem elements				
	Birds	Fish	Mammals	Invertebrate	Reptiles
Species					
Number of findings	378	160	121	88	6
Number of species	111	49	11	39	Not specified
Distribution, abundance and/or biomass	49 (13%)	73 (46%)	28 (23%)	56 (64%)	
Behaviour (including movement and migration)	175 (46%)	54 (34%)	77 (64%)	12 (14%)	3 (50%)
Fecundity, survival, and mortality/injury rates	154 (41%)	31 (19%)	15 (12%)	14 (16%)	3 (50%)
Species composition, abundance and/or biomass (spatial and temporal variation)		2 (1%)	1 (0.8%)	6 (7%)	
Population growth			<1%		
	Habitats, ecosystem structure, functions and processes				
Number of findings	114				
Species composition, abundance and/ or biomass	36 (32%)				
Physical, hydrological and chemical characteristics	25 (22%)				
Seabed substrate and morphology	15 (13%)				
Wave and current regimes	9 (8%)				
Turbidity and transparency	7 (6%)				
Habitat distribution and extent	4 (4%)				
Habitat for the species	4 (4%)				
Other indicators	14 (12%)				

**Fig. 3** Proportion of scientific findings about the impacts of wind energy devices on marine ecosystems. The information is classified according to impact type (a) and magnitude of the impact (b). ESFP ecosystem structure, functions, and processes.

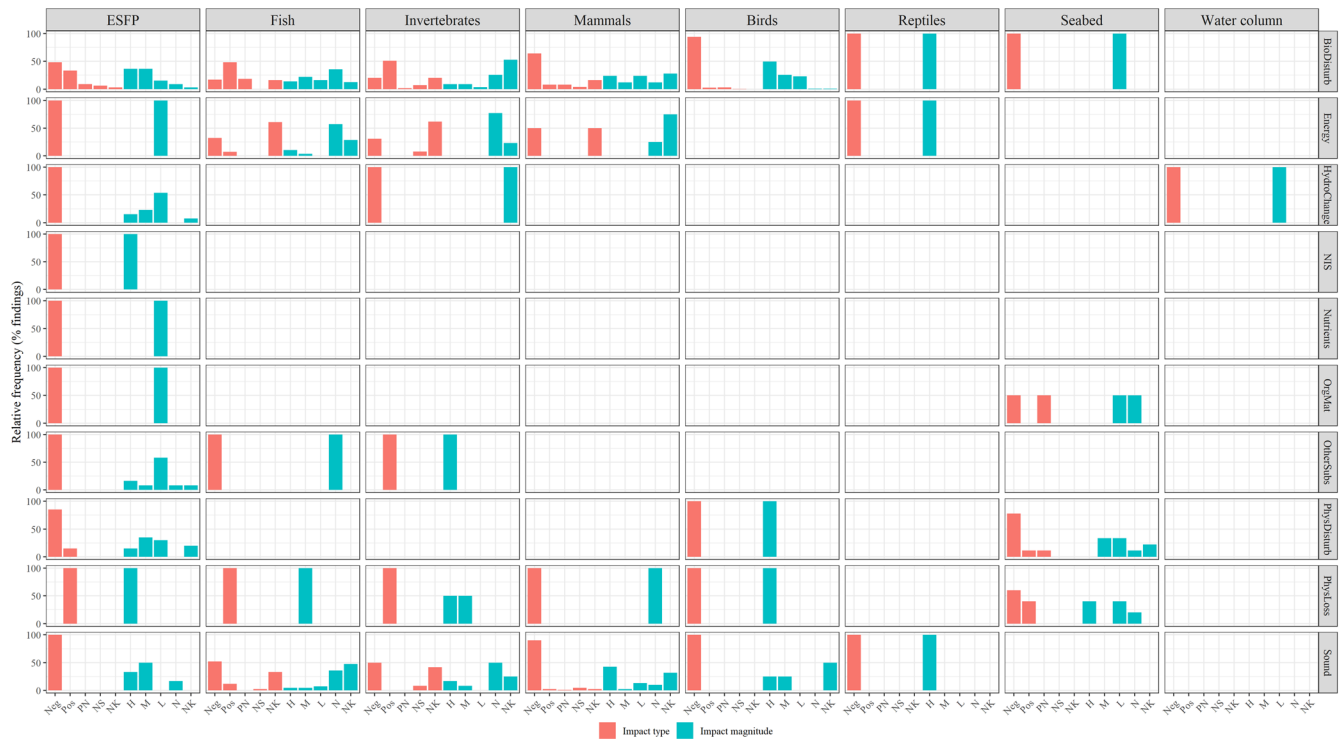
developments and the high density of wind turbines may hinder the achievement of good environmental status for biodiversity or seafloor integrity<sup>76,77</sup>.

### IMPACT TYPE AND MAGNITUDE

Among the 867 findings extracted from the analysed publications, 72% reported negative impacts, while 13% were positive (Fig. 3a). Regarding impact magnitude (either positive or negative), 54% were reported as being high or moderate, while low or negligible impacts accounted for 32% (Fig. 3b). The distribution of impact type and magnitude on each ecosystem element is shown in Fig. 4, while the level of certainty is shown in Supplementary Fig. S4. For instance, the impact type of 'biological disturbance' pressure (row 1) over ecosystem element 'birds' (column 5) is

mostly reported as being negative (Fig. 4; red-coloured bars). There is also a high degree of scientific consensus (see Supplementary Fig. S4; row 1, column 5, left bar). Conversely, impact magnitude is more evenly distributed among classes (Fig. 4; row 1, column 5, green-coloured bars) and, therefore, certainty is lower (Supplementary Fig. S4; row 1, column 5, right bar). Note that the number of analyses found in literature plays an important role in certainty interpretation (e.g., when only one paper describes the impact and magnitude of a pressure type on an ecosystem element, interpretation must be cautious). Supplementary Figs. 5–20 present detailed information on the assessed ecosystem element indicators per group.

The relatively high degree of agreement regarding impact type (e.g., positive, negative) of wind devices on ecosystem elements is noteworthy. By contrast, certainty regarding impact magnitude is



**Fig. 4** Impact type and magnitude of wind energy devices for each pressure over each ecosystem element based on information extracted from the systematic literature review. The intersection between a pressure type (rows) and an ecosystem element (column) shows the relative frequencies of each impact type (red), and magnitude (green). ESFP ecosystem structure, function, and processes, Neg negative, Pos positive, PN positive and negative, NS not significant, NK unknown, H high, M medium, L low, N negligible.

relatively low, especially for marine mammals and ecosystem structure, functions, and processes. This highlights the lack of empirical evidence needed to assess impact magnitude and, hence, the full ecological risks associated with OWFs (Supplementary Table 11).

For all ecosystem components together, high-moderate negative impacts accounted for 45% of the findings (Supplementary Table 12), 32% of which referred to effects on birds. Negative impacts are associated with changes in bird abundance due to collision mortality and displacement, changes in distribution patterns, and alteration of behaviour to avoid OWFs<sup>78–80</sup> (Supplementary Table 5). Species differed greatly in their sensitivity to pressures, with different responses depending on their ecology (i.e., flight altitude, season, sex). In turn, only 1% of the findings reported high-moderate positive impacts on birds (e.g., attraction behaviour toward OWFs by gulls or cormorants)<sup>47,71</sup>.

As for marine mammals, up to 7% of the findings referred to negative impacts, depending on the OWF development phase. Pile driving can have a significant impact on mammal's abundance and distribution (e.g., avoidance behaviour with porpoises temporarily leaving the construction area)<sup>53,81</sup>. By contrast, 0.5% of the findings reported positive effects. It has been reported that the abundance of harbour porpoises increased after construction ended, with animals using the OWFs more frequently than reference areas<sup>45</sup>. This is potentially related to food availability due to reduced fishing, artificial reef effects, and the absence of vessels.

In what regards fish, over 2% of the findings reported high-moderate negative impacts. The magnitude of such impacts depends on the affected species and its level of vulnerability/sensitivity, with potentially more severe effects for elasmobranchs<sup>30,50</sup>. The same percentage of findings reported high-moderate positive impacts related to shelter (against currents and predators) and food availability, stimulating aggregation behaviour<sup>45,82</sup>. OWFs may act as fish aggregation devices, with spill-over

effects. Fish species from rocky environments were more abundant close to OWFs than those from sedimentary environments<sup>54,83</sup>.

#### IMPLICATIONS FOR MANAGEMENT AND DECISION MAKING

One of the most relevant non-technical barriers affecting the expansion of the offshore renewable energy sector is the potential environmental risk (and related uncertainties)<sup>84,85</sup>. The latter entails significant repercussions in the promptness of the consent process and associated economic costs<sup>86</sup>.

Legal frameworks are emerging worldwide to support sustainable exploitation of marine resources while preserving healthy and functioning ecosystems<sup>87,88</sup>. Among other instruments, Strategic Environmental Assessments (SEAs) and Environmental Impact Assessments (EIAs) are used globally to manage the environmental impacts of human activities and identify projects risks<sup>89–92</sup> to avoid adverse effects and adopt mitigation and compensation measures<sup>93</sup>. Updated, integrative, and systematic scientific information on the risk of each potential interaction between OWFs and different ecosystem elements is needed to inform managers and decision-makers during OWE planning<sup>14,92,94–96</sup>. It is valuable information for designing monitoring programmes at the project location (particularly those focused on ecosystem elements with higher vulnerability to the pressures produced by the wind turbines) and implementing mitigation measures in the context of the consent processes<sup>97</sup>.

This review is not intended to question the potential of OWE production as a credible source of clean and renewable energy, with its direct and indirect economic, social, and environmental benefits. Instead, it intends to highlight the potential ecological effects that the sector's expansion will cause at local and regional scales. While legislation to reduce local impacts of OWE is necessary, it must be proportionate and weighed against the global environmental, social, and economic benefits that derive from reducing fossil-fuel emissions<sup>98</sup>.

## A WAY FORWARD

Structured and science-based information such as the one presented in this review is vital to anticipate ecological impacts and adopt mitigation measures<sup>43</sup>, ensuring that the OWE sector is environmentally sustainable. Still, we must acknowledge that there are significant scientific discrepancies regarding the magnitude of OWE impacts, as highlighted by the lack of evidence on the assessment of ecological risks associated to OWE projects. Moreover, most publications are derived from studies conducted at more localized scales (e.g., in shallow waters, close to the coast, with few turbines, low production capacity, and occupying a small area). The acquisition of new data through dedicated monitoring activities around OWE developments is, therefore, highly relevant to overcome scientific knowledge gaps—being, in turn, of high value to policymakers, managers, decision-makers, and industry. Monitoring processes need to focus on pressures and impacts on specific ecosystem elements (including protected and vulnerable habitats and species) for which higher uncertainty has been identified. Another important aspect to consider is the limited number of scientific studies addressing the environmental impacts of multiple pressures produced by wind turbines. Assessments of cumulative pressures and impacts of OWFs and other existing maritime activities must be further promoted, as multiple human activities will continue to take place in the same areas as OWFs being likely to exacerbate environmental impacts. The limited number of studies addressing with impacts on ecosystem services must also be emphasised<sup>42,99,100</sup>. More in-depth analyses on OWFs effects on the provision of ecosystem services will potentially highlight unknown impacts affecting (positively or negatively) other maritime sectors operating in surrounding areas.

The progressive expansion of OWFs to meet energy production objectives, including floating devices in deeper areas and farther offshore<sup>8,43</sup>, faces relevant technical, economic, social, and ecological concerns worldwide. Among other challenges, it will add to and be affected by the increasing demand for ocean space<sup>101,102</sup>. Interactions with other traditional and strategic human uses of the ocean need to be considered in order to avoid, or at least minimise, spatial conflicts<sup>103</sup>. A future perspective on this topic includes using integrative approaches to gather relevant information, thereby providing a holistic view of the positive and negative impacts, and of the trade-offs between different management options. These approaches include the development of tools for ecological risk assessment of OWE projects<sup>104</sup> and the implementation of machine-learning and modelling approaches (such as Bayesian networks)<sup>105</sup>. Such tools are to be further integrated into decision-support tools<sup>106–108</sup> to identify future deployment areas, inform the consent process, and contribute to making the OWE sector more environmentally sustainable.

## DATA AVAILABILITY

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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I.G.: conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review and editing, visualization, supervision, project administration and funding acquisition. I.M.: investigation, review and editing. J.M.G.: investigation, review and editing. Á.B.: conceptualization, investigation, writing—original draft, writing—review and editing, visualization. A.D.M.: formal analysis, writing—original draft, writing—review and editing, visualisation. G.I.: writing—review and editing. J.B.: writing—review and editing and funding acquisition.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

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