Mapping potential environmental impacts of offshore renewable energy

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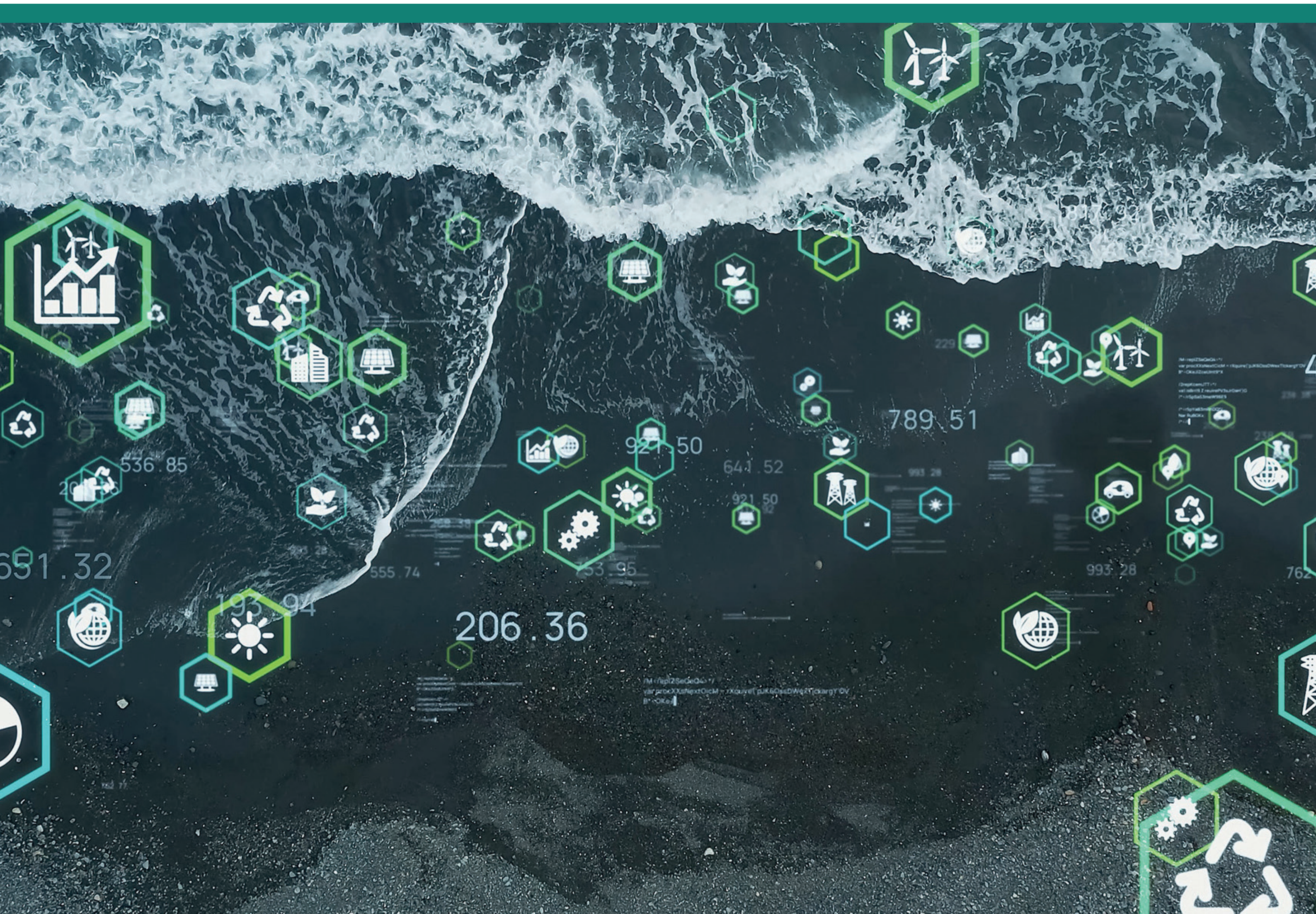

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Executive summary

The European Green Deal sets out the ambition to make Europe the first climate-neutral continent by 2050, while addressing other environmental challenges, boosting the economy, improving people's health and quality of life, and ensuring an inclusive and just transition (European Commision, 2019). As part of the Green Deal, the Commission adopted the EU Offshore Renewable Energy Strategy to give a strategic direction for the ambitious development and integration of offshore renewable energy by 2030 and 2050 (European Commission, 2020b).

Harnessing offshore renewable energy can produce negative environmental impacts on marine ecosystems, both on biological (flora and fauna, biodiversity, etc.) and physical components (marine dynamics, seafloor integrity, pollution, etc.), which still need to be better understand. The Biodiversity Strategy to 2030 (European Commission, 2020c) recognises the positive climate impacts of offshore energy, but at the same time recognises the potential for negative impacts on sensitive species and habitats. In addition, the environmental impacts must be evaluated on a project-by-project basis as these are site-specific. Hence, there is a need to anticipate the development of ocean energy farms by assessing the potential environmental risks, to minimize the impacts and to identify the ecosystem elements that should be focused. To allow for full biodiversity impacts to be assessed, there exists an urgent need for additional multi and inter-disciplinary research in this area ranging from engineering to policy.

The first section of the present report determines the potential interaction between different offshore renewable energy devices (i.e., wind turbines, wave energy converters, current turbines, photovoltaic and ocean thermal energy conversion systems) and ecosystem components, by identifying the pressures (stressors) and vulnerable group of species, habitats, or ecosystem elements (receptors), based on a literature review.

The second section presents the methodology and results from a risk map, or cumulative impact index, analysis made primarily using GIS software and the open-source program EcoImpactMapper. The analysis uses spatial data for ecological stressors from offshore energy production methods (i.e., wind, tidal and wave energy) with ecological spatial data to estimate areas with high cumulative environmental impact from offshore energy production. Ecosystem sensitivity maps were also produced, showing areas where many ecosystem components susceptible to stressors from offshore energy production overlap. The analysis shows that some stressors caused by offshore energy production can have a spatially large radius of effect, although the highest cumulative impacts clearly occur at the immediate vicinity of the offshore installations.

The third section gives an overview of the most relevant policies, strategies, and directives for managing the environmental impacts of the development of offshore energy, namely the Offshore Renewable Energy Strategy, the Sustainable Blue Economy Strategy, the Habitats and Birds Directives, the Marine Strategy Framework Directive (MSFD), the Biodiversity Strategy, as well as the Maritime Spatial Planning (MSP) and Strategic Environmental Assessment Directives. The next section focusses on the synergies and trade-offs between these policies and strategies. While they are generally aligned with regard to the overarching aims of climate change mitigation, biodiversity protection and sustainable economic development, there are the objectives set out in the Offshore Renewable Energy and the Sustainable Blue Economy Strategies that have potential for conflict with the objective of marine environmental protection. Following the policy evaluation, the section contains a detailed review of the maritime spatial plans of Finland, Ireland, Latvia and Belgium, which are summarised in country-specific evaluations and a comparison table. The evaluations include information about the context in which the plans were created; the MSP process; the form of the final outcome; the treatment of climate and energy as well as marine environmental objectives; how potential trade-offs between these objectives are handled; as well as the implementation of the maritime spatial plans.

The main driver for this work is to support Member States and the EU in fulfilling the 2050 vision of the Offshore Renewable Energy Strategy whilst ensuring that the expansion of offshore energy does not imperil achievement of the Biodiversity Strategy or MSFD.

1 Introduction

The European Green Deal sets out the ambition to make Europe the first climate-neutral continent by 2050, while addressing other environmental challenges, boosting the economy, improving people's health and quality of life, and ensuring an inclusive and just transition (European Commission, 2019). As a step to achieving climate neutrality by 2050, the EU has committed to cutting emissions by 55 % by 2030. As part of the 'Fit for 55 package', the European Commission proposed to increase the target for renewables to 40 % by 2030 in June 2021 (European Commission, 2021b). Moreover, as a reaction to the Russian invasion of the Ukraine and its consequences in terms of energy supply, in May 2022 the European Commission adopted the REPower EU package which proposes to further increase the 2030 target for renewables from 40 % to 45 % and revise the Renewable Energy Directive to accelerate permitting (European Commision, 2022).

The proposals made under both packages are still being negotiated by the European Parliament and Council. Renewable energy will play a major role in Europe's energy future, including renewable energy produced offshore. The European Commission is supporting the development of the ocean energy sector through an array of activities: the Green Deal, the Energy Union and the Strategic Energy Technology Plan (SET-Plan) (Commission et al., 2019) in particular, as well as the Sustainable Blue Economy (IEA-OES, 2021). In addition, as part of the Green Deal, the Commission also adopted the EU Offshore Renewable Energy Strategy to give a strategic direction for the ambitious development and integration of offshore renewable energy by 2030 and 2050 (European Commission, 2020b).

The EU Sustainable Finance Taxonomy aims to classify economic activities as "sustainable", and therefore could also increase investment in such projects (Regulation (EU) 2020/852). The Technical Expert Group for the EU taxonomy for sustainable activities[1] defined a set of criteria to classify economic activities as making a substantial contribution to climate change mitigation or adaptation, while avoiding significant harm to the four other environmental objectives: sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention control, and protection and restoration of biodiversity and ecosystems. Among others, offshore renewable energy production is identified as contributing to climate change mitigation. However, the group also identified that offshore renewable energy production might affect other environmental objectives due to potential impacts (i) during construction, deployment, operation and maintenance of ocean energy installations; and (ii) pollution from lubricants and anti-fouling paints and emissions from maintenance and inspection vessels.

The Biodiversity Strategy to 2030 (European Commission, 2020c) recognises the positive climate impacts of offshore energy but at the same time recognises the potential for negative impacts on sensitive species and habitats. It calls for "win-win" solutions that deliver renewable energy whilst reducing the adverse impacts of human activities. Indeed, it calls for the full implementation of the Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC) to achieve Good Environmental Status (GES) in EU marine waters, and for an ecosystem-based approach to sustainably manage human impacts on the environment. The Biodiversity Strategy also refers to the Maritime Spatial Planning Directive (MSPD) (Directive 2014/89/EU), which requires an ecosystem-based approach, and the Strategic Environmental Assessments (Directive 2001/42/EC) to ensure that marine activities (including offshore energy) do not imperil the achievement of GES in Europe's seas. In addition, in June 2022 the European Commission adopted the proposal for a Nature Restoration Law (European Commission, 2022), as a key element of the EU Biodiversity Strategy, which aims to restore ecosystems, habitats and species across the EU's land and sea areas.

[1] https://ec.europa.eu/info/publications/sustainable-finance-technical-expert-group_en

Offshore renewable energy has huge potential to contribute to the global energy supply chain, including the production of energy from offshore wind, tidal range and tidal stream, ocean currents, waves, thermal and salinity gradients, as well as biomass (Borthwick, 2016). The importance of ocean (marine) energy and its applications for energy production is already recognised (Dincer et al., 2018). New offshore renewable energy industries aspire to energy production on a grand scale, partly mitigating climate change. However, as with any large-scale development in the marine environment, the expansion of offshore renewable energy comes with uncertainty about potential environmental impacts, most of which have not been adequately evaluated in part because many of the devices have yet to be deployed and tested (Boehlert and Gill, 2010). In other cases, the additive effect of environmental impacts produced by most developed technologies (i.e., wind energy production), may be trivial under current levels of development but could become ecologically significant as offshore installations increase as projected (Allison et al., 2008b). Due to that, environmental licensing procedures are precautionary and new industries must declare their detrimental impacts and provide mitigation measures. However, on-site environmental impacts are yet to be established (Hammar et al., 2017). Hence, there is a need to anticipate the development of ocean energy farms by assessing the potential environmental risks, to minimize the impacts and to identify the ecosystem elements that should be focused. In a new industry like offshore renewables, there may be interactions between devices and marine organisms or habitats that regulators or stakeholders perceive as risky. In many instances, this perception of risk is due to the high degree of uncertainty that results from a paucity of data collected in the ocean. Consequently, there is an urgent need to better understand these interactions and the potential risk that the negative impacts of offshore renewable energy may have on the marine environment. On the other hand, it is also important to consider the positive environmental impacts, such as reserve and reef effects of the area of deployment and device mooring structures.

The negative and positive impacts of offshore energy differ by habitat and ecosystem type. Determining the risk for each potential interaction between a component of an offshore renewable energy device or system (stressors) and vulnerable group of species, habitats, or ecosystem elements (receptors) represents a method by which the scientific community can provide advice to regulators, stakeholders, and the emerging offshore energy industry. In addition, mapping the potential environmental impacts of offshore renewable energy on vulnerable species and ecosystems provides valuable information for avoiding sensitive areas.

The main driver for this work is to support Member States and the EU in fulfilling the 2050 vision of the Offshore Renewable Energy Strategy whilst ensuring that the expansion of offshore energy does not imperil achievement of the Biodiversity Strategy or MSFD.

2 Present status

The environmental impacts produced by offshore energy farms may become ecologically significant as offshore installations increase as projected or commercial status (Allison et al., 2008a). Whilst these offshore renewable energy developments are typically characterised as environmentally desirable, there are some associated adverse impacts that deserve careful consideration. However, the renewable energy industry is in some ways still in its infancy and, as such, not all of its impacts are clear or fully assessed (Dolman et al., 2007). The energy production farms should be compatible with biodiversity and environmental protection objectives, and, therefore, compatible with the Sustainable Development Goals (SDGs) of the United Nations (i.e., SDG 14: Life Below Water) (Cormier and Elliott, 2017), the conservation of biodiversity (e.g., EU Biodiversity Strategy (European Commission, 2020c)), and with the conservation of vulnerable habitats and species (e.g., Bird (Directive 2009/147/EC) and Habitats (Council Directive 92/43/EEC) Directives).

The construction, operation and decommissioning phases of offshore renewable energy developments exert pressures on the marine environment (Bergström et al., 2014). The most important environmental effects include: habitat disturbance, degradation or loss, the creation of new habitats, noise, emission of vibration and electromagnetic fields (EMFs) (produced by electricity transmission cables) which changes the environmental conditions and affects the ecosystem components (Galparsoro et al., 2021; Galparsoro et al., 2022; Thomsen et al., 2016).

In the context of the 2030 Climate Target Plan[2], the Commission's proposal is to cut greenhouse gas emissions by at least 55 % by 2030 compared to 1990. According to the EU Offshore Renewable Energy Strategy, this would require less than 3 % of the European maritime space. Today's installed offshore wind capacity is 14.6 GW (European Commission, 2021b), and the Commission, through the Offshore Renewable Energy Strategy (European Commission, 2020), estimates to have an installed capacity of at least 60 GW of offshore wind and at least 1 GW of ocean energy by 2030, reaching 300 GW and 40 GW of installed capacity, respectively, by 2050. This means multiplying the capacity for offshore renewable energy by nearly 30 times and investment by up to EUR 800 billion.

Recent offshore wind projects have seen increasing capacity factors: the average power capacity of the turbines increased from 3.7 MW in 2015 to 6.3 MW in 2018. This is due to improvements on increasing turbine size, the floating applications, the infrastructure developments, and the digitalisation. Moreover, 93 % of the European installed offshore capacity in 2019 (which includes bottom-fixed wind turbines) was produced in Europe, representing 42 % of the global market. In contrast, floating offshore wind is an emerging technology.

In addition, the EU is the current leader in ocean energy, with 66 % and 44 % of patents in tidal and in wave energy, respectively, developed by EU companies and with 70 % of the global ocean energy capacity developed by EU27 based companies. However, tidal technologies can be considered as being at the pre-commercial stage, generating a significant amount of electricity (over 30 GWh since 2016)[3]. In the case of wave energy, most of the technological approaches are at technology readiness level (TRL) 6–7, and the sector has shown resilience during the past five years[4]. In this sense, despite advances in technology development and demonstration, significant cost reduction is still needed for tidal and wave energy technologies to exploit their potential and to become competitive with other renewable energy sources.

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[2] https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en

[3] Ofgem Renewable Energy Guarantees Origin Register. https://www.renewablesandchp.ofgem.gov.uk/

[4] European Commission (2017) Study on Lessons for Ocean Energy Development, EUR 27984.

Nowadays, according to the EMODnet platform (last update in July 2020 for ocean energy and in January 2021 for wind energy), there are many operational wave test sites established across Europe: in Belgium (1), United Kingdom (5), Ireland (1), Portugal (1), Spain (3), Denmark (2), Sweden (1), Norway (1) and France (1) (Table 1). However, there are very few operational wave farms: the Spanish Mutriku Wave Power Plant, connected to the grid in 2011 (reached a record of 2 GWh of cumulative energy generation); a wave farm installed in Netherlands (Slow Mill Sustainable Projects); as well as commercial wave energy farms in Finland (24 integrated WaveRoller units (IEA-OES, 2021)).

Table 1 Operational Wave Test Sites established across Europe (from EMODnet platform)

Test site	Country	Sea basin	Coast distance (m)	Start year	Capacity (kW)	Depth (m)	Area (km^2)	Grid connection
Ostend Wave Energy Test Site		Greater North Sea	0	2019				N/A
NBPB	D	Greater North Sea	164	1999	5	4	1.00	No
DanWEC	D	Greater North Sea	2,745	2016	500	15	5.00	Under consideration
SEM-REV	FR	Atlantic	10,461	2013	8,000	35	1.00	Yes
Galway Bay	IR	Atlantic	1,600	2006	8	21	0.37	Yes
Maren	NO	Atlantic	589	2009	1,000	50	4.00	Yes
Ocean Plug	PT	Atlantic	11,539	2010	250,000	30	320.00	Yes
PLOCAN test site	SP	Atlantic	2,601	2010	10,000	20	23.00	Yes
BIMEP	SP	Atlantic	3,225	2008	20,000	45	5.30	Yes
Punta Langosteira test site	SP	Atlantic	1,013	2017	20,000		1.89	N/A
Lysekil	SW	Greater North Sea	605	2004	30–1,000	25		Yes
Billia Croo	UK	Atlantic	1,513	2004	11,000	BE 50		Yes
Scapa Flow	UK	Greater North Sea	904	2011		21		No
WaveHub	UK	Atlantic	17,173	2010	48,000	48		Yes
FaBTest	UK	Atlantic	3,634	2012	3,000	25	2.80	No
Steady Towing test field site	UK	Atlantic	53			12		N/A

In relation to tidal energy, the operational tidal test sites established across Europe are in France (2), in the Netherlands (2) and in the United Kingdom (3) (Table 2). Moreover, there are very few operational tidal projects: Sabella D10 and La Rance Tidal Barrage in France; Kobold I in Italy; the Eastern Scheldt and BlueTec floating platform in the Netherlands; and Meygen Pentland Firth, Bluemull Sound, Shetland Tidal Array Phase 1 and Holyhead Deep in the United Kingdom. Apart from the La Rance Tidal Barrage project (with a maximum capacity of 240,000 kW), in operation since 1966, the rest of the projects do not exceed 500 kW.

Table 2 Operational Tidal Test Sites established across Europe (from EMODnet platform)

Test site	Country	Sea basin	Coast distance (m)	Start year	Capacity (kW)	Depth (m)	Area (km^2)	Grid connection
SEENEOH	FR	Atlantic	0	2014	250	8		Yes
Paimpol Bréhat	FR	Greater North Sea	9,214	2013	2,000	30		Yes
Dutch Marine Energy Centre – Den Oever site	NE	Greater North Sea	171	2013	1,000			Yes
Tidal Technology Center Grevelingendam	NE	Greater North Sea	0	2019	2,500		1	Yes
Fall of Warness	UK	Greater North Sea	1,301	2006	40,000	12		Yes
Shapinsay Sound	UK	Greater North Sea	1,012	2011		21		No
QUB tidal test site	UK	Atlantic	147	2004		10		N/A

Finally, in relation to offshore wind, the highest capacity production was installed in the United Kingdom and Germany (Table 3 and Table 4).

Table 3 Offshore wind polygons (consented area for offshore wind farms) established across Europe (from EMODnet platform)

Country	Turbines (nº)	Capacity (MW)	Mean distance to coast (km)	Total area (km^2)
Belgium				
Approved	188	1,140	37.2	21.3
Production	380	1,676	33.5	12.4
France				
Planned	428	2,940	11.0	94.4
Germany				
Approved	448	2,636	60.4	21.7
Planned	77	428	50.1	11.1
Production	1,118	5,499	47.0	30.7

Country	Turbines (nº)	Capacity (MW)	Mean distance to coast (km)	Total area (km²)
Netherlands				
Approved	171	1,406	30.3	68.6
Production	289	958	33.9	30.7
Spain				
Production	**16**	**0.3**	**0.3**	**0**
Test site	4	20	1.7	5.3
Sweden				
Approved	160	1,100	15.6	41
Production	5	12	0	0.2
United Kingdom				
Approved	1,270	15,424	40.9	186.8
Dismantled	7	12	48.3	4.5
Planned	964	12,287	19.8	178.3
Production	2,441	9,664	18.8	31.7

Table 4 Offshore wind points (sites and locations) established across Europe (from EMODnet platform)

Country	Turbines (nº)	Capacity (MW)	Mean distance to coast (km)
Belgium			
Production	1	6	43.9
Denmark			
Construction	72	605	25.8
Production	558	1,701	7.2
Finland			
Production	20	74	1.8
France			
Approved	12	89	15.2
Production	1	10	10.5
Germany			
Approved	187	1,611	32.0
Production	232	1,073	10.5
Ireland			
Approved	100	1,010	9.7
Production	10	25	6.1
Italy			
Approved	10	30	1.3
Netherlands			
Approved	229	1,802	22.9
Production	76	161	6.8

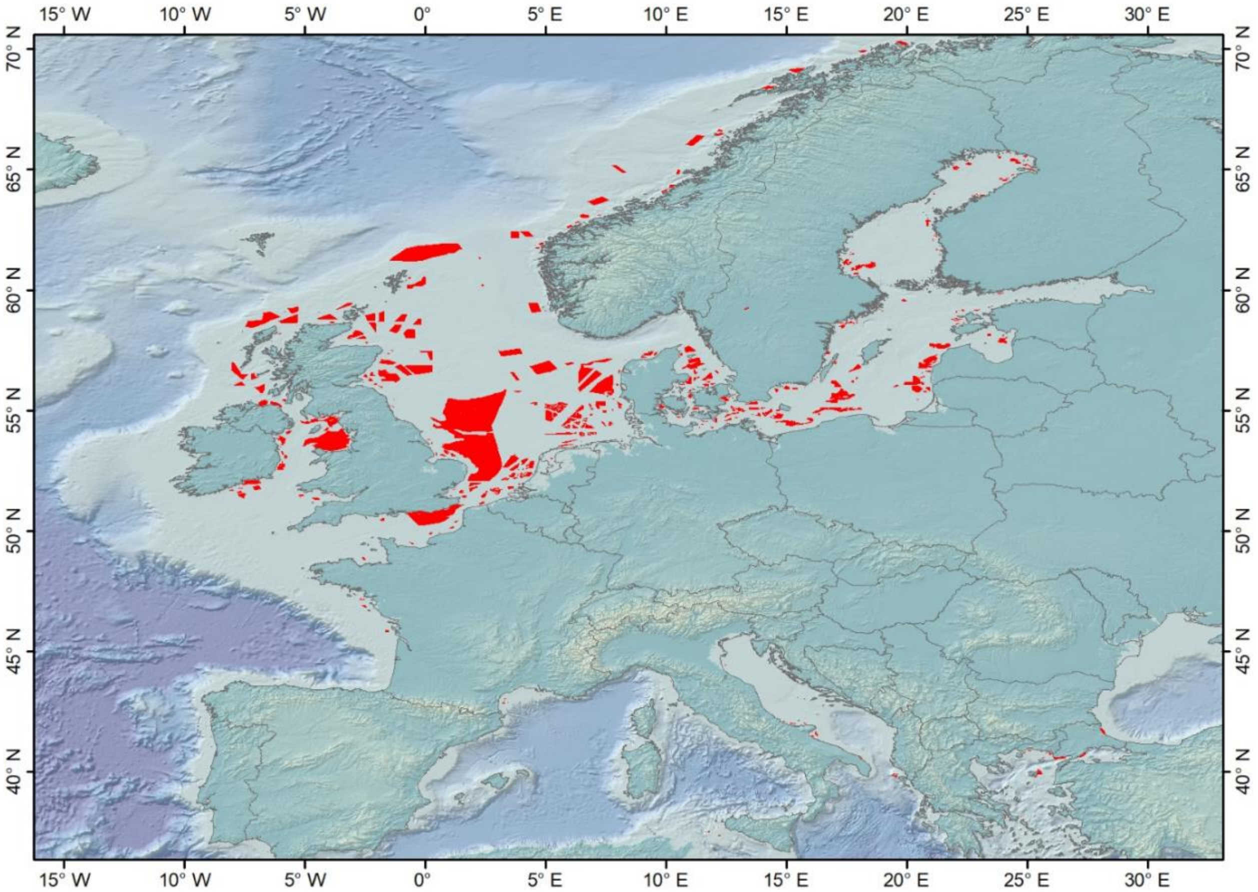
Country	Turbines (nº)	Capacity (MW)	Mean distance to coast (km)
Norway			
Approved	59	478	20.7
Production	5	22	6.3
Poland			
Approved	400	2,400	32.6
Portugal			
Production	3	25	12
Spain			
Production	7	60	2.1
Sweden			
Approved	198	1,160	49.3
Production	79	191	36.9
United Kingdom			
Approved	239	1,880	22.0
Production	250	1,042	12.4

Besides, in the European seas area, offshore wind farm data downloaded from the 4C Global Offshore Wind Farm Database in January 2020 lists 118 sites in early planning, 23 sites that have a consent application submitted, 42 sites with consent authorised, 10 sites in pre-construction, 8 sites under construction, 4 sites in partial generation, and 112 sites fully commissioned. The 4C data shows that fully commissioned wind farms occupy a total of 2,959 km^2, while the other categories (planned, etc.), occupy a total of 22,648 km^2, for a total of 25,607 km^2 (0.4 % of the EEZ). Furthermore, there are 103,684 km^2 declared as development zones, corresponding to 1.63 % of the EEZ) (Table 5 and Figure 1).

Table 5 Windfarms development status and characteristics derived from the 4C Global Offshore Wind Farm Database (January 2020)

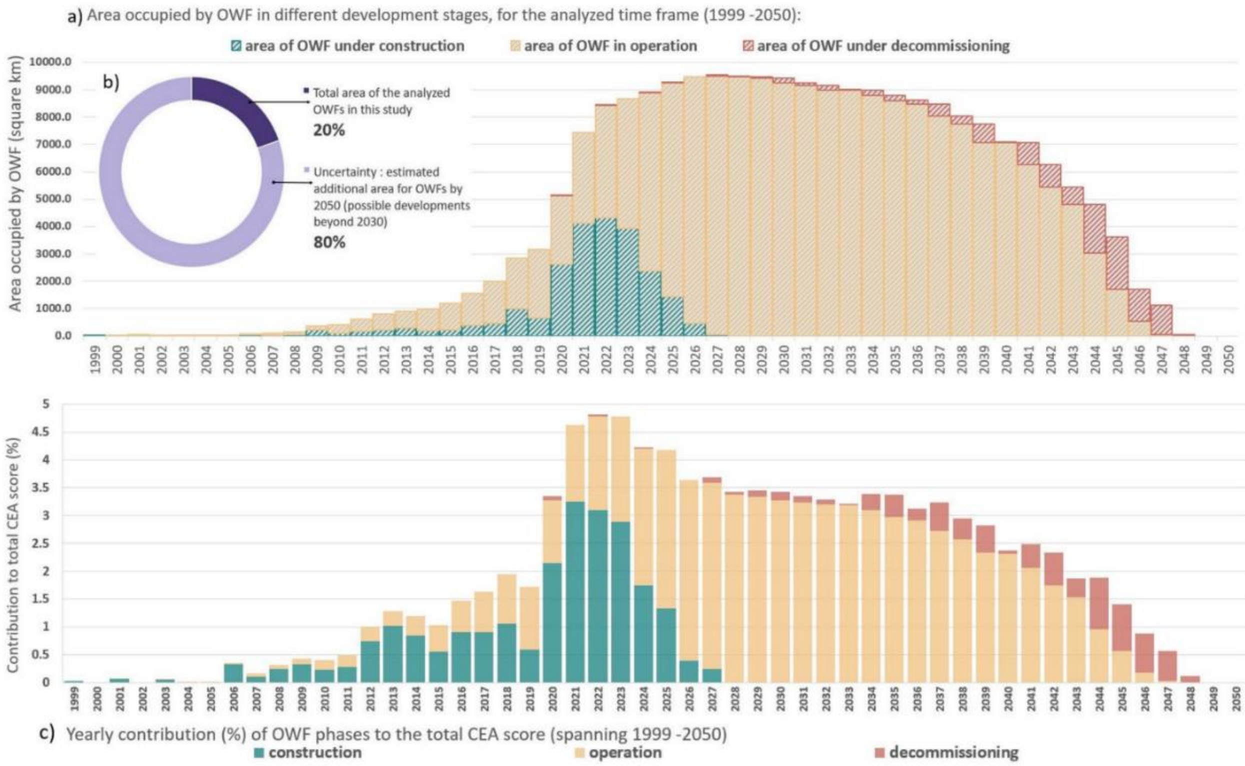
Status	Nº of farms	Area (km^2)	Exclusive Economic Zone (Continental Europe) (%)
Fully commissioned	112	2,959	0.05
Partial generation / under construction	4	627	0.01
Pre-construction	10	1,123	0.02
Under construction	8	484	0.01
Consent application submitted	23	3,415	0.05
Consent Authorised	42	4,910	0.08
Concept/Early Planning	118	12,089	0.19
Development zone	113	103,684	1.63

Figure 1: Offshore windfarms in continental Europe (source: 4C Global Offshore Wind Farm Database (January 2020))



According to Gușatu et al. (2021), the area occupied by the offshore wind farm (OWF) developments in the North Sea basin increased from 0.4 km^2 in 1999 to a total of 9,577 km^2 by 2027. The total area occupied by the studied OWFs represent approximately 1.8 % of the Greater North Sea ecoregion, except for Belgium, Kattegat, the English Channel, as well as estuaries and fjords (which were omitted from the study area) (Figure 2).

Figure 2: (a) An overview of the area required for the authorised OWFs (consent-authorised, authorised), those in the construction phases (pre-construction, under construction) or those in operation (fully commissioned) OWFs in the North Sea basin for the time frame 1999–2050; b) Estimated additional area for OWFs by 2050 (search areas, development areas, scoping areas for deployments beyond 2030) – Uncertainty; c) Yearly contribution (%) of OWF phases to the total cumulative effect assessment score (spanning 1990–2050). From Gușatu et al. (2021) (http://creativecommons.org/licenses/by/4.0)



3 Environmental Risks associated to offshore energy production

A Systematic Literature Review (SLR) (Mengist et al., 2020; Xiao and Watson, 2017) was conducted to obtain the most updated scientific evidence on environmental studies related to energy devices from peer-reviewed literature and selected technical reports. Firstly, the research objectives and questions were defined. Next, a pre-screening of terminologies was performed to guarantee that the search terms and strings were aligned with the most used scientific terminology (see Annex 1, Tables A1, A2, A3, A4 and A5.). The search terms were defined by combining the most frequently used terms. The literature search and manuscript selection workflow followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA Statement) (Moher et al., 2009). Finally, the quantitative and qualitative information from the selected literature was extracted, in terms of pressures addressed, ecosystem elements, effects reported and their magnitude. The reference list of pressures, ecosystem elements and indicators was adopted from the European MSFD (Directive 2008/56/EC).

The MSFD is the main European legislation covering all the environmental aspects to reach good environmental status and the terminology and concepts used are familiar to managers (Borja et al., 2010). A total of 16 potential pressures and 27 ecosystem elements according to the MSFD were considered. The MSFD was used because it covers a set of potential environmental pressures that could be exerted by human activities and all the ecosystem elements that could be affected by them. The pressures are classified into three themes: biological, physical and introduction to the environment of substances/litter/energy. In addition, a total of 27 ecosystem elements considered are divided into: (i) species, including marine cephalopods, fish, reptiles, birds and mammals; (ii) seabed and the water column (pelagic) habitats, as well as their associated biological communities (macroalgae, macroinvertebrates); and (iii) ecosystems, including physical and hydrological characteristics, chemical characteristics, biological structure, food webs, functions and processes. For each ecosystem element, its sensitivity to each individual pressure was adopted from Galparsoro et al. (2021).

In the subsequent sections, we provide the results obtained to gain insights into the environmental impacts produced by five offshore energy technologies to extract energy from wind, currents, waves, solar, and thermal conversion results.

3.1 Wind

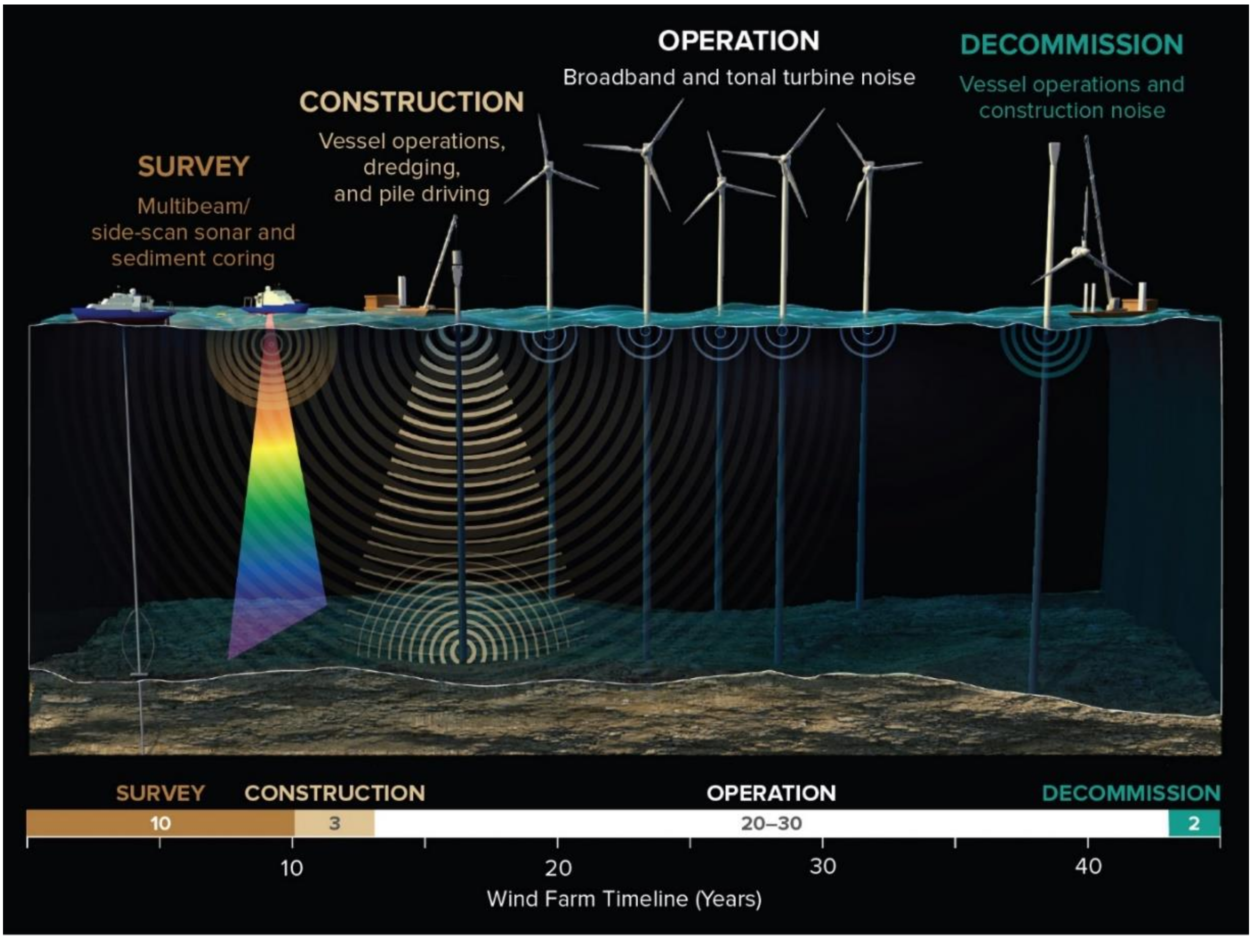
Offshore wind energy (OWE) is the most widespread type of offshore renewable energy (Dalla Longa et al., 2018; Ruiz et al., 2019).

The main pressures in relation to the offshore wind projects are the following, numbered by order of importance:

1. The increase of underwater noise and vibration which comes from two sources: firstly, during the construction activities and decommissioning (including piling and increased boat traffic for service), noise can be intensity generated but within a limited time period; secondly, during the operational phase of the offshore wind farm, where turbine machinery (and maintenance activities) creates a low-intensity, yet almost continuous, underwater noise (Tougaard et al., 2008).
2. The presence of offshore wind turbines and activities around a wind farm could present a barrier to the movement of certain species and the creation of a new habitat or reef effects.
3. Changes in the electromagnetic fields, during the operational phase, have a negative impact on specific fish which use electromagnetic signals in detecting prey (Gill, 2005). It also interferes with their capacity to orientate in relation to the geomagnetic fields, potentially changing their migration patterns (Gill et al., 2012).

The main ecosystem components affected by the aforementioned pressures are mammals, fish, seabirds and invertebrates which can be distinguished in a different range of intensity depending on the phase of the project (Figure 3). The most studied mammals are harbour porpoise (Phocoena phocoena) and seals.

Figure 3: Acoustic life of an offshore wind farm area, including during site surveys, construction, operation, and decommission. From Mooney et al. (2020) (Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/))



According to Bergström et al. (2014), research on the environmental effects of offshore wind farms has gone through a rapid maturation and learning process, with significant knowledge being developed within previous years.

3.1.1 Prior to construction

The increase of the underwater noise, proved with active airguns, showed a decrease in porpoise echolocation signals of up to 8–12 km, indicating temporary displacement of porpoises or a change in echolocation behaviour (Sarnocińska et al., 2020). However, no general displacement of harbour porpoises away from the seismic survey area could be detected when comparing to reference stations 15 km away from any seismic activity (Sarnocińska et al., 2020). Studies, carried out prior to the construction phase, have produced evidence that underwater noise has the potential to temporarily affect foraging efficiency in porpoises (Sarnocińska et al., 2020). It is important to mention that the effect of seismic surveys conducted prior to construction on harbour porpoise behaviour was smaller than what has been found for piledriving during the construction phase (Sarnocińska et al., 2020).

3.1.2 Construction

The nature of noise generated during the construction of offshore wind farms is similar to noise caused by other offshore activities such as oil and gas extraction and construction of piers and bridges (Degraer et al., 2019). This noise is related to percussive pile driving of monopile foundations which has considerable intensity, with peak levels well above 200 dB re 1 μPa close to the piling site (Tougaard et al., 2008).

However, although the sounds are audible to fish and marine mammals at large distances (tens of kilometres or more) and considerable energy is present in the ultrasonic range (where certain animals hearing is best, i.e., marine mammals), the impact of the pile-driving noise is unclear (Tougaard et al., 2008). Most energy is present at very low frequencies and the duration of the sounds is small (about 0.1 s). In this sense, sound exposure levels do not exceed levels known to produce temporary or permanent damage to marine mammal hearing, except perhaps within a few hundred metres from the piling site (Bailey et al., 2010; Haelters et al., 2014).

The monitoring program on harbour porpoises at Horns Rev Offshore Wind Farm in the Danish North Sea (1999–2006), which covers time before, during and after construction of the wind farm, indicated a weak negative general effect from the construction and semi-operation on porpoises, with more specific effects linked to pile driving activities (Brandt et al., 2009).

In general, there is evidence that there are negative effects on mammals (Thompson et al., 2010) which can vary depending on a range of local factors such as density of animals, importance of the area to the animals, sound transmission characteristics, and possibility for the animals to withdraw temporarily to other areas during piling (Tougaard et al., 2008). Modifications in mammals behaviour (displacements) have been demonstrated at distances of up to 15 km from the piling site (Carstensen et al. 2006; Tougaard et al. 2006), beyond 20 km for harbour porpoises (*Phocoena phocoena*) (Haelters et al., 2014; Tougaard et al., 2009a) and up to 50 km away for bottlenose dolphins (Bailey et al., 2010). Graham et al. (2019) also showed that distance proved as good a predictor of responses as audiogram-weighted received levels, assuming total displacement for harbour porpoise within 26 km of pile driving (van Beest et al., 2018). Kastelein et al. (2013) observed that wild porpoises moved tens of kilometres away from offshore pile driving locations, concluding that these response distances can vary with context, the sounds' source level, parameters influencing sound propagation, and background noise levels (Pine et al., 2019).

Auditory injury on bottlenose dolphins would have occurred within 100 m of the pile-driving (Bailey et al., 2010), although at distances of up to 2 km on porpoises (Brandt et al., 2009). A sudden decrease in the length of effect was found with porpoise detectors (POD-positions) south of the reef at distances of at least 10 km (Tougaard et al., 2012). However, porpoise density recovered in the area within one to two days after construction was finished (Brandt et al., 2009). Indirectly, harbour porpoises' (*Phocoena phocoena*) habitat-use changed substantially, with the porpoises leaving the construction area of the offshore wind farm (Carstensen et al., 2006) and even affecting on porpoise abundance in the Rødsand area (Tougaard et al., 2006a). However, after a partial displacement during construction, due to the affection of their echolocation behaviour, there is a return to baseline activity in the second year of operation, indicating that the acoustic behaviour of porpoises in the wind farm area returned to baseline levels (Tougaard et al., 2006b). For instance, the echolocation activity inside the wind farm (Nysted Offshore Wind Farm) was gradually increasing (from 11 % to 29 % of the baseline level) since the construction of the wind farm, possibly due to habituation of the porpoises to the wind farm or enrichment of the environment due to reduced fishing and to artificial reef effects (Teilmann and Carstensen, 2012).

Continuing with the displacement, the presence of Hector's dolphin (*Cephalorhynchus hectori*) decreased at the detector closest to the piling but increased at the mid-harbour detector (Brandt et al., 2016). Finer-grained analyses showed that close to the piling operation, detections decreased with increasing sound exposure level, that longer piling events were associated with longer reductions in detections, and that effects were long-lasting – detection rates took up to 83 h to return to pre-piling levels (Leunissen and Rayment, 2019).

Lower densities of harbour porpoises were also documented during the construction period of the wind farm 'alpha ventus' in the German North Sea in 2009. The spatial distribution pattern recorded on two aerial surveys three weeks before and exactly during pile-driving, points towards a strong avoidance response within 20 km distance of the noise source (Dähne et al., 2013a). Generalized additive modelling of Static Acoustic Monitoring (SAM) data showed a negative impact of pile-driving on relative porpoise detection rates at eight positions at distances less than 10.8 km (Dähne et al., 2013a). Increased detection rates were found at two positions at 25 and 50 km distance suggesting that porpoises were displaced towards these positions. A pile-driving related behavioural reaction could thus be detected using SAM at a much larger distance than a pure avoidance radius would suggest (Dähne et al., 2013b).

An exception from this observed displacement was during the construction period in spring and summer in 2002 in Nysted Offshore Wind Farm, where very few seals were observed inside and in the immediate surroundings of the wind farm (Tougaard et al., 2006c). Moreover, the number of porpoise detections by the SAM units increased during the pile driving activities toward the end of the construction period. Habituation, ecological parameters, and external effects are considered as potential reasons for this increased presence of harbour porpoises in the vicinity of the construction site (Lucke et al., 2011). Finally, construction did not lead to a visibly increased mortality of harbour porpoises (Leopold and Camphuysen, 2008). The problem is that these are northern species and there is not much information on other species.

In the same way, the measured frequency range directly overlaps the auditory bandwidth of many fish and invertebrate species across multiple lifestyles (e.g., pelagic, epibenthic, demersal), including cod, salmon, black sea bass, flatfish, and squid (Mooney et al., 2020). Moreover, many injury types were observed in laboratory experiments, when hybrid striped white bass (*Morone chrysops/saxatilis*) in large and small size classes were exposed to simulated pile-driving signals using a high intensity-controlled impedance fluid-filled wave tube, increasing with fish size (Casper et al., 2013). However, these findings cannot be extrapolated to fish larvae in general, as interspecific differences in vulnerability to sound exposure may occur, they do indicate that previous assumptions and criteria may need to be revised (Bolle et al., 2012). Moreover, fish close to piling activity, the impact of strong impulsive sound can lead to barotraumas and hair cell damage (De Backer et al., 2014b; Halvorsen et al., 2012a; Halvorsen et al., 2012b). In relation to possible stress, physiological changes, Debrusschere et al. (2016) recorded a decreased oxygen consumption rate (50 %) in young sea bass during piling activities. Contrary to this, caged northern anchovy (*Engraulis mordax*) and common sole larvae (*Solea solea*) showed no increase in mortality or pathology compared to control groups when exposed to four minutes of pile driving and simulated pile-driving sound levels (Abbott et al., 2005; Bolle et al., 2012). This could be due to fishes without swim bladders, such as sole, possibly being less susceptible to injury (Mooney et al., 2020). Furthermore, intense, impulsive sounds have been documented to affect primary (cortisol) and secondary responses (adenylate, glucose, lactate) in European seabass (*Dicentrarchus labrax*) at considerable distances from the sound source (2 km) (Mooney et al., 2020).

However, there is a range of reactions about the affection to fish behaviour (displacements) during the construction phase. First field relevant experimental proof that piledriving sound affects the behaviour of cod and sole was carried out by Mueller-Blenkle et al. (2010). Moreover, there was evidence of potential displacement from the exposure wharf that coincided with the start of pile driving observed for two out of four grey snappers, along with a decrease in daytime residency for a subset of this species with high site fidelity prior to the event (Mueller-Blenkle et al., 2010). For example, Boyle and New (2018) suggested a range of up to 15.4 km within which fish could be disturbed by the sound of piling. Contrary to this, no significant decrease in sheepshead daytime residency was observed during pile-driving within the central portion of the wharf and area of highest sound exposure, and no major indicators of displacement from the exposure wharf with the onset of pile-driving were observed (Nehls et al., 2016). Results indicate that snapper may be more likely to depart an area of pile driving disturbance more readily than sheepshead, but were less at risk for behavioural impact given the lower site fidelity of this species (Iafrate et al., 2016). The affection to fish behaviour (displacements) due to the pile-driving noise during construction (very high sound pressure levels) could potentially prevent fish from reaching breeding or spawning sites, finding food, and acoustically locating mates that could result in long-term effects on reproduction and population parameters. There is also the possibility that avoidance reactions might displace fish away from potential fishing grounds that could lead to reduced catches (Thomsen et al., 2012). European seabass increased ventilation rates and/or oxygen uptake when exposed to replayed and in situ pile-driving noise, whereas European plaice (*Pleuronectes platessa*) showed no significant changes (Bruintjes et al., 2016; Poulton et al., 2017). Contrary to this, sheepshead (*Archosargus probatocephalus*) showed no significant decrease in daytime residency or displacement during 35 days of pile-driving (Iafrate et al., 2016). In the same way, field studies of flatfish in US waters showed no effects from OWF construction pile-driving or cable laying (Wilber et al., 2018).

Finally, the knowledge about the impact of the impulsive sound on invertebrates remains poor (Edmonds et al., 2016; Roberts and Elliott, 2017). It was reported that noise associated with pile-driving caused short-term behavioural responses in marine invertebrates within a distance of approximately 10 m from the source of the disturbance (Brand and Wilson, 1996; McCauley, 1994). Solan et al. (2016) registered behaviour changes in *Nephrops norvegicus* associated with bio-irrigation. Changes in feeding of the longfin squid, *Doryteuthis pealeii*, with reduction in capture rates and higher failed predation events, increasing inking, jetting, startle responses and altering body pattern (visual communication), associated with the pile-driving noise from OWF construction have been also reported (Jones et al., 2019; Jones et al., 2020). From experimental evidence, when exposed to sediment vibrations, blue mussel (*Mytilus edulis*) exhibit changes in valve gape and oxygen demand, reducing respiration rates and impair the ability to remove wastes (Roberts et al., 2015). Solé et al. (2017) observed statocyst injury in cephalopods, proportional to the distance from source, showing clear escape behaviours when presented with intense and low frequency (< 1,000 Hz) impulsive sounds (Mooney et al., 2016).

3.1.3 Operation

Underwater noise from the turbines appears to be one of the main potential negative sources of impact of practical relevance which is generated in the machinery in the nacelle and is transmitted through the tower to the foundation, from which it is radiated into the water (Tougaard et al., 2008). The intensity of this underwater noise is low (in the range of 100–120 dB re 1 µPa), with energy concentrated at low frequencies (below a few kilohertz) (Madsen et al., 2005).

Despite the low intensity, the noise may contribute significantly to the local noise level because it is present almost continuously during the lifetime of the wind farm (Tougaard et al., 2008). Under favourable conditions (low background noise, low transmission loss), the sound may be audible to seals, odontocetes, and fish at distances up to some kilometres from the turbines (Tougaard et al., 2008). However, due to the low intensity and low frequencies of the noise during the operation of a wind farm, no negative effects were observed on mammals (Tougaard et al., 2006b). As a consequence, the impact on marine mammals (seals and porpoises) is considered marginal, this is, masking is irrelevant and behavioural reactions, if any, are likely to be found only in the close vicinity of the foundation (a few hundred metres or less) (Tougaard et al., 2009b). Direct damage to the hearing of marine mammals is also unlikely because noise intensities, even right at the foundation, are unlikely to ever exceed known thresholds for inflicting damage (Tougaard et al., 2008).

Moreover, it has been reported that the occurrence of porpoises inside the operational wind farm increased, changing in distribution significantly between the reference areas and the impact area. The reasons of this apparent preference for the wind farm area are not clear. Two possible causes are discussed: an increased food availability inside the wind farm (reef effect) and/or the absence of vessels/fisheries in an otherwise heavily trafficked part of the North Sea (sheltering effect) (Scheidat et al., 2011). The increase of harbour porpoise abundance inside the operational wind farm is in contrast to results from other offshore wind farms meaning that results from one wind farm are not necessarily transferable or valid for another wind farm located in a different area (Scheidat et al., 2009).

In relation to negative effects on fish, a significant impact is unlikely but cannot be ruled out (Tougaard et al., 2008). The current knowledge about wind energy impacts on fish presents large uncertainties (Boesen and Kjaer, 2005; Thomsen et al., 2006). The low frequency noise may be audible to many fish species. Studies on goldfish, cod and Atlantic salmon indicated that they could detect offshore turbines from 0.4 to 25 km at wind speeds of 8 to 13 m s^{-1} (Tougaard et al., 2009c). The detection distance depends on the size and numbers of wind turbines, the hearing organs of the fish, the water depth and bottom substrate.

The fish produce a variety of sound for communication that may be interfered with by the noise from turbines. This could decrease the effective range of communication by fish. However, the extent of this interference and its influence on the behaviour and fitness of fish is not known and additional studies are needed. There is no evidence that turbines damage the hearing of fish, even at short distances of a few metres. The avoidance distance is about 4 m, but only at high wind speeds of 13 m s^{-1}, masking communication and orientation signals, but not producing serious damage to hearing organs and producing strong avoidance reactions (Wahlberg and Westerberg, 2005; Greenpeace, 2005).

Andersson et al. (2009) observed differences in fish distribution, with higher abundances and species numbers of fish on the pillars compared to the surrounding soft bottom habitats. Two species (*Gobiusculus flavescens* and *Ctenolabrus rupestris*) were attracted to the pillars, indicating a reef effect. However, it was depending on the species, because the bottom-dwelling gobies, *Pomatoschistus* spp. did not show such preferences. Benthic and fish aggregation inside an offshore wind farm was also observed by (Raoux et al., 2017). In the same way Stenberg et al. (2015) observed that fish abundance increased slightly in the OWF area (*Merlangius merlangus*, dab *Limanda limanda* and sandeels *Ammodytidae spp*) but declined in the control area 6 km away. None of the key fish species or functional fish groups showed signs of negative long-term effects due to the OWF. Moreover, species diversity was significantly higher close to the turbines. Overall, these results indicate that the artificial reef structures were large enough to attract fish species with a preference for rocky habitats, but not large enough to have adverse negative effects on species inhabiting the original sand bottom between the turbines. According to Methratta and Dardick (2019), the overall effect size was positive and significantly different from zero, indicating greater abundance of fish inside of wind farms. Contrary to this, it is not known whether operational auditory masking occurs and influences fish survival and reproduction within a wind farm area (Mooney et al., 2016).

Moreover, according to Berkel et al. (2020) hydrodynamic impacts of OWFs are transferred to the ocean via two routes: (1) modification of the wind field (showing a reduction of wind speed by 5–25 % inside the wind wake, 5 km downwind of a wind farm) (Lampert et al., 2020) and, consequently, alterations on the wave and current fields due to the power extraction from the wind, and (2) turbines' effects on ocean currents and consequently on turbulence, mixing, and vertical stratification. Berkel et al. (2020) concluded that it is not possible to relate changing on fish sampling density with local OWF-induced hydrodynamic impacts (sediment resuspension or sedimentation, temperature, and nutrient transport), even less on a regional scale.

Fouling assemblages on the vertical foundation surfaces and on the seabed just below differed from those on the seabed further away by having higher coverage of blue mussel (*Mytilus edulis*) and less algal growth (Andersson et al., 2010a). These results suggest that the introduction of offshore wind turbines in marine waters could have a positive effect on fish numbers and the presence of sessile invertebrates (Andersson et al., 2010b). Furthermore, turbine frequency components seem important: wind farm turbine noise delaying metamorphosis of crab megalopae (larval stage), while no effects were seen in natural soundscape playbacks at the same level (Pine et al., 2012).

During the operational phase, the electric currents in submarine cables induce changes in the electromagnetic fields and there is a concern of how they may influence fishes and invertebrates (Sigray and Westerberg, 2008). Laboratory analysis on several benthic organisms exposed to static magnetic fields of 3.7 mT for several weeks showed no differences in survival between experimental and control populations. Similarly, mussels living under these static magnetic field conditions for three months during the reproductive period did not present significant differences with the control group, concluding that static magnetic fields of power cable transmissions did not seem to influence the orientation, movement or physiology of the tested benthic organisms (Köller et al., 2006). Moreover, the Greenpeace study mentioned that the electromagnetic fields of submarine cables have no significant impacts on the marine environment (Greenpeace, 2005).

Contrary to this, the results from the study carried out on Nysted (Denmark) about the influence of electromagnetic fields on fish were not conclusive. Some impacts on fish behaviour were recorded, but it was not possible to establish any correlation, concluding that additional research is needed (DEA, 2006; Köller et al., 2006). More recent studies have shown behavioural effects on Crustacea when exposed to magnetic fields (Hendrick et al., 2016; Hutchison et al., 2018; Scott et al., 2018; Woodruff et al., 2013; Woodruff et al., 2012) and responses by some fish species but not others (Hutchison et al., 2020; Woodruff et al., 2013; Woodruff et al., 2012).

In relation to the changes in the behaviour (including movement and migration) on seabirds, the impact depends on the presence of specific species and on their vulnerability. Post-construction studies of 20 OWFs in European waters evidenced the displacement or attraction of 33 different seabird species. Divers and northern gannets showed consistent and strong avoidance behaviour/displacement, and this may also be the case for great crested grebe and northern fulmar. Long-tailed duck, common scoter, Manx shearwater, razorbill, common guillemot, little gull and sandwich tern showed less consistent displacement from OWFs (Dierschke et al., 2016). Several gull species and red-breasted merganser showed weak attraction, while great cormorant and European shag showed strong attraction to OWFs (Dierschke et al., 2016). Other species showed little response. Displacement seems mainly to be due to bird responses to OWF structures and appears stronger when turbines are rotating but could in part be due to boat traffic to and from OWFs (Dierschke et al., 2016). Contrary to this, the attraction of cormorants relates at least in part to their use of structures for roosting and for drying plumage, but increases in food availability at OWFs appears to be an important influence for several species (Dierschke et al., 2016). Desholm and Kahlert (2005) confirmed a low impact of the operational turbines on seabirds, this is, less than 1 % of the ducks and geese migrated close enough to the turbines, avoiding any risk of collision. Day-flying waterbirds, such as eider *Somateria mollissima* modified their flight trajectories at an average distance of 3 km from the Nysted offshore wind farm (Denmark) during daylight (less by night) compared to pre-construction flight patterns (Desholm and Kahlert, 2005), although most modification occurred within 1 km (and less at night) (Kahlert et al., 2004). However, observations from Mendel et al. (2019) suggested a major displacement effect from newly constructed windfarms out to at least 16 km, and bird reduction densities of more than 60 % in an area within 10 km of the turbines. At meso-scale, Vanermen et al. (2020) observed a significant decrease in the number of flying lesser black-backed gulls (*Larus fuscus*) from up to a distance of at least 2,000 m towards the middle of the wind farm. At micro-scale, birds respond to the proximity of the blades and the monopile within 10 m (Skov et al., 2018). In contrast, about 30 % of the measured birds (mainly large gulls and to some extent cormorants, *Phalacrocorax carbo*) flew within the rotor-swept area, meaning a moderate impact (Borkenhagen et al., 2017). In another study, terns did not avoid the farm and used it for foraging, while gannets, scoters, auks, guillemots and divers showed strong avoidance behaviour in their flight pattern in the vicinity of the farm (Lindeboom et al., 2011). Welcker and Nehls (2016), confirmed a high impact with significant displacement of 5 species (75−92 % lower abundance inside compared to outside the wind farm) and for 3 species the response distance to the outermost turbines was estimated to exceed 1 km. In another study, 63 % of common guillemots (*Uria aalge*) reduced the resource selection of the OWF areas compared with the surroundings. Furthermore, OWF avoidance was increased to 75 % when the turbine blades were rotating (Peschko et al., 2020). Vanermen et al. (2015) demonstrated that northern gannet (*Morus bassanus*), common guillemot (*Uria aalge*) and razorbill (*Alca torda*) avoided the wind farm area, and decreased in abundance with 85 %, 71 %, and 64 %, respectively. According to Fox and Petersen (2019), because of the aforementioned high levels of avoidance by many larger-bodied seabirds to offshore wind installations, the experience has generally been that collision rates are low.

It is known that the artificial reef and new habitat formed on the foundations and scour protection potentially benefit some mammals in the area through an increase in food availability (Tougaard et al., 2006c). Glarou et al. (2020) revealed frequent increases in abundances of species associated with hard substrata after the establishment of artificial structures in the marine environment. Wilhelmsson et al. (2006) confirmed the positive local effects on commercial species, this is, the offshore windfarms contribute as fish aggregation devices for small demersal fish but finding a lower diversity of demersal fish around the turbine foundations compared to the seabed 1 to 20 m away. In this sense, Bach et al. (2013) observed that the attraction of fish to the offshore structures could function as feeding stations for the harbour porpoises. Moreover, changes in hydrographic conditions at the platform locations could influence the availability of prey in the area, influencing the activity level of the harbour porpoises. Haan et al. (2013) showed that the creation of new habitat (new hard substrate habitats) attracted species such as cod, edible crab, bib, bullrout, sea scorpion and common dragonet. Apart from the mentioned mammal and fish attraction, OWFs seem to be particularly favourable for the growth of mussels (Bergström et al., 2014). Mussel debris can cause a moderate organic enrichment, affecting the benthic community and causing quite severe reductions in sediment oxygenation, but only on very local scales depending on the hydrographic setting of the artificial structure (Wilding, 2014). Floeter et al. (2017) also evidenced increased vertical mixing (reduced stratification during the summer) in the North Sea due to associated epifauna (filter-feeders) on the artificial structures and subsequent nutrient transport enabling primary production throughout the water column. Moreover, Friedlander et al. (2014) suggested that species that are restricted in their distribution range might use these new artificial structures as new pathways of invasion by the steppingstone's hypothesis for their spread. However, there is now evidence to support this hypothesis both from established wind farms (Coolen et al., 2016; Coolen et al., 2018) and other marine renewable energy devices (Nall et al., 2017).

Contrary to this, OWFs cause alterations in local ecosystems by adding artificial hard substrates into naturally soft-bottom areas, changing the seafloor habitats (Mavraki et al., 2020) (Figure 4. However, trophic plasticity appears an important mechanism for the co-existence of invertebrate species along the depth gradient of an offshore wind turbine (Mavraki et al., 2020). Based on wind turbine in Belgium, in the immediate vicinity of an offshore gravity, changes of the sedimentary characteristics (grain size distributions and organic matter), affecting the associated soft sediment macrofauna, increasing significatively in abundance and species richness (Coates et al., 2014): sediments directly around the turbine classified as medium sands (250–500 µm); finer grain size observed close to the turbine (15–50 m) in comparison to stations positioned further away gradients (100–200 m) (Figure 6). Sedimentation changes are linked to the reduction in current speed around the foundation.

In relation with temporal scale changes, early succession was observed in epifauna at the North Sea wind farms, with high turn-over initially followed by only seasonal patterns after 1–1/2 years (De Mesel et al., 2015). It is well known that after 2–4 years, the community changes from initial colonisers (e.g., tubeworms and hydroids) to secondary colonisers (e.g., anemones) which stay dominant up to 11 years after oil platform construction (Whomersley and Picken, 2003). De Backer et al. (2014b) identified epibenthos and fish assemblages stabilised within < 6 years.

Finally, the increased levels of turbidity caused by offshore wind devices (up to ± 15 mg SPM. l^{-1} (Baeye and Fettweis, 2015) can be in wakes of 30–150 km wide and several km in length (Vanhellemont and Ruddick, 2014), reducing the offshore primary production within the nutrient- and light-limitation context. A synthesis of the main pressures, effects and spatial effect magnitude produced by wind farms on different ecosystem elements depending on the phase of the project are provided in Table 6.

Figure 4: Offshore wind farm structures provide habitat for invertebrate organisms that foul the foundation along the depth gradient and attract predator fish, seabirds, and marine mammals. Illustration by Hendrik Gheerardyn. From Degraer et al. (2020). Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0)

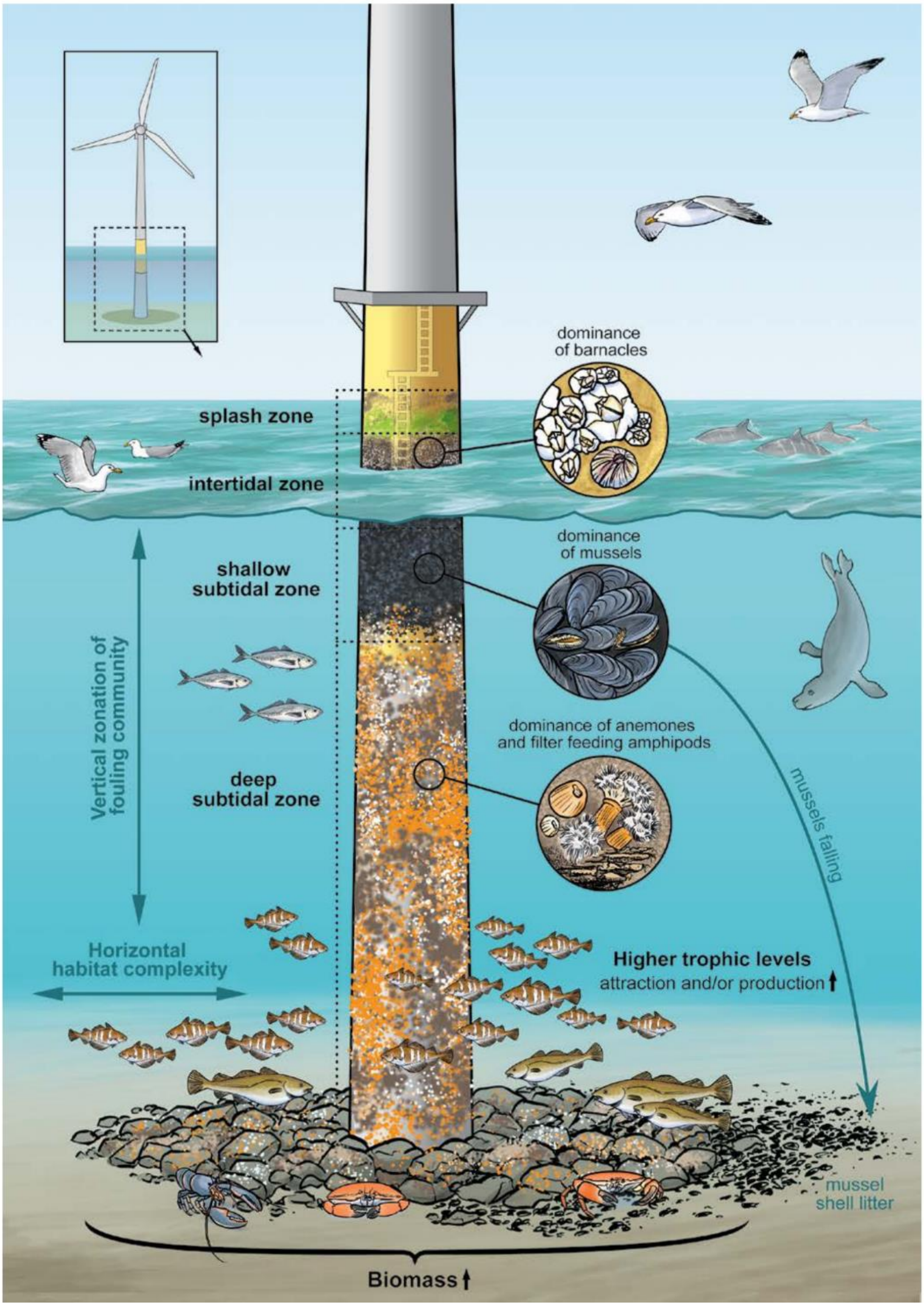


Figure 5: While the offshore wind farm artificial reef effect is particularly detectable at the scale of the wind turbine and the wind farm (small-scale effects), some effects extend well beyond the scale of a single such operation (large-scale effects) as exemplified by the increased connectivity of hard substrate species (the steppingstone effect). Illustration by Hendrik Gheerardyn. From Degraer et al. (2020). Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0)

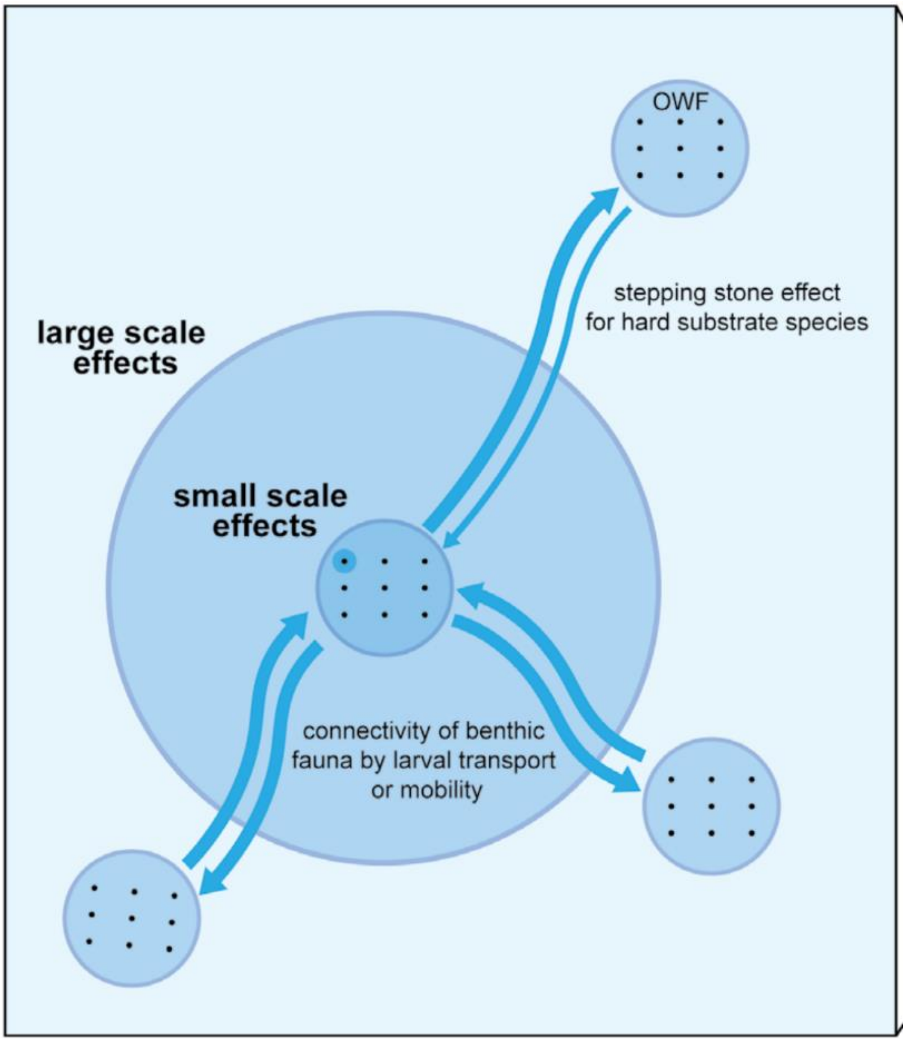


Table 6 Synthesis of the main pressures, effects and spatial effect magnitude produced by wind farms on different ecosystem elements depending on the phase of the project. Note that the type of foundation of the wind turbine is not considered.

Pressure type	Ecosystem element	Effect type	Impact magnitude	Spatial extent	Phase	Reference
Noise	Mammals	Behaviour (displacement/aggregation)	High	8–12 km	Prior to construction	Sarnocińska et al. (2020)
			High	26–50 km	Construction	Haelters et al. (2014); Bailey et al. (2010)
			Low	Close vicinity of the foundation (a few hundred metres or less)	Operational	Tougaard et al. (2009c)
		Auditory injury	High	2 km	Construction	Brandt et al. (2009)
	Fish	Physiological	High	2 km	Construction	Mooney et al. (2020)
		Behaviour (displacement/aggregation)	High	15 km	Construction	Boyle and New (2018)
			High	Close vicinity of the foundation (4 m)	Operational	Wahlberg and Westerberg (2005)
		Auditory injury	Moderate	Around the pilling	Construction	De Backer et al. (2014a) Halvorsen et al. (2012a) Halvorsen et al. (2012b)
	Invertebrates	Behaviour	Moderate	10 m	Construction	Solan et al. (2016); Jones et al. (2019); Jones et al. (2020); Roberts et al. (2015)

Pressure type	Ecosystem element	Effect type	Impact magnitude	Spatial extent	Phase	Reference
Electromagnetic field	Fish	Behaviour	Low	Around the cable	Operational	Hutchison et al. (2020)
	Invertebrates	Behaviour	Low	Around the cable	Operational	Sigray and Westerberg (2008)
New habitat/ Artificial reef effect	Benthic habitats	Habitat heterogeneity	Moderate	Inside the wind farm	Operational	Mavraki et al. (2020)
	Invertebrates	Mortality/alteration through #sediment removal	High	Inside the wind farm	Construction	Dannheim et al., 2019
		Colonisation by non-indigenous species	Moderate	From shipping, ballast water, translocated equipment	Operational	Degraer et al. (2020); Dannheim et al. (2019a)
		Increased hard-substrate fauna (increasing moderate organic enrichment, severe reductions in sediment oxygenation)	Moderate	Inside the wind farm	Operational	Dannheim et al. (2019b)
		Altered food availability	High	Inside the wind farm	Operational	Dannheim et al. (2019b)
	Fish	Aggregation	Moderate	Inside the wind farm	Operational	Stenberg et al., 2015; Raoux et al. (2017)

Pressure type	Ecosystem element	Effect type	Impact magnitude	Spatial extent	Phase	Reference
Barrier effect	Birds	Injury/mortality	Low-High (?)	Local	Operational	Brabant et al. (2015); Fox and Petersen (2019)
		Behaviour (displacement)	High	< 1–3 – 16 km	Operational	Mendel et al. (2019)
	Wind	Radius of deformation	Moderate (?)	5–20 km	Operational	van Berkel et al. (2020)
	Hydrodynamic	Alteration seawater's vertical density stratification	Moderate?	Inside the wind farm	Operational	Floeter et al. (2017)
		Changes of the sedimentary characteristics	High	100–200 m	Operational	Coates et al. (2014)
Mechanical sea floor disturbance	Invertebrates	Soft sediment macrobenthic biomass/abundance/species richness	Moderate	15–50 m	Operational	Coates et al. (2014)
	Phytoplankton	Primary production reduction (turbidity/suspended matter increased and light penetration reduction)	High	10 km	Operational	Vanhellemont and Ruddick (2014)

3.2. Ocean currents

The kinetic energy available in currents can be converted to electricity using relatively mature turbine technologies. The exploitable marine current power with present technologies is estimated at about 75 GW in the world and 11 GW in Europe (Zhou et al., 2017). Basically, there are two ways of harnessing power from marine tidal resources: either by building a tidal barrage across an estuary or a bay, or by extracting kinetic energy directly from flowing tidal currents (Zhou et al., 2017). The main drawback of the barrage solution is that large barrage system could change the hydrology and may have negative impacts on the local ecosystem (Pelc and Fujita, 2002).

According to Copping et al. (2015), eight stressors can be recognized that apply: physical presence of the turbines (static or dynamic), increase of noise, changes in EMFs, chemical leaching, energy removal from flowing water, changes in flow regime (wake or downstream interactions) and accidents or disasters. These stressors have a direct/indirect impacts on the following components of the marine environment: on tidal current velocity; on tidal current dynamics; on waves; sedimentation and seabed and marine ecology (El-Geziry, 2010). In this sense, early-stage environmental monitoring can successfully provide baseline information about some ecosystem impacts (i.e. fish aggregation) thus reducing uncertainty risks for stakeholders (Scherelis et al., 2020b).

Hence, considering the offshore tidal projects (excluding intertidal zones, rivers or lagoons) the main effects in relation to the tidal current energy projects are as follows (Table 7):

- In relation to the energy removal consequences, such as the alteration of sediment transportation, Chatzirodou et al. (2019) showed that changes to the morphodynamics of sandbanks as a result of large scale tidal energy extraction far exceeds the morphology change under the natural hydrodynamic regime, and the severity of morphology change depends on the level of energy extraction. Furthermore, Robins et al. (2014) showed that the sedimentary impacts of tidal arrays with less than 50 MW were considered detrimental to the local environment. Fairley et al. (2015) suggested that the cumulative impact of 4 currently proposed arrays was equal to the sum of the impacts of the individual arrays, with minimal effect on the baseline morphodynamics of the large sandbanks in the region. Unfortunately the implications that come with altering the hydrodynamics are still poorly understood (du Feu et al., 2019). In this sense, habitat suitability maps for species that respond to changes in bed-shear stress caused by an altered tidal regime can be performed (du Feu et al., 2019). Tidal energy extraction induces noticeable reductions of tidal currents and bottom shear stresses up to 15 km from the array considered till surrounding sandbanks, showing variations of shear stresses from 9 to 17 %, with possible implications on local sediment deposition (Guillou and Thiébot, 2016).
- Due to the physical presence of devices, Van Der Molen et al. (2016) suggested minor effects on the tides and undetectable effects on the biogeochemistry from 800 MW projects. However, these authors observed effects over hundreds of kilometres away with changes of up to 10 % in tidal and ecosystem variables from an 8 GW scenario. Auguste et al. (2020) observed that changes to current speed and bed shear stress were found to be localised around the tidal farms and did not extent more than 7 km from the farm (300 turbines).
- Furthermore, organisms may be attracted to or avoid the device, altering their ability to forage, rest, reproduce, and migrate. However, the results indicated a very small probability of the animals (i.e., mammals) randomly swimming into the turbine, assuming that animals are likely to hear the acoustic output of the device and actively avoid it (Copping et al., 2015). More concretely, Sparling et al. (2018) showed that the effect of the turbine on Strangford Lough (UK) harbour seals was minor and that collision risk was reduced by the behaviour of the seals.
- Changes in the electromagnetic fields can impact on animal movement/migration, including fish and turtle aggregating behaviour (Ward et al., 2010).

- The analysis of toxicity from anti-biofouling coatings used on ocean energy devices for scenarios of tidal energy development (copper and zinc) and biocides (diuron and ingarol) concluded that the risk of toxicity would be small over flora and fauna and with negligible contributions to water and sediment (Copping et al., 2015).
- Finally, according to Copping et al. (2015), the acoustic output from a single tidal turbine may not contribute significant noise above, but a large array of devices might have the potential to generate enough noise to confuse and mask communication for marine mammals and fish. Pine et al. (2019) confirmed that the maximum distance within Listening Space Reductions (LSR) were more than 10 % and ranged between 2.3 and 2.5 km for the harbour seal (*Phoca vitulina*), but between 1.5 and 1.7 km for the harbour porpoise (*Phocoena phocoena*), depending on the type of turbine: over 80 % at 100 m from the kite device and 70–80 % at the same distance from the Schottel device, with the maximum masking effect range at 3 km from the kite and at 3.3 km from the device respectively. Moreover, results demonstrated that LSR was influenced also by species. For instance, LSRs for harbour seals were more than 80 % within 60 m, whilst for harbour porpoises they were more than 55 % within 10 m of the devices. (Hastie et al., 2018) observed a significant spatial avoidance of the sound by tagged harbour seals, with a reduction in the usage between 11% and 41 %, at 500 m from turbine location. In the case of mobile hydroacoustics, Shen et al. (2016) observed that fish likely avoided one device with horizontal movement beginning 140 m away. In the same way, Grippo et al. (2020) confirmed a significant decline in fish numbers with a decreasing distance to the turbine, beginning approximately 140 m from the turbine, resulting from horizontal displacement, not vertical, avoiding the mobile hydroacoustic surveys.

Table 7 Synthesis of the main pressures, effects and spatial effect magnitude produced by currents and tidal energy farms on different ecosystem elements. Note: Not sufficient information was found to split it in different exploitation phases.

Pressure	Pressure	Ecosystem element	Effect type (Positive/ negative)	Impact magnitude	Spatial extent of the effect	Proxy for spatial extent of the effect	Reference
Energy	Electromagnetic fields	Fish	Negative	Low	-	-	Copping et al. (2015)
		Turtles	Negative	Low	-	-	Copping et al. (2015)
Input of other substances	Antifouling	Fish	Negative	Very low	-	-	Copping et al. (2015)
		Mammals	Negative	Low	-	-	Copping et al. (2015)
		Marine birds	Negative	Low	-	-	Copping et al. (2015)
Physical disturbance	Presence of tidal farm	Ecosystem structure, functions and processes	Negative	High	> 100 km	Effects on the surrounding area	Van Der Molen et al. (2016)
					-	-	Chatzirodou et al. (2019)
				Low	0 km	Farm extension	Robins et al. (2014)
							Van Der Molen et al. (2016)
					3 km	Effects on the surrounding area	Auguste et al. (2020)
					15 km	-	Guillou and Thiébot (2016)
				Low-High	-	-	Chatzirodou et al. (2019)
				Moderate	10 km	Effects on the surrounding area	Robins et al. (2014)
					7 km	Effects in the surrounding area	Auguste et al. (2020)
				None	0 km	Farm extension	Auguste et al. (2020)
			Positive	High	> 100 km	Effects on the surrounding area	Van Der Molen et al. (2016)
				Low	0 km	Farm extension	Van Der Molen et al. (2016)
		Fish	Negative	Very low	0 km	Farm extension	Copping et al. (2015)

Pressure	Pressure	Ecosystem element	Effect type (Positive/ negative)	Impact magnitude	Spatial extent of the effect	Proxy for spatial extent of the effect	Reference
		Mammals	Negative	High	0 km	Farm extension	Copping et al. (2015)
				Low	0 km	Farm extension	Sparling et al. (2018)
		Marine birds	Negative	Moderate	0 km	Farm extension	Copping et al. (2015)
		Seabed (benthic)	Negative	High	-	Farm extension	du Feu et al. (2019)
			Positive	Low	-	Farm extension	du Feu et al. (2019)
Sound	Noise	Fish	Negative	High	140 m	Effects on the surrounding area	Shen et al. (2016)
				Low	140 m	Effects on the surrounding area	Grippo et al. (2020)
				Very low	-	-	Copping et al. (2015)
		Mammals	Negative	High	1.5 km	Effects on the surrounding area	Pine et al. (2019)
					1.7 km	Effects on the surrounding area	Pine et al. (2019)
					2.3 km	Effects on the surrounding area	Pine et al. (2019)
					2.5 km	Effects on the surrounding area	Pine et al. (2019)
					500 m	Effects on the surrounding area	Hastie et al. (2018)
				Moderate	-	-	Copping et al. (2015)
		Marine birds	Negative	Low	-	-	Copping et al. (2015)

3.3 Waves

Unlike in the case of wind energy, the present situation shows a wide variety of wave energy systems, at several stages of development (Drew et al., 2009; Falcão, 2010). Due to this, the negative impact of the installation of the Wave Energy Converter (WEC) in the sea environment is very low, due to the small distribution of WECs (mostly still in the prototype testing stage) (Satriawan et al., 2021). However, it is necessary to identify the impacts on the overall environment, considering that wave energy appears to be one of the most promising energy sources among the renewable energies (Fadaeenejad et al., 2013).

The main pressures in relation to the wave energy projects are described below (Table 8).

According to the review made by Copping et al. (2015), some mammals, marine birds and reptiles can be negatively affected by changes in the EMFs, during the operational phase, from generators or electrical cables. On the one hand, according to the review made by Frid et al. (2012), some species of shark have been shown to respond to localized magnetic fields of 25–100 µT; European eels (*Anguilla anguilla*) may detect a 3-phase 130 kV cable (unburied) but did not disrupt their migration; from low temporary disorientation near a cable or structure of sea turtles (particularly loggerhead turtles) to altered nesting patterns due to large-scale magnetic field changes; contrary to this, the survival and reproduction of several benthic organisms are not affected by long-term exposure to static magnetic fields.

Moreover, according to Carballo and Iglesias (2013) and Iglesias and Carballo (2014), the changes in the nearshore wave climate due to the presence of the wave farm is negligible at a distance of 5,000 or 6,000 m or greater past the farm. According to Millar et al. (2007), the 30 MW-rated wave farm ('Wave Hub'), located 20 km off the north coast of Cornwall (UK) would affect the shoreline wave climate, although the magnitude of effects decreases linearly as wave energy transmitted increases, in this sense, the predicted change in shoreline wave climate would be small. Moreover, Palha et al. (2010) showed that energy extraction does not exceed 9.3–23 % of the incident energy in the wave farms, along the bathymetric line of 10 m, and a length of 26 km as the maximum extension of coast affected. Neill et al. (2012) observed an impact of 10 % energy extraction on bed level change after 6 months of simulation. Diaconu and Rusu (2013) showed a significant influence near the wave dragon array operating in the Black Sea (10 km) which gradually decreases to the coastline level, concluding that the longshore current velocities appeared to be more sensitive to the presence of the wave farm than the significant wave height. Oleinik et al. (2019) showed that the installation of a wave farm near the coast line of Laguna–SC (Brazil) produced a small reduction of wave heights not bringing any harm to the local hydrodynamics. Li and Phillips (2010) assessed the impact of the wave hub development (subsea facilities, interconnecting cables, offshore and onshore 24 kV cable and two alternative wave energy converter device layouts) on coastal processes (wave climate, tidal currents and sediment regime) and geomorphological processes. This study demonstrated that the impact of the wave hub and WEC devices on coastal processes was minimal.

Furthermore, due to the presence of the of the wave farm, Krivtsov and Linfoot (2012) showed that the area of benthic habitats adversely were affected by the leading mooring line on a typical wave energy converter, increasing with the increase in wave height, this is, regular waves of a 6 m height and 8 s period, 60 m^2 of the area of benthic habitats would be adversely affected.

In addition, Rodriguez-Delgado et al. (2018) proved that the presence of the wave farms can be used for coastal protection on gravel-dominated beaches, this is, the changes of the wave height at breaking and, therefore, changes in the erosion/accretion patterns, modifies the resulting dry beach area, changing the shoreline position and increasing the dry beach surface (25.94 m^2).

Moreover, according to the review made by Frid et al. (2012), the presence of the wave farm could change the currents which would affect the transportations of fish larvae, being harmful to fish populations. At the same time, the wave power plants act as wave breakers, calming the sea, and the result may be to slow the mixing of the upper layers of the sea, which could cause an adverse impact on the marine life and fisheries (Frid et al., 2012). In addition, according to these authors, lines on structures can cause the entanglement of marine mammals, turtles, larger fish and seabirds. Conversely biodiversity could increase due to increased substrate availability, food availability and feeding efficiency could also be higher, which could cause an enhancement of the larval recruitment in the area, providing more ecological niches, allowing more animals to recruit (Frid et al., 2012). Bicknell et al. (2019) detected differences between WEC project and reference locations that could be considered large (e.g., > 50 %).

In relation to the affection on seabirds due to the presence of the wave farm, there is a very strong consensus in the published literature that ocean renewable technologies are unlikely to represent as great a hazard to this ecosystem component (Furness et al., 2012). According to the revision of Furness et al. (2012), there is a range of risk depending on the species, identifying divers as the species most vulnerable to adverse effects from wave energy devices in Scottish waters. Wade et al. (2014) found that the overlap of great skuas with leased and proposed marine renewable energy developments was low, presenting no risk to great skuas. In the same way, Lees et al. (2016) observed that the density of seabirds close to the mooring points increased for great skua, northern gannet, and northern fulmar during summer in the presence of a device, suggesting that none of the four species analysed have shown avoidance or an extreme change in distribution as a result of the presence of a WEC (area 5.5 km^2, approximately).

In relation to the affection on macrofauna due to the presence of the wave farm, (Bender et al., 2020), after a 12 year assessment, showed a distinct reef effect on the wave power foundations in Sweden, with significant greater species richness, total number of individuals, greater values of the Shannon-Wiener diversity index, and greater abundance of specific reef fauna. In the same way, Langhamer (2010) observed during a period of 5 years that WECs' surrounding seabed were mainly composed by organisms typical for the area and depth off the Swedish west coast. However, during the first years of sampling, the species assemblages were significantly different between the research site and the reference site, with higher species abundance and with an accumulation of organic matter in the research area.

In relation to the introduction of biocide or antifouling substances in the marine environment, according to the review made by Copping et al. (2015), some mammals, marine birds and reptiles can be negatively affected, but in a low or very low way .

Finally, the increase of underwater noise has been found to affect fish, crustaceans (Frid et al., 2012; Haikonen et al., 2013), reptiles and marine mammals (Copping et al., 2015). Haikonen et al. (2013) examined the sound emitted from operating WECs and showed that the main noise was a transient noise with most of its energy in frequencies below 1 kHz. These results indicate that several marine organisms (fish and mammals) will be able to hear the operating WECs of a distance of at least 20 m. Copping et al. (2014a) reduced the distance to 1 m for fish and increased to 300–2,130 m for mammals (from drilling and device signature). Buscaino et al. (2019) supposed the possible masking of fish choruses at 1,000 m from a WEC device, with 800 Hz peak frequency and 10 dB above the WEC signal.

Table 8 Synthesis of the main pressures, effects and spatial effect magnitude produced by wave farms on different ecosystem elements

Type of pressure	Pressure	Pres-sure	Ecosystem element	Effect type	Impact magnitude	Spatial extent of the effect	Spatial proxy for calculation	Reference
Energy	Substances, litter and energy	Electromagnetic fields	Fish	Negative	Low-Moderate	-	-	Frid et al. (2012)
					Moderate	-	-	Frid et al. (2012)
			Invertebrates	Negative	None	-	-	Frid et al. (2012)
			Mammals	Negative	Very low	-	-	Copping et al. (2015)
			Marine birds	Negative	Very low	-	-	Copping et al. (2015)
			Reptiles	Negative	High	-	-	Frid et al. (2012)
					Low	-	-	Copping et al. (2015)
Hydrological change	Physical	Presence of wave farm	Ecosystem structure, functions and processes	Negative	High	< 5 km	Hydrodynamic effect in the surrounding area	Carballo and Iglesias (2013)
					Low	> 20 km	Wave farm extension	Millar et al. (2007)
						26 km	Changes in hydro-dynamic conditions in the surrounding area	Palha et al. (2010)
					Moderate	6 km	Sealed area by foundations	Iglesias and Carballo (2014)
						-	-	Frid et al. (2012)
				Positive[5]	High	6 km	Sealed area by foundations	Iglesias and Carballo (2014)

[5] Coastal protection effect

Type of pressure	Pressure	Pres-sure	Ecosystem element	Effect type	Impact magnitude	Spatial extent of the effect	Spatial proxy for calculation	Reference
					Moderate	10 km	-	Diaconu and Rusu (2013)
						-	-	Frid et al. (2012)
Other substances	Substances, litter and energy	Antifouling	Mammals	Negative	Very low	-	-	Copping et al. (2015)
			Marine birds	Negative	Low	-	-	Copping et al. (2015)
			Reptiles	Negative	Low	-	-	Copping et al. (2015)
Physical disturbance	Physical	Presence of wave farm	Ecosystem structure, functions and processes	Negative	High	60 m^2	Sealed area by foundations	Krivtsov and Linfoot (2012)
					Low	-	-	Oleinik et al. (2019)
				Positive	High	25.94 m^2	Sealed area by foundations	Rodriguez-Delgado et al. (2018)
			Fish	Negative	High	0 km	Wave farm extension	Frid et al. (2012)
				Positive	High	0 km	Wave farm extension	Bicknell et al. (2019)
					Moderate	0 km	Wave farm extension	Frid et al. (2012)
			Invertebrates	Negative	Low	-	-	Frid et al. (2012)
				None	Low	0 km	Wave farm extension	Bicknell et al. (2019)
				Positive	High	0 km	Wave farm extension	Frid et al. (2012)
			Mammals	Negative	High	0 km	Wave farm extension	Frid et al. (2012)
					Low	0 km	Wave farm extension	Copping et al. (2015)
			Marine birds	Negative	High	0 km	Wave farm extension	Frid et al. (2012)
					Low	0 km	Wave farm extension	Copping et al. (2015)
					None	0 km	Wave farm extension	Wade et al. (2014)
				None	Low	5.5 km^2	Wave farm extension	Lees et al. (2016)

Type of pressure	Pressure	Pres-sure	Ecosystem element	Effect type	Impact magnitude	Spatial extent of the effect	Spatial proxy for calculation	Reference
				Positive	Low	0 km	Wave farm extension	Wade et al. (2014)
			Reptiles	Negative	High	0 km	Wave farm extension	Frid et al. (2012)
					Moderate	0 km	Wave farm extension	Copping et al. (2015)
			Seabed (benthic)	Negative	High	> 60 m^2	Wave farm extension	Krivtsov and Linfoot (2012)
		Presence of wave farm (foundations)	Ecosystem structure, functions and processes	Positive	High	593.46 m^2	Wave farm extension	Bender et al. (2020)
Physical Loss	Physical	Presence of wave farm	Ecosystem structure, functions and processes	Positive	Moderate	0.4 km^2	Sealed area by foundations	Langhamer (2010)
			Marine birds	Negative	Low	0 km	Wave farm extension	Furness et al. (2012)
					Moderate	0 km	Wave farm extension	Furness et al. (2012)
					Very low	0 km	Wave farm extension	Furness et al. (2012)
Sound	Substances, litter and energy	Noise	Fish	Negative	High	-	-	Frid et al. (2012)
					None	20 m	Wave farm extension	Haikonen et al. (2013)
				Positive	High	-	-	Frid et al. (2012)
			Invertebrates	Positive	High	-	-	Frid et al. (2012)
			Mammals	Negative	High	15 km	Effect on surrounding area	Frid et al. (2012)
						-	-	Frid et al. (2012)

Type of pressure	Pressure	Pres-sure	Ecosystem element	Effect type	Impact magnitude	Spatial extent of the effect	Spatial proxy for calculation	Reference
					Low	20 m	Wave farm extension	Haikonen et al. (2013)
						-	-	Copping et al. (2015)
					None	20 m	Wave farm extension	Haikonen et al. (2013)
			Marine birds	Negative	Very low	-	-	Copping et al. (2015)
			Reptiles	Negative	Low	-	-	Copping et al. (2015)
			-	Negative	Low	-	-	Frid et al. (2012)
		Noise (drilling)	Mammals	Negative	Non specified	2,130 m	Effect on surrounding area	Copping et al. (2014a)
						300 m	Wave farm extension	Copping et al. (2014a)
		Noise (installation/ driving pin-piles)	Mammals	Negative	High	300 m	Wave farm extension	Copping et al. (2014a)
		Noise levels (ambient environment and device signature)	Fish	Negative	None	1 m	Wave farm extension	Copping et al. (2014a)
			Mammals	Negative	Moderate	2,130 m	Effect on surrounding area	Copping et al. (2014a)

3.4 Photovoltaic

According to Golroodbari and van Sark (2020), photovoltaic system performance at sea can be 13 % higher than land-based systems. Marine demonstrations of floating solar photovoltaic arrays (floatovoltaics) have occurred in shallow tropical lagoons (Maldives), deep, protected fjords (Norway), the rough North Sea (The Netherlands), and nearshore in the Persian Gulf (Dubai) (Hooper et al., 2021). According to Karpouzoglou et al. (2020) there are no studies that consider the possible environmental effects of offshore floating platforms on the marine ecosystem. In this sense, due to the nascent state of this type of offshore renewable energy, information about marine floatovoltaic impacts can only be deduced from experience with other man-made structures at sea (particularly other offshore energy platforms) (Hooper et al., 2021). Possible effects include spread of invasive species, anchoring and cable impacts on the substrate, disturbance during installation including sediment resuspension and electromagnetic field effects.

Karpouzoglou et al. (2020) investigated the potential effects of large-scale arrays of offshore floating platforms on the ecosystem of coastal seas such as the North Sea, adjacent to the Netherlands. Although these authors recognized that the results are based on models, ignoring several physical and biological processes and assuming a “unit” horizontal extent and spatial homogeneity, they confirmed that the platform-induced light deficit (blocking sunlight penetration), with net primary production decreasing more than 10 % (for 20 % coverage of the model surface with platforms). Moreover, depending on the tidal current amplitudes at the three study locations, the estimated tidal excursion lengths would be different: 3.3 km for Oyster Grounds, 7.3 km for Noordwijk-10 and 12.5 km for West Gabbard.

3.5 Ocean Thermal Energy Conversion

According to Arcuri et al. (2015) the Ocean Thermal Energy Conversion (OTEC) is achieved in tropical zones exploiting the warmer surface seawater as a heat source for the vaporization of a specific working fluid, and the coldest water pumped from the depths for its condensation. These issues include the intake, transport and discharge of large quantities of seawater, occupying an ocean location with a large industrial platform anchored to the bottom and power transmission via subsea cabling to suitable shore locations (Havens et al., 2010). This alternative energy source does not depend on fossil fuels, is not vulnerable to world market fluctuations and has less environmental impact than other energy sources (Plocek et al., 2009). The main pressures and impacts in relation to the OTEC projects are described below (Table 9).

The resulting mixed deep and surface seawater could have an impact on phytoplankton. Giraud et al. (2019b) carried out in situ microcosm experiments where two scenarios of water mix ratio: 2 % and 10 % of deep water were tested at two incubation depths, with Deep Chlorophyll-a Maximum (DCM) and with Bottom of the Euphotic Layer (BEL). DCM was most impacted by the highest deep seawater addition (10 %), with a development of diatoms and haptophytes, whereas 2 % addition induced only a limited change of the phytoplankton community (Giraud et al., 2019a). These results suggested OTEC plant would significantly modify the phytoplankton assemblage (picophytoplankton toward micro-phytoplankton, only in the case of a discharge affecting the DCM and restricted to a local scale) (Giraud et al., 2019a). These authors recommended BEL depth for the discharge of the deep seawater to exploit the OTEC plant.

Giraud et al. (2019b) confirmed that there was a thermal effect limited at < 1 km^2 on the area and at 150 m-depth waters (in a worst-case scenario) with temperature differences of 0.3 °C (absolute value) which produced a negligible thermic impact on the phytoplankton assemblage. Wang et al. (2016) showed that the affected area where the temperature dropped more than 0.1 ºC was largest (about 8 km^2) at a depth of 25 m: the discharged water from an OTEC plant was colder and heavier than the surrounding seawater and flowed downward as being mixed with ambient water and horizontally, spread at the depth where the density of mixed water becomes equal to that of surrounding seawater. Allender et al. (1978) estimated that redistribution of available potential energy in the ocean by the combined operation of many OTEC plants will not be sufficient to generate mesoscale (approx. 50–100 km) anomalies, this is, naturally occurring anomalies in the thermohaline structure will be greater than the anomalies that an OTEC can produce.

Moreover, these authors showed changes in nutrients, this is, nitrate concentration increased in a larger area at a depth of 35 m (rather than at a depth of 15 m), with phytoplankton concentration decreasing at the place where the OTEC plant is located (in the low temperature), around 8 km^2, but increasing in the northeast area (Wang et al., 2016).

Another aspect to consider would be the discharge plume volume from OTEC plants and its physicochemical composition, which can lead to the proliferation of harmful algal blooms (Rivera et al., 2020).

Table 9 Synthesis of the main pressures, effects and spatial effect magnitude produced by currents and tidal energy farms on different ecosystem elements

Type of pressure	Pressure (theme)	Ecosystem element	Effect type (Positive/negative)	Impact magnitude	Spatial extent of the effect	Proxy for the spatial extent of the effect	Reference
Water	Substances, litter and energy	Ecosystem structure, functions and processes	Negative	High	< 1 km^2	Effects on the surrounding area	Giraud et al. (2019b)
				Medium	8 km^2	Effects on the surrounding area	Wang et al. (2016)
				Medium	< 1 km^2	Effects on the surrounding area	Giraud et al. (2019b)
			Positive	Medium	8 km^2	Effects on the surrounding area	Wang et al. (2016)
			Unknown	Medium	8 km^2	Effects on the surrounding area	Wang et al. (2016)

4 Environmental risk maps

According to the EMODnet the human activities dataset on wind power, some areas, especially the North Sea, have large concentrations of existing and planned offshore wind power installations. Using the spatial data for offshore renewable energy, cumulative pressure maps can be created that include both operational and planned sites. Each type of environmental pressure produced by offshore renewable energy installations can be mapped separately and then combined into a single map.

Using ecological data, an ecosystem sensitivity map can be created to identify areas that are not suitable for wind power from an ecological point of view. Values can be given to all ecological datasets/ecosystem components based on how vulnerable they are to wind power and these classified ecosystem components can then be aggregated into a single map layer. Ecosystem sensitivity scores that experts estimated for the EEA combined effects assessment (Korpinen et al., 2019) and research literature can be utilized to estimate the vulnerabilities of ecosystem components to different environmental pressures produced by offshore wind power.

An offshore power production cumulative impact assessment can then be created by combining the stressor map with the ecosystem sensitivity map. The EcoImpactMapper software (Stock, 2016) can be used to create the cumulative impact assessment, as well as the cumulative pressure map and ecosystem sensitivity map.

4.1 Map production

EcoImpactMapper calculates human impact indices based on the methodology developed by (Halpern et al., 2008). The program uses three types of input data: stressors, ecosystem components and sensitivity scores. Normalised (0–1) stressors and ecosystem components are represented as raster data, in this analysis with a cell size of 10*10 km and need to be entered into the program in CSV format. The sensitivity scores are gathered in a matrix table that is also entered in CSV format.

Where a stressor and ecosystem component spatially overlap, EcoImpactMapper calculates an impact by multiplying the stressor intensity with the ecosystem intensity (which can for example be the amount of the ecosystem component present, but data can also be presence/absence) and the sensitivity score for the corresponding stressor/ecosystem component pair: impact score = stressor * ecosystem component * sensitivity score. EcoImpactMapper then sums the impact score for each stressor/ecosystem component combination for each raster cell. Additionally, EcoImpactMapper can also calculate ecological sensitivity indices and weighted stressor indices. An ecological sensitivity index is created by summing all ecosystem component layers, each one being weighted by the mean of their sensitivity scores. A weighted stressor index is like an ecological sensitivity index: all stressors are summed, and each stressor is weighted with the mean of all ecosystem components' sensitivity scores for each stressor.

The range of the sensitivity scores is up to the user, in this case a scale from 0 to 5 was used. A sensitivity score of 0 was considered no sensitivity, 1 low sensitivity, 2 moderate, and 5 high. Sensitivity scores were derived for each corresponding offshore renewable energy production method. Averages were calculated in cases where an effect type listed several impact magnitudes (see Table A6 for the ecosystem components sensitivity scores for wind, tidal and wave energy stressors).

Stressors were based on pressure types in the synthesis tables (Table 6, Table 7 and Table 8), and each stressor was given a spatial extent based on the spatial extent listed in the tables. In cases where several spatial extents were listed, the highest value range was used. The intensity of stressors with large spatial extents was calculated to decrease linearly from the stressor source. The input data used to create the stressor maps can be viewed in Figure A1.

In the offshore wind power analysis, if the stressor extent was confined to the extent of the farm area (i.e., the effect was local), the intersecting area (square kilometres) of the wind farm in the cell was used as intensity. Stressors that had a very small extent, for example only around cables, were excluded due to the large scale of the maps. For tidal and wave power, their kW production capacity was logarithmically transformed and used as a proxy for intensity.

The wind power analysis is a combined impact index of the ecological stressors from active wind farms and from stressors present in the construction phase of upcoming, planned wind farms, i.e., wind farms were divided into two groups, those already operating and those that will most likely be “in construction” in the next several years. The tidal and wave power analysis’ treated operational sites and soon to be constructed sites the same.

Ecosystem components used in the analysis were turtle, mammal (whale and seal), fish, bird and invertebrate distributions, and chlorophyll concentrations. Wind, seabed, and ecosystem structure, functions and processes layers were also included as constant presence (1) layers covering the whole research area. The ecosystem components were based on the synthesis tables (Table 6, Table 7 and Table 8).

4.1.1. Data sources

Wind energy

The main portion of the offshore wind farm spatial data used to create wind farm caused stressors was downloaded from the 4C Global Offshore Wind Farm Database in January 2020. The dataset is stored in a ESRI file geodatabase in polygon format and contains attribute information about farm name, project status, production capacity, and turbine amount, among other information.

EMODnet 2021 offshore wind farm spatial polygon data and point data for wind – wave hybrid test sites were used to supplement the 4C data. After this, the aggregated dataset included a total of 136 operational offshore wind farm sites and 123 sites that were either planned or under construction.

Tidal and wave energy

EMODnet 2021 spatial data on offshore tidal and wave energy production was used to produce the stressor layers for tidal and wave energy production. The EMODnet data consisted of only point data. Attribute data included, among other things, name, project status, and kW production capacity.

Ecosystem components

Ecosystem components were created from data from several different sources. The turtle, and fish distribution maps are the same layer used in the “Multiple pressures and their combined effects in Europe's seas” analysis by Korpinen et al. (2019). The mammal map was created by aggregating the whale and seal distribution maps from the combined effects analysis.

The invertebrate map was created by aggregating Arthropoda, Cnidaria, Echinodermata and Mollusca distribution maps downloaded from aquamaps.org, using a method similar to how Korpinen et al. (2019) created the whale, seal and turtle maps.

The bird species index map was created from bird species distribution data received from BirdLife International. The dataset is a joint production by BirdLife International and the Handbook of the Birds of the World.

Copernicus satellite data, download from the Copernicus website, on 2020 chlorophyll concentrations was used to create an aggregated concentration map. This was used in the analysis as the phytoplankton ecosystem component.

4.2. Environmental risk maps of offshore renewable energy

Using the modelling capabilities of EcoImpactMapper, a total of 9 indices were created: a weighted stressor, ecological sensitivity and cumulative impact map for each of the three offshore renewable energy production methods analysed (see Figure 6 to Figure 14). In addition, aggregated models were also created, which are simply all the weighted stressor, ecological sensitivity, or cumulative impact models summed together (Figure 15 to Figure 17). For the cumulative impact and weighted stressors indices, finer map scale images for the North Sea were also created. All figures list a theoretical maximum value. This value is the maximum value if all stressors and/or ecosystem components would overlap with maximum intensity.

Results suggest that while all three energy production methods have some spatially far-reaching ecological effects, these effects are minor, and the bulk of the ecological stressors occur in the immediate vicinity of the installations. The largest concentration of operational and planned energy production installations, and thus also stressors, can be found roughly in the North Sea, English Channel, and Irish Sea region.

Although the main cumulative impact for offshore wind power farms occurs at the site of the farm (Figure 7 and Figure 8), operational offshore wind farms can affect primary production reduction and fish behaviour up to 10 and 15 km respectively, while farm construction can affect bird and mammal behaviour up to 16 and 50 km respectively (Vanhellemont and Ruddick, 2014; Boyle and New, 2018; Mendel et al. 2019; Haelters et al. 2014; Bailey et al. 2010). Additionally, van Berkel et al. (2020) estimate that wind farms can cause wind deformation in a 5-20 km radius.

The large radius of a certain tidal power stressor can be clearly observed in Figure 9 and Figure 10. This stressor represents the estimation from Van Der Molen et al. (2016) that tidal power installations can have a potential environmental impact on tidal and ecosystem variables >100 km from the installations. Although the extent of this stressor is large, it should be noted that cumulative impact values from the EcoImpactMapper analysis (Figure 11) are usually >10 times larger at the site of the tidal power installations than at even 10 km from the installations.

For wave power, the stressor with the largest spatial extent is the hydrological change stressor as wave power installations can affect hydrological conditions up to 26 km according to Palha et al. (2010). However, as can be seen in Figure 12 and Figure 13, the intensity and cumulative effects from this stressor are low, and similarly to the tidal power analysis, cumulative impact values are much higher at the site of the installation, neighbouring raster cell values typically being 10–20 times lower.

According to the ecological sensitivity indices (Figure 7, Figure 10, Figure 13 and Figure 16), ecosystem components susceptible to the stressors caused by offshore wind, tidal and wave energy production can mostly be found in Atlantic and Mediterranean coastal waters. The aggregated ecological sensitivity map (Figure 16) indicates that the coastal waters around Portugal, Spain, the British Isles, the Azores archipelago, Madeira and Canary Islands have high concentrations of ecosystem components sensitive to the stressors.

Figure 6: Weighted stressors index for offshore wind farms, whole research area and the North Sea. The index is a sum of all stressors weighed by their mean sensitivity scores. Ecosystem components are not included in a weighted stressors index.

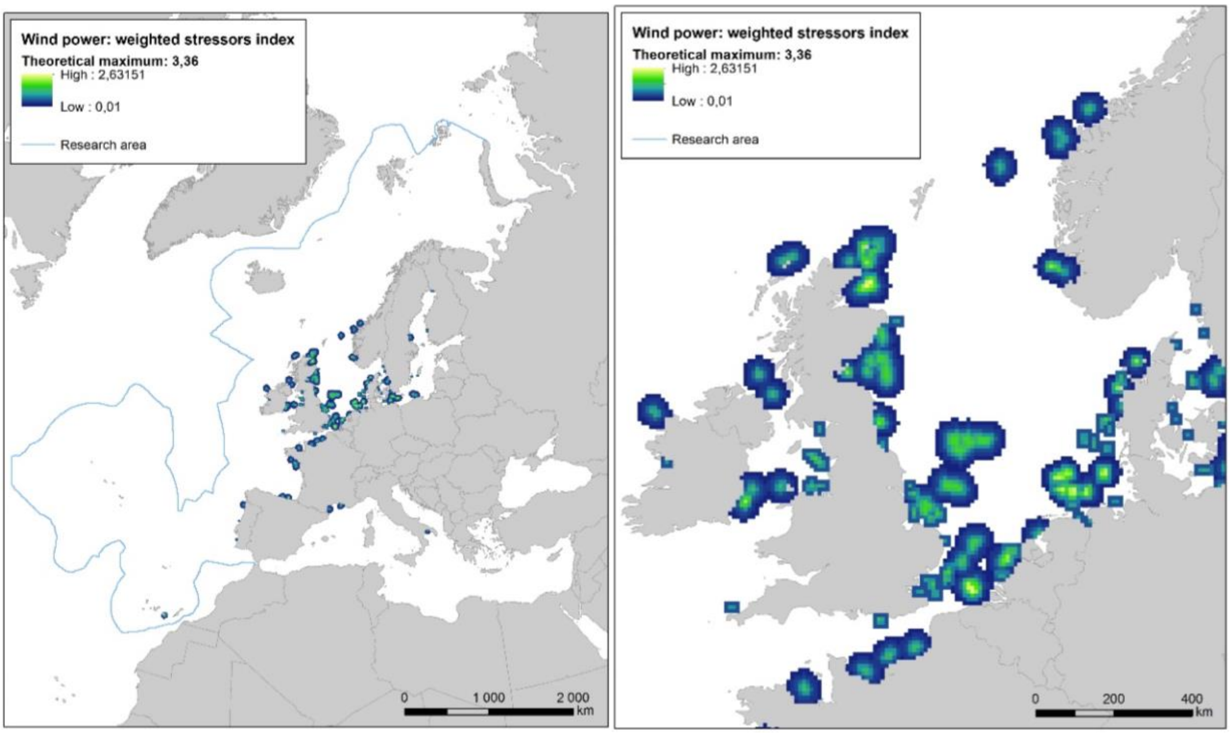


Figure 7: Ecological sensitivity index for offshore wind farms. The index is a sum of all ecosystem components weighed by their mean sensitivity scores. Stressors are not included in an ecological sensitivity index. Note that the index does not show ecological resilience, rather it shows hot spots with ecosystem components that are sensitive to the activity in question.

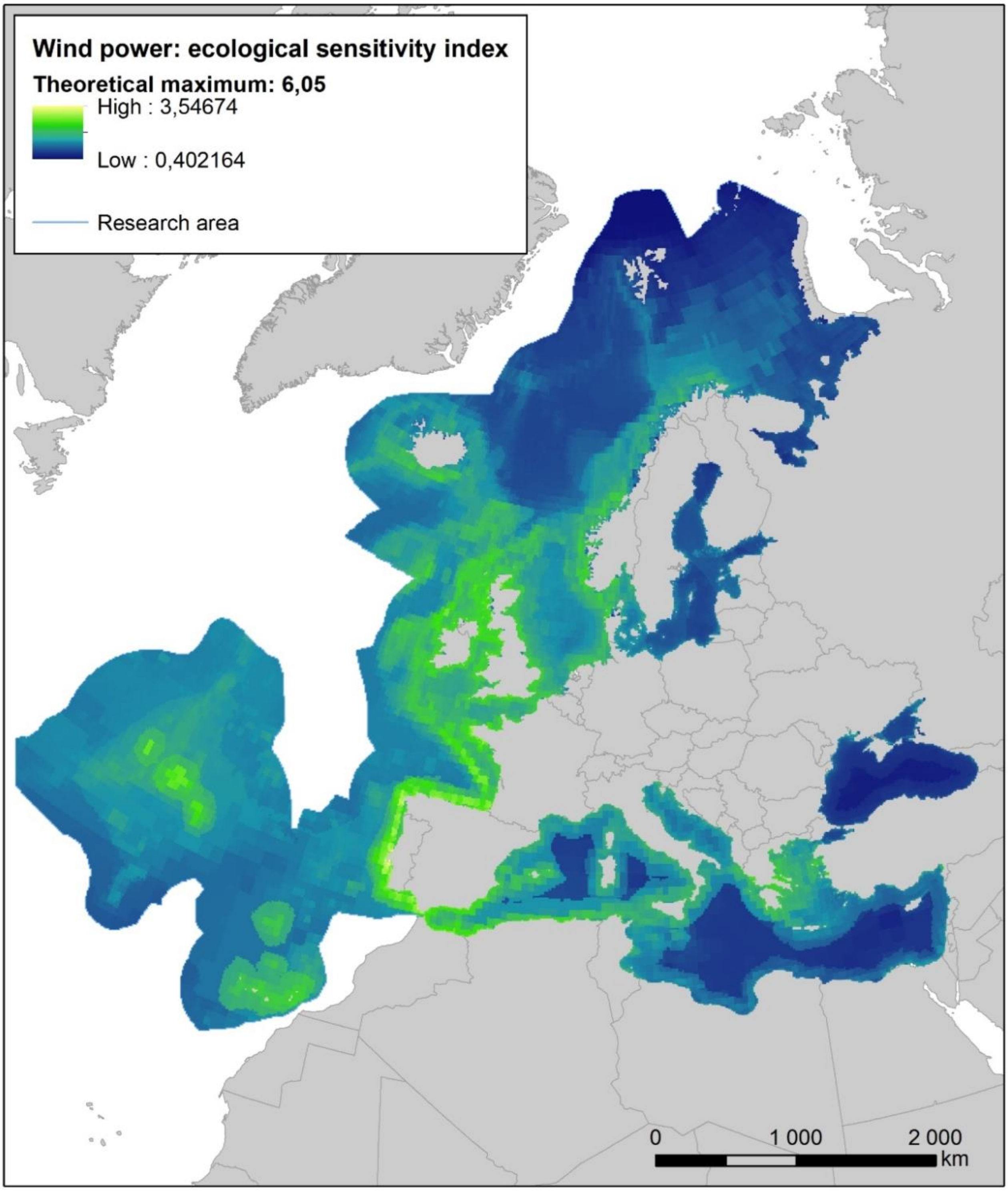


Figure 8: Additive cumulative impact index for offshore wind farms, whole research area and the North Sea. The index shows the summed effects of stressors on ecosystem components. The effect of each stressor on an ecosystem component is determined by the assigned sensitivity score (ranging from 0 to 5).

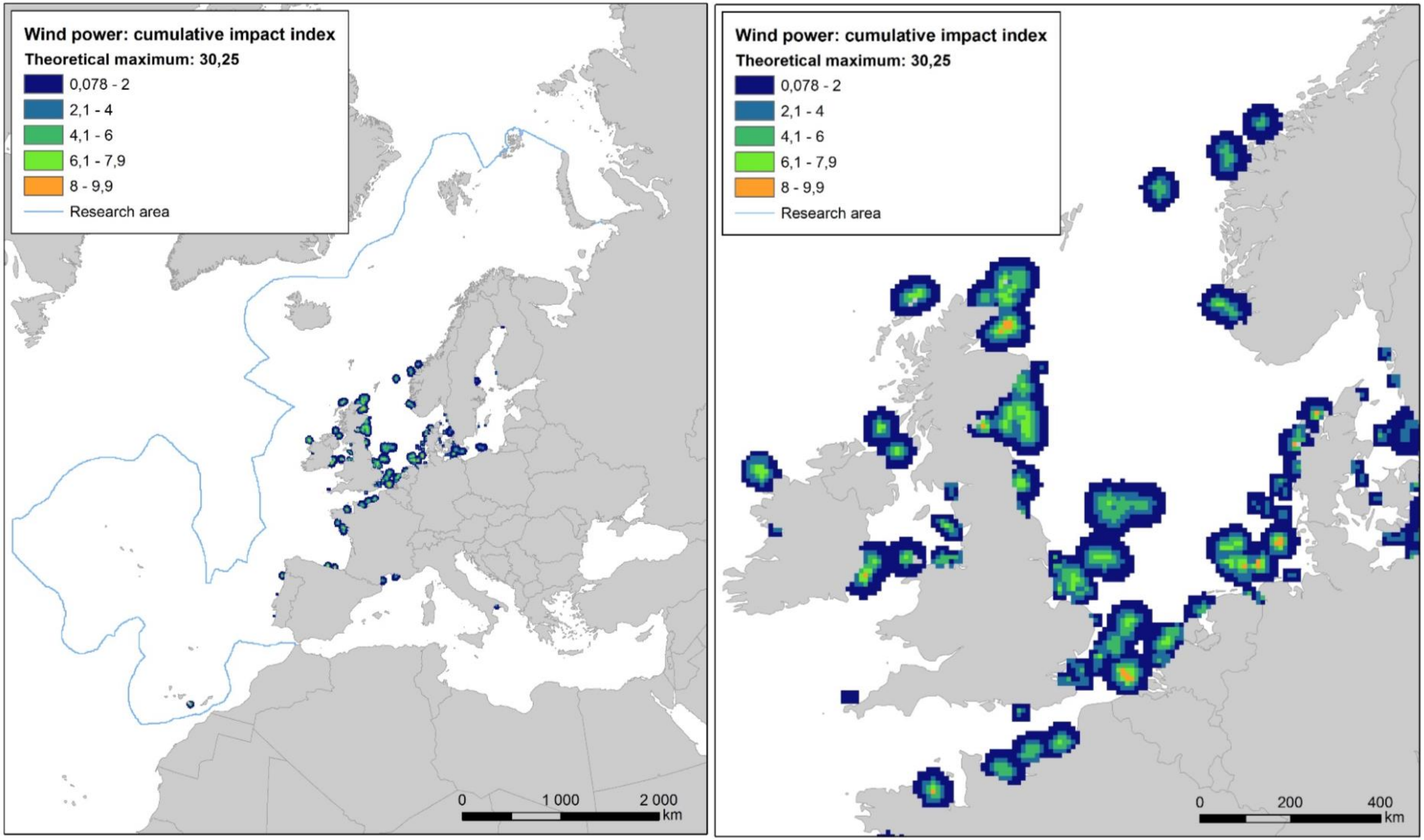


Figure 9: Weighted stressors index for tidal power sites, whole research area and the North Sea. The index is a sum of all stressors weighed by their mean sensitivity scores. Ecosystem components are not included in a weighted stressors index.

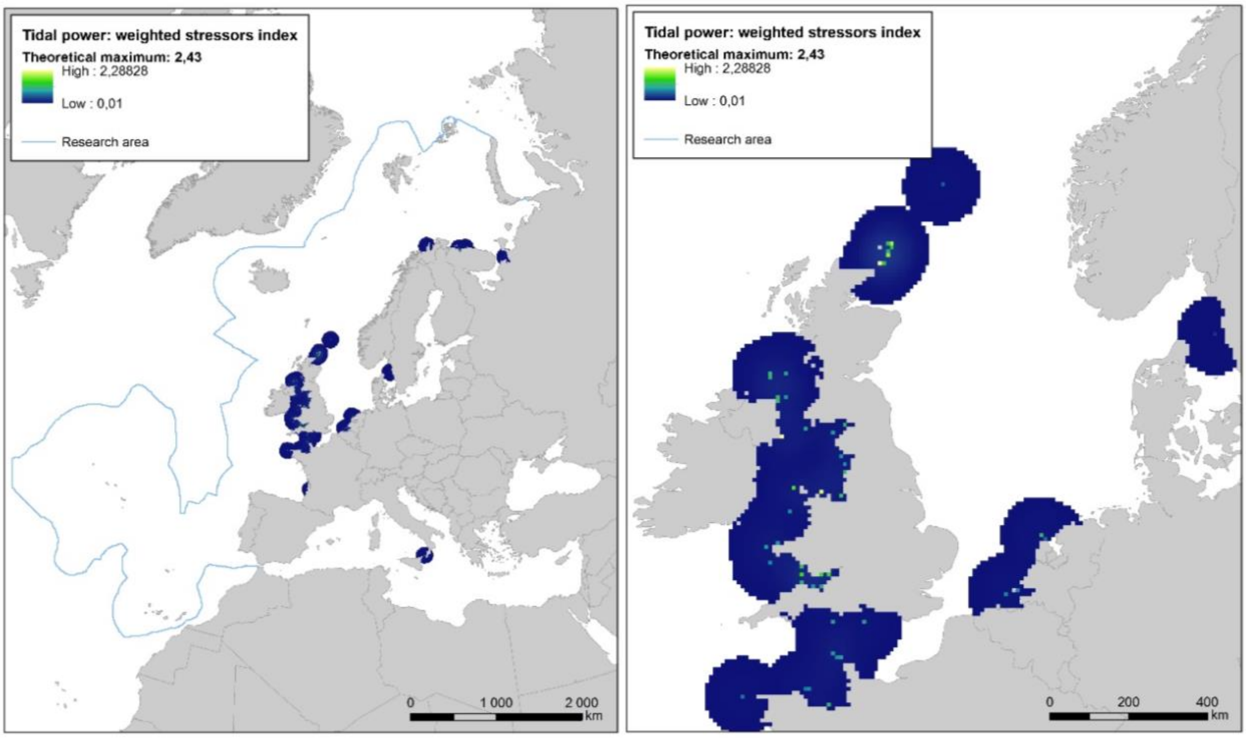


Figure 10: Ecological sensitivity index for tidal power sites. The index is a sum of all ecosystem components weighed by their mean sensitivity scores. Stressors are not included in an ecological sensitivity index. Note that the index does not show ecological resilience, rather it shows hot spots with ecosystem components that are sensitive to the activity in question.

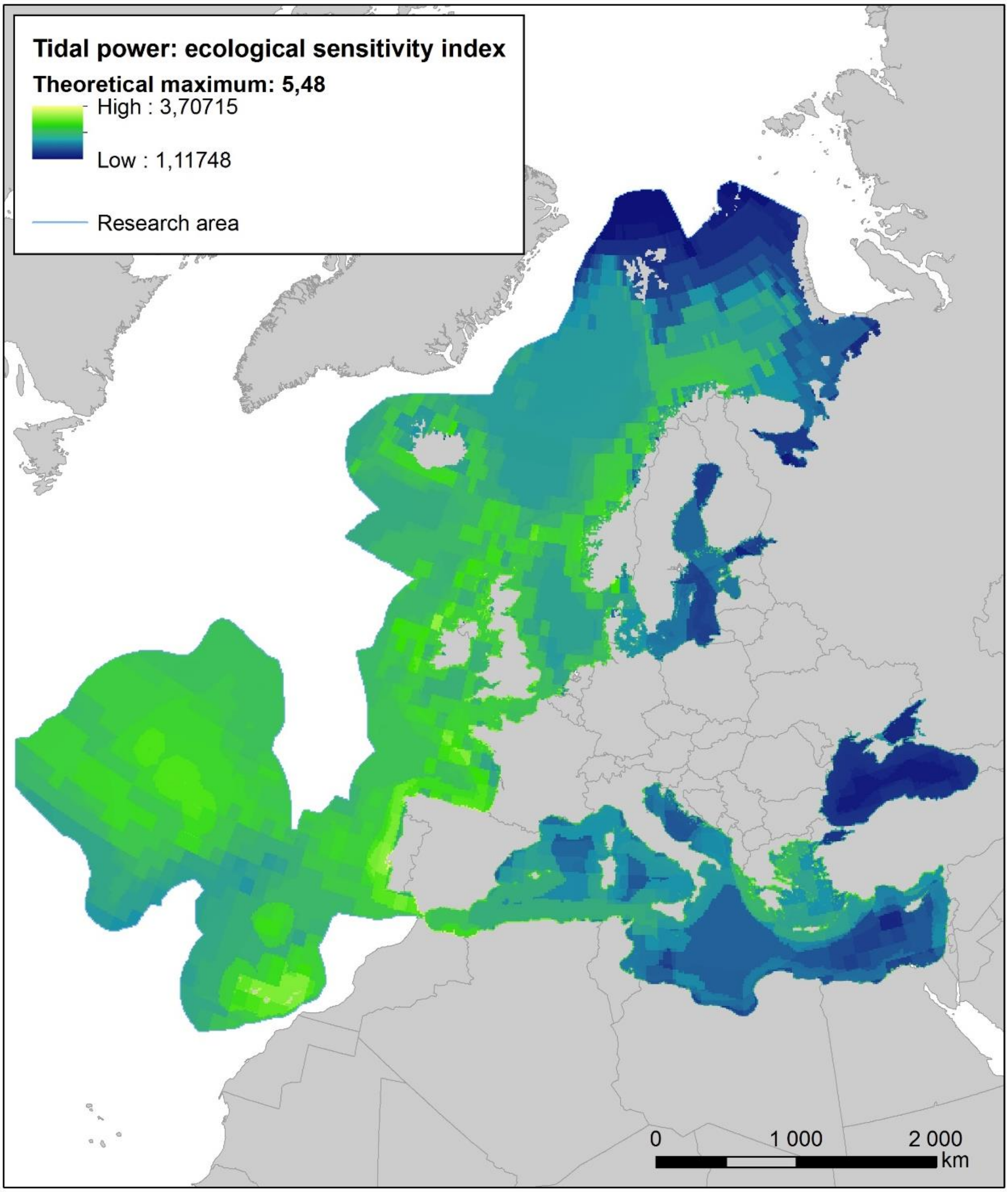


Figure 11: Additive cumulative impact index for tidal power sites, whole research area and the North Sea. The index shows the summed effects of stressors on ecosystem components. The effect of each stressor on each ecosystem component is determined by the assigned sensitivity score (ranging from 0 to 5).

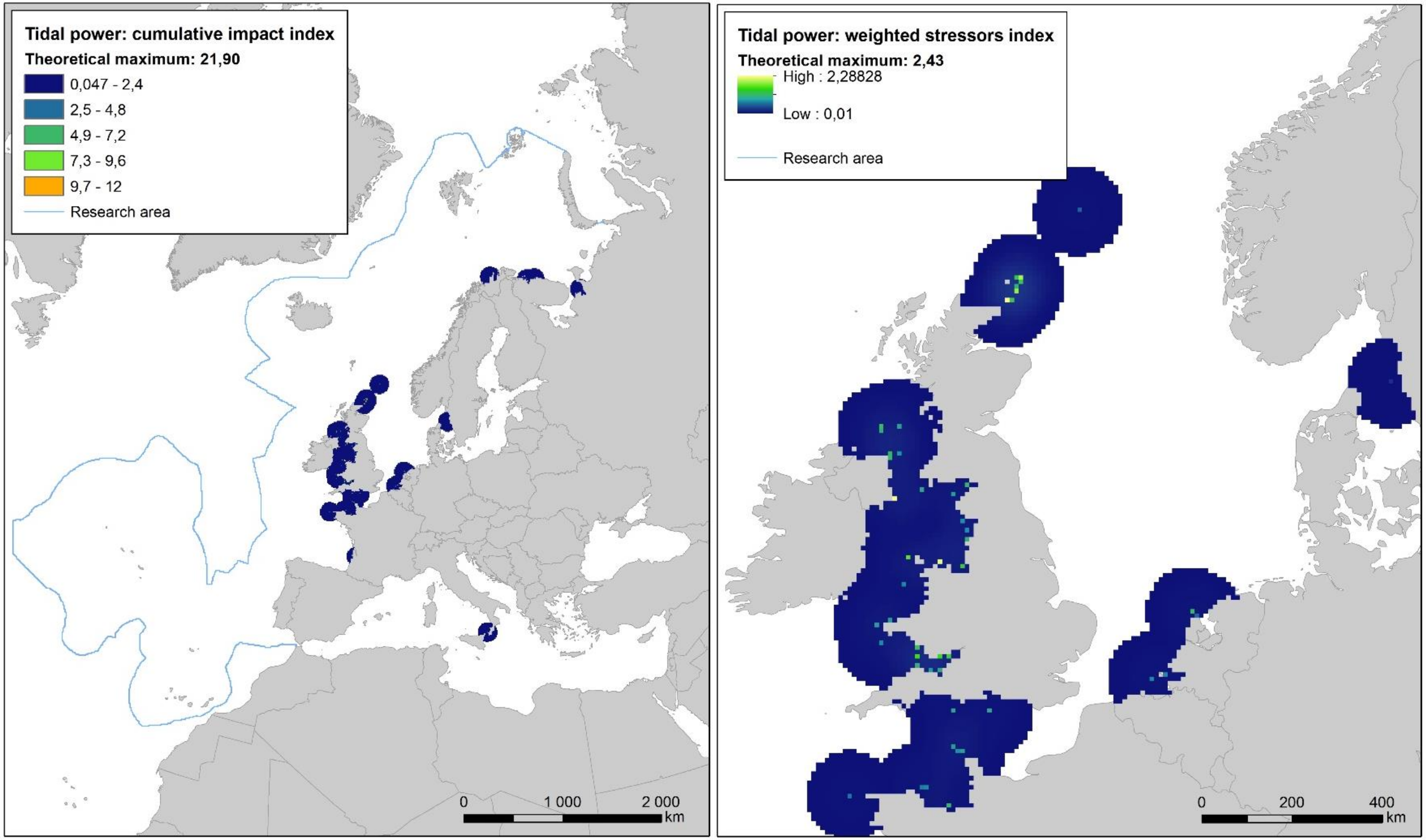
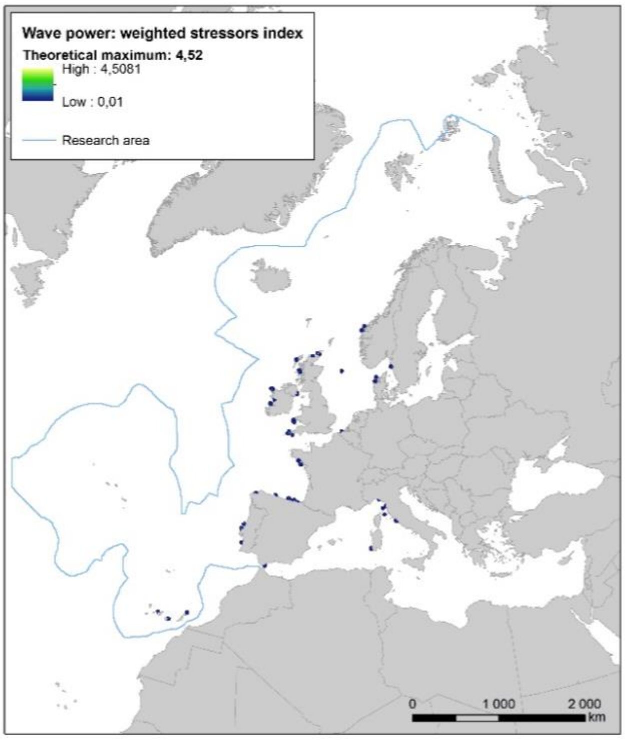


Figure 12: Weighted stressors index for wave power sites, whole research area and the North Sea. The index is a sum of all stressors weighed by their mean sensitivity scores. Ecosystem components are not included in a weighted stressors index.



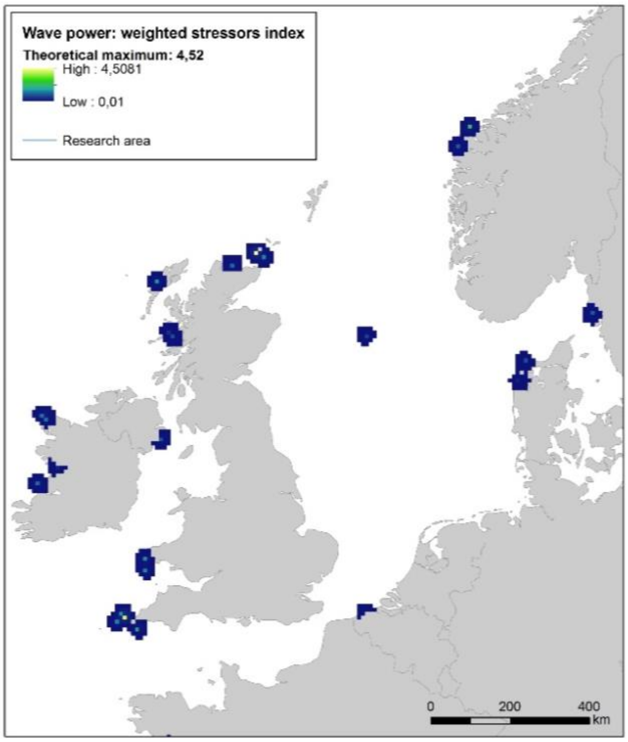


Figure 13: Ecological sensitivity index for wave power sites. The index is a sum of all ecosystem components weighed by their mean sensitivity scores. Stressors are not included in an ecological sensitivity index. Note that the index does not show ecological resilience, rather it shows hot spots with ecosystem components that are sensitive to the activity in question.

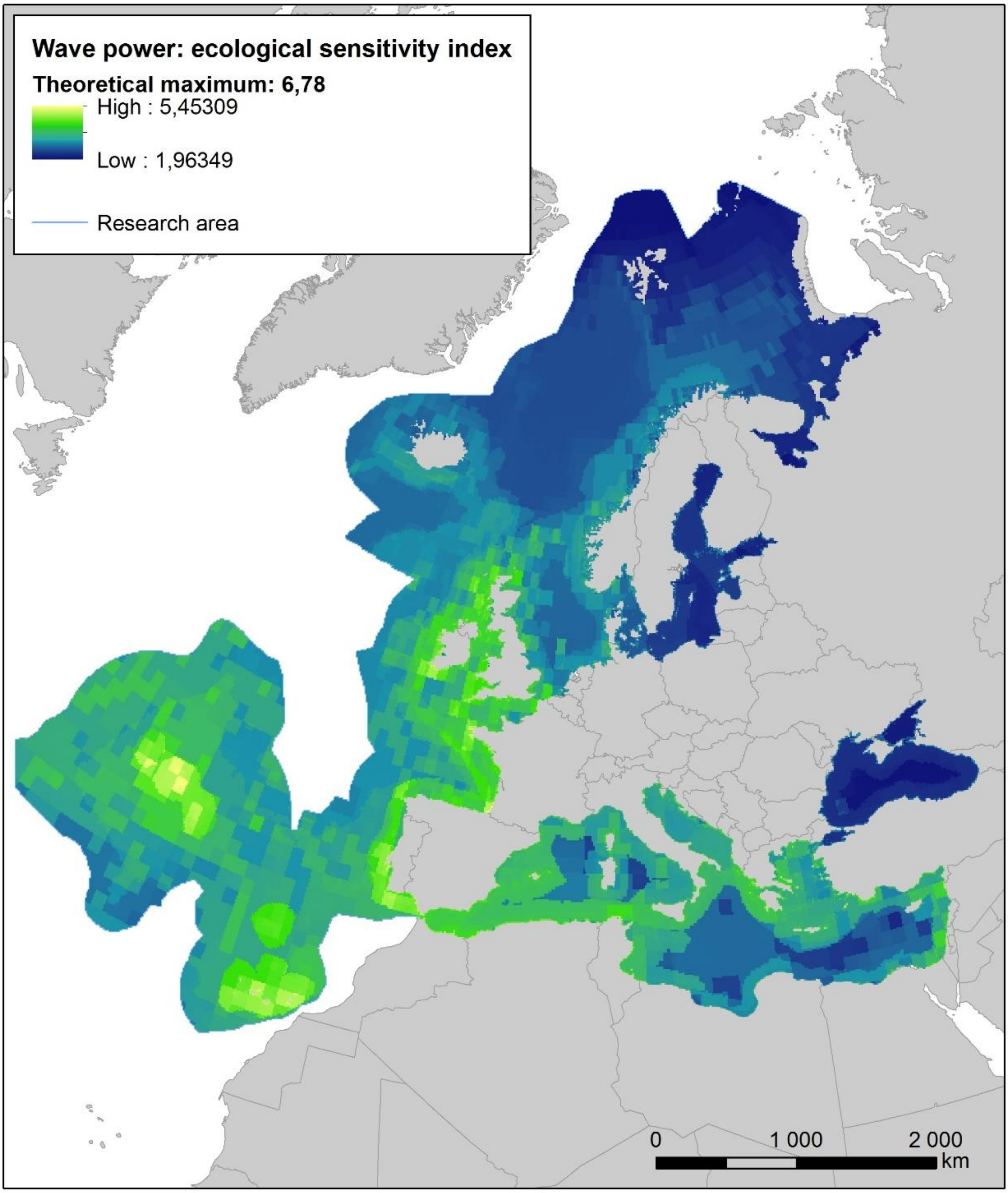


Figure 14: Additive cumulative impact index for wave power sites, whole research area and the North Sea. The index shows the summed effects of stressors on ecosystem components. The effect of each stressor on each ecosystem component is determined by the assigned sensitivity score (ranging from 0 to 5).

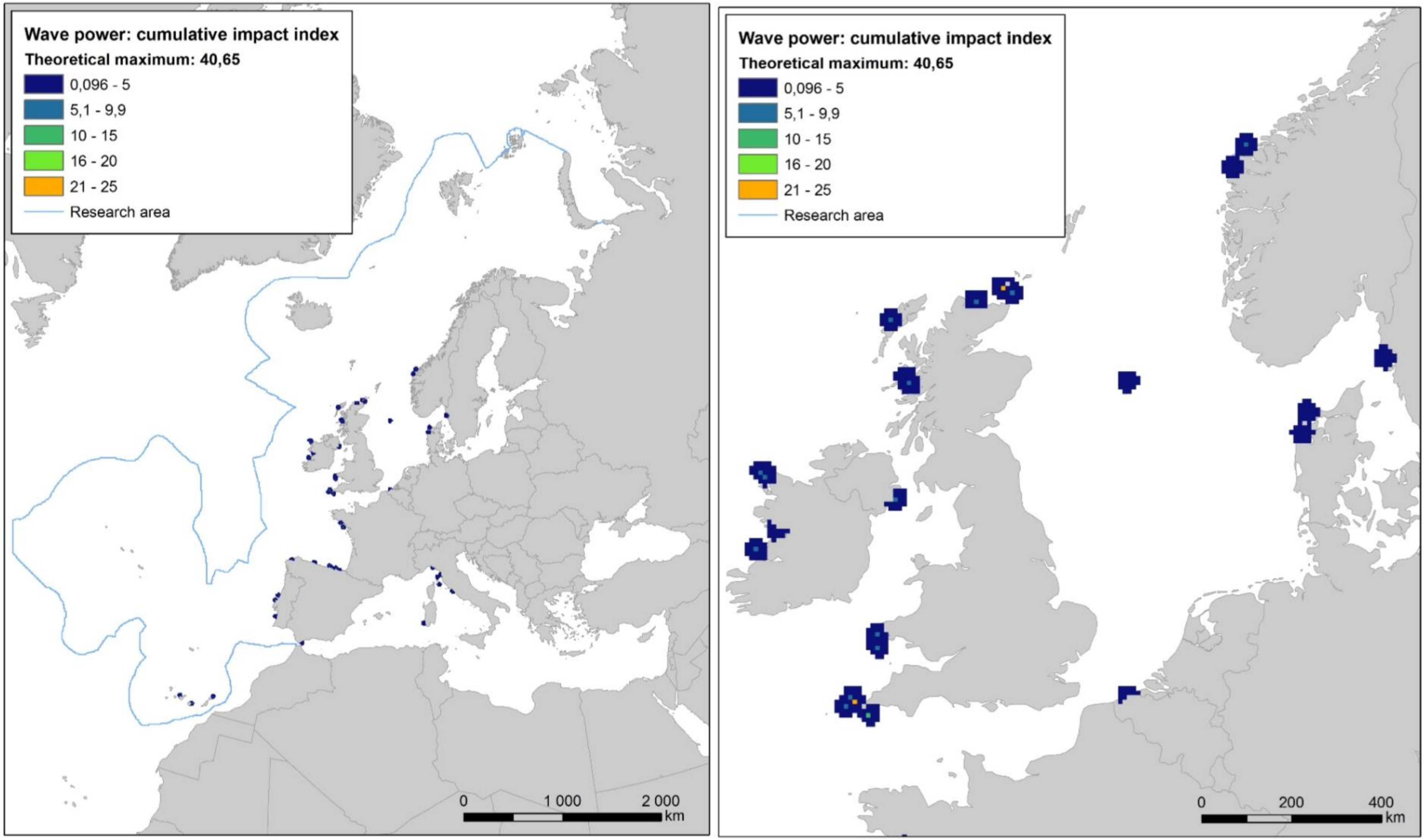


Figure 15: Aggregated weighted stressors index, whole research area and the North Sea. All three analysed offshore renewable energy production methods (wind, tidal, wave) are aggregated into one index. A weighted stressors index is a sum of all stressors weighed by their mean sensitivity scores. Ecosystem components are not included in a weighted stressors index.

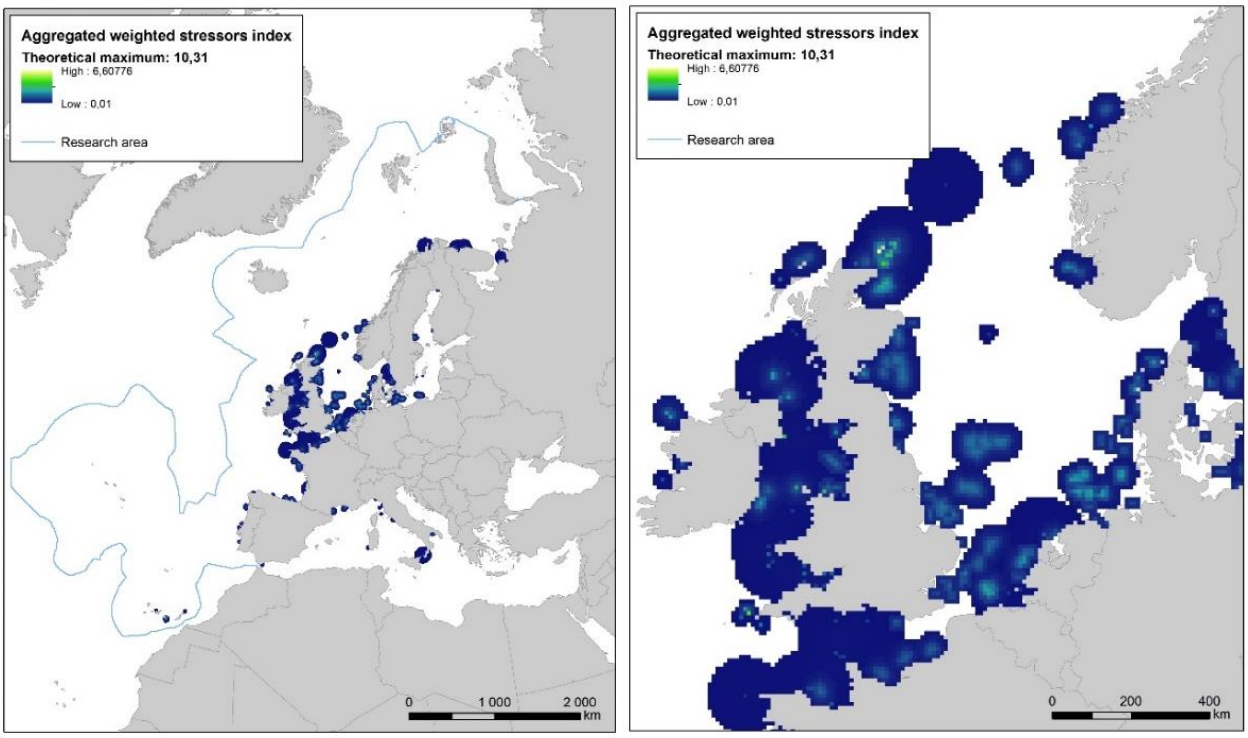


Figure 16: Aggregated ecological sensitivity index. All three analysed offshore renewable energy production methods (wind, tidal, wave) are aggregated into one index. An ecological sensitivity index is a sum of all ecosystem components weighed by their mean sensitivity scores. Stressors are not included in an ecological sensitivity index. Note that the index does not show ecological resilience, rather it shows hot spots with ecosystem components that are sensitive to the activity in question.

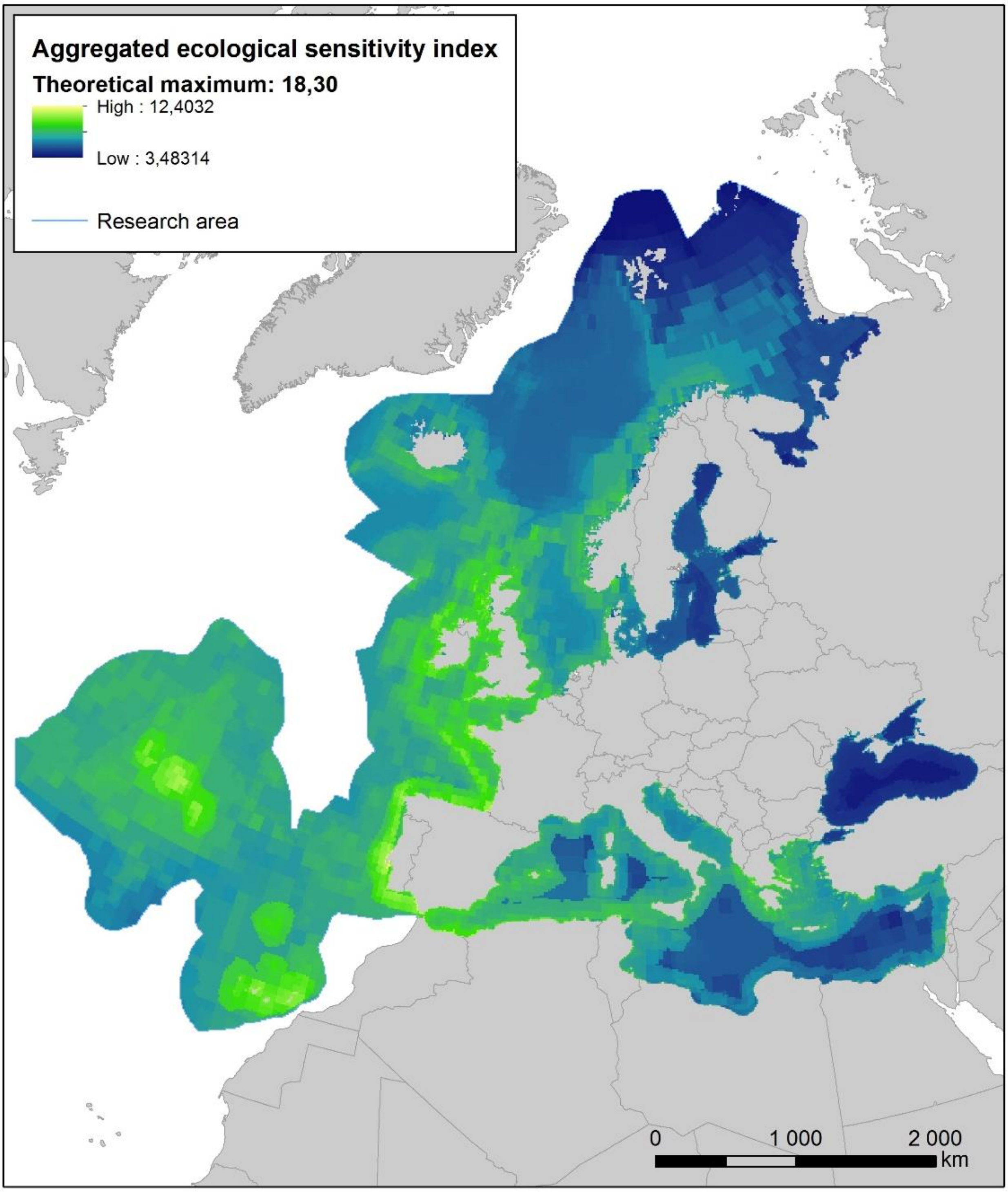
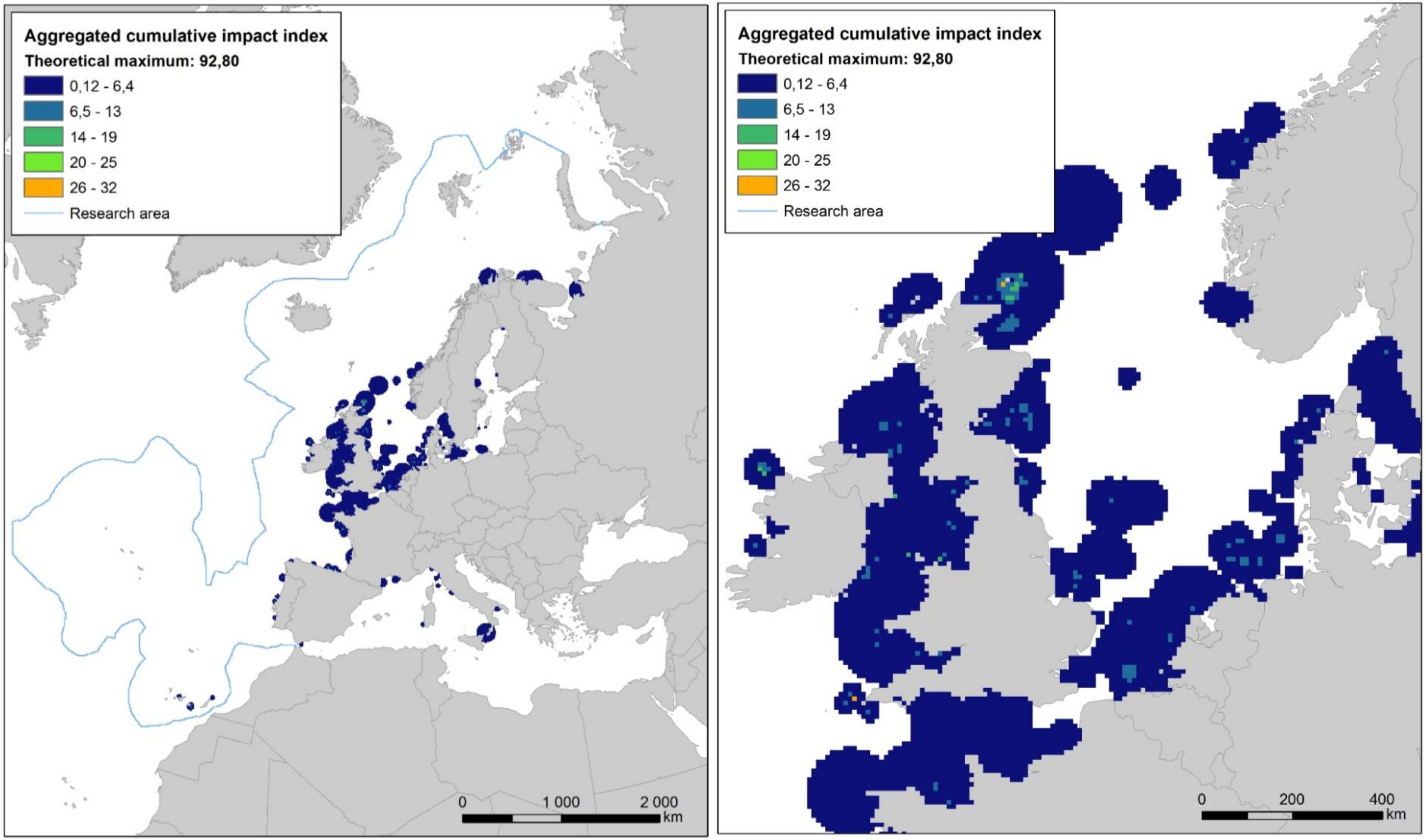


Figure 17: Aggregated cumulative impact index, whole research area and the North Sea. All three analysed offshore renewable energy production methods (wind, tidal, wave) are aggregated into one index. A cumulative impact index shows the summed effects of stressors on ecosystem components. The effect of each stressor on each ecosystem component is determined by the assigned sensitivity score (ranging from 0 to 5).



5 Maritime Spatial Planning approaches to manage environmental risk of offshore energy

While offshore renewable energy holds large potential for reaching climate objectives, its potential negative effects on marine biodiversity conservation must be taken into consideration. The health of marine ecosystems in the EU is already severely compromised; many species and habitats are in an 'unfavourable conservation status' and the condition of marine ecosystems is generally not 'good' (European Environment Agency, 2019). Despite efforts of Member States to halt it, the loss of marine biodiversity continues, driven by sea-based activities, upstream land-based activities and the impacts of anthropogenic climate change (European Environment Agency, 2019). As outlined elsewhere in this report (see Section 3) the construction, operation and decommissioning of offshore energy infrastructure could add to already existing pressures on marine ecosystems.

MSP is a tool to manage the increasing activities taking place at sea; it can also help to balance potential trade-offs between climate and environmental objectives in the development of offshore renewable energy. The EU MSPD (Directive 2014/89/EU) was adopted in 2014 with the objective of promoting the sustainable coexistence of different activities and uses of the European seas. It requires Member States to develop maritime spatial plans by 31st March 2021. It sets a number of minimum criteria for the maritime spatial plans, requiring Member States to consider the environmental, economic and social aspect, apply ecosystem-based approaches, involve stakeholders, among other requirements (Peters et al., 2020). This chapter considers four recently published maritime spatial plans by Finland, Ireland, Latvia and Belgium, and analyses how they reconcile the need to expand their renewable energy systems while at the safe time safeguarding marine ecosystems.

5.1 Review of the policy framework

In this section, we give an overview of the most relevant and recent policies, strategies, and directives for managing the environmental impacts of the development of offshore energy. This includes those focussed on both offshore renewable energy and marine environmental protection, as well as those aimed at managing potential conflicts between different marine activities (see Table 10 for an overview)[6]. Taken together, these policies aim at climate change mitigation, sustainable economic development, and marine environmental protection. While these policy objectives are related to each other and synergies exist, there are also potential trade-offs. This will be analysed in the following section.

It should be noted that the policy framework for the planning and deployment of offshore renewable energy is evolving to accommodate the growing need for renewable energy and achieve Europe’s emission reduction targets. For example, in May 2022 the European Commission adopted the REPower EU package which proposes to revise the Renewable Energy Directive to accelerate the permitting of renewable energy installations (European Commission, 2022). This may also have an influence on how potential trade-offs between offshore renewable energy and marine environmental protection are handled.

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[6] In addition to the MSP Directive and SEA Directive, the European Commission provides a number of tools supporting the management of the marine environment. An essential input is the data produced or compiled by the Commission, including satellite data from the Copernicus programme, spatial data gathered by EMODnet, along with economic and environmental data collected by EUROSTAT and the European Environment Agency (for example in WISE Marine). The importance of these data streams has been recognised and supported by EU Strategies, such as the EU Sustainable Blue Economy Strategy, which directs funding towards data development.

Table 10 Overview of policies included in the review

Name	Year	Objective
Offshore Renewable Energy Strategy	2020	Make offshore renewable energy a core component of the European energy system by 2050.
Sustainable Blue Economy Strategy	2021	Promote the Sustainable Blue Economy and embed it into the transition envisioned by the Green Deal and the EU Recovery Plan.
Nature directives (Birds Directive and Habitats Directive)	2009/ 1992	Conserve biodiversity by maintaining or restoring habitats and species to a ' favourable conservation status'
Marine Strategy Framework Directive	2008	Protect, preserve and restore the marine environment into a 'Good Environmental Status'.
Biodiversity Strategy for 2030	2020	Put Europe's biodiversity on the path to recovery by 2030 by addressing changes in land and sea use, overexploitation, climate change, pollution, and invasive alien species.
Maritime Spatial Planning Directive	2014	Promote the sustainable coexistence of different activities and uses of the European seas through maritime spatial planning.
Strategic Environmental Assessment Directive[7]	2001	Regulate the integration of environmental considerations into the preparation and adoption of public plans and programmes.

5.1.1 Offshore Renewable Energy Strategy

Objectives: The Offshore Renewable Energy Strategy (European Commission, 2020b) outlines how to make offshore renewable energy a core component of Europe's energy system by 2050. This is necessary both to meet Europe's climate targets[8] and its rising electricity demand. The EU has installed offshore wind capacity of 14.6 GW (Akar and Akdoğan, 2016); floating offshore wind, wave and tidal energy are not yet implemented at scale. The Strategy recalls that by 2030 the Commission aims to have installed a capacity of at least 60 GW of offshore wind and 1 GW of ocean energy (i.e., wave and tidal energy), with a view to reach 300 GW and 40 GW, respectively, by 2050.

Measures: As a strategy, this policy document contains no enforceable management measures. To reach its goals, the Strategy instead calls for an estimated EUR 800 billion from private and public sources for infrastructure and research, the strengthening of supply and value chains across Europe and a predictable and stable legal framework to reduce investment risks. In addition to supporting the decarbonisation of Europe, the strategy aims to deliver jobs and economic growth and contribute to a sustainable recovery from the COVID-19 pandemic. It moreover states that developing Europe's offshore renewable energy sector also requires facilitating the coexistence of offshore installations and other uses of the sea space such as fishing, aquaculture and biodiversity protection. To manage potentially conflicting offshore energy and environmental objectives, such as achieving GES in accordance with the MSFD, the Strategy calls for the

[7] We did not include the Environmental Impact Assessment (EIA)Directive (85/337/EEC) in our analysis, because MSP plans are subject to SEAs, and not to EIAs. However, EIAs are significant for the permitting of concrete offshore renewable energy projects.
[8] The EU aims to cut greenhouse gas emissions by at least 55 % by 2030 and reach climate neutrality by 2050, as set out in the European Climate Law and the 2030 Climate Target Plan.

timely development of maritime spatial plans by national governments under the MSPD. The Strategy moreover calls for multi-use of sea space to achieve sustainability, as well as advancing analysis and data collection capacities to better understand cumulative impacts on the marine environment. It mentions that reaching the EU's 2030 climate targets would require less than 3 % of the European sea space and can therefore be compatible with EU environmental legislation and the goals of the EU Biodiversity Strategy to 2030.

5.1.2 Sustainable Blue Economy Strategy

Objectives: The aim of the EU Sustainable Blue Economy Strategy (European Commission, 2021a) is to embed the Sustainable Blue Economy into the transition envisioned by the Green Deal and the EU Recovery Plan. The strategy calls for a shift from "blue growth" to a Sustainable Blue Economy", which treats the maritime industry, the environment and the economy as intrinsically linked. It aims to replace "unchecked expansion with clean, climate-proof and sustainable activities that tread lightly on the marine environment".

Measures: The Strategy contains no enforceable management measures. Instead, it aims to achieve its objectives by cooperating with existing initiatives, launching new or adjusting existing funding measures, or developing action plans. It mentions that offshore energy could help reach climate targets and generate a quarter of the EU's electricity in 2050. To reach this target, the document refers to the EU Offshore Renewable Energy Strategy (see 5.1.1). In addition, biodiversity conservation and protection are highlighted as foundational principles of maritime economic activity in line with the EU Biodiversity Strategy for 2030 (see 5.1.5). In order to realize the potential of the Sustainable Blue Economy, the strategy underlines the need for high-quality ocean data, targeted research, sustainable public and private investment and addressing skills shortages in blue jobs. It estimates that in the offshore wind energy sector alone, the number of jobs could triple by 2030. In addition, the strategy stresses the importance of MSP to prevent conflict between policy priorities and overexploitation of marine resources. In order to further develop MSP, the strategy also announces that the European Commission will prepare a guidance on how to implement an ecosystem-based approach to maritime spatial planning and promote the multi-use of sea space (European Commission, 2021c), which has since been published.[9]

5.1.3 Nature directives (Birds Directive and Habitats Directive)

Objectives: The Birds Directive (Directive 2009/147/EC) and the Habitats Directive (Council Directive 92/43/EEC), often referred to as the 'nature directives', are the backbone of EU biodiversity protection. The objective of the Habitats Directive is to conserve biodiversity by maintaining or restoring habitats and species to a 'favourable conservation status'; the Birds Directive specifically targets the protection of wild birds and their habitats.

Measures: Under the Habitats Directive, Member States designate Special Areas of Conservation (SACs) to ensure the conservation of over 200 types of habitats and more than 1000 plant and animal species, of which nine habitat types and eighteen species are marine[10]. Under the Birds Directive, Special Protection Areas (SPAs) are designated for 194 particularly threatened species and all migratory bird species. The protection of 64 of the particularly threatened bird species requires the protection of marine sites

[9] https://maritime-spatial-planning.ec.europa.eu/msp-resources/msp-tools-and-guidance

[10] The nine marine habitat types considered in the Habitat's Directive are sandbanks, *Posidonia* beds, estuaries, mudflats and sandflats not covered by sea water at low tide, coastal lagoons, large shallow inlets and bays, reefs, submarine structures made by leaking gases, submerged or partially submerged caves. The full list of marine species can be found in the referenced document (European Commission, 2007).

(European Commission, 2007). Members States shall also strive to avoid pollution or deterioration of habitats outside of the protected areas. Together, SACs and SPAs form the EU-wide Natura 2000 network of protected areas. It currently stretches over 18 % of the EU's land area and more than 8 % of its marine territory (European Environment Agency, 2020)[11].

5.1.4 Marine Strategy Framework Directive

Objectives: The objective of the MSFD (Directive 2008/56/EC) is to protect and preserve the marine environment, prevent its deterioration or, where feasible, restore marine ecosystems in areas where they have been adversely affected. It also aims to enable the sustainable use of marine goods and services by present and future generations. The Directive sets out that Member States should achieve or maintain GES by 2020 (now, 2027). The criteria for reaching GES in a marine region or sub-region are determined by Member States. The Directive proposes eleven qualitative descriptors of GES concerning i) biological diversity, ii) non-indigenous species; iii) populations of commercially exploited fish; iv) marine food webs; v) human-induced eutrophication; vi) sea-floor integrity; vii) permanent alteration of hydrographical conditions; viii) contaminant concentrations; ix) contaminants in fish and other seafood for human consumption; x) marine litter; and xi) introduction of energy, including underwater noise[12].

Measures: Member States must identify indicators and specify environmental targets to monitor their progress towards GES. After deciding on the criteria, Member States draw up a Programme of Measures to reach GES. Types of measures proposed by the Directive include i) input controls; ii) output controls; iii) spatial and temporal distribution controls; iv) management coordination measures; v) measures to improve the traceability of marine pollution; vi) economic incentives; vii) mitigation and remediation tools; and viii) communication and stakeholder involvement. Member States are free to decide which measures to include but shall ensure that they are cost-effective and technically feasible and carry out impact assessments, including cost-benefit analyses, prior to the introduction of any new measure. Initially Member States were to reach GES by 2020, but progress has not been fast enough (European Commission, 2020a). Achieving GES of marine ecosystems has subsequently been included as one of the objectives of the Biodiversity Strategy for 2030 (see 5.1.5).

5.1.5 Biodiversity Strategy for 2030

Objectives: The Biodiversity Strategy for 2030 (European Commission, 2020c) outlines the Commission's plan to protect and restore biodiversity. It addresses five drivers of biodiversity loss (changes in land and sea use, overexploitation, climate change, pollution, and invasive alien species) to put Europe's biodiversity on the path to recovery by 2030. Moreover, the Strategy aims to support a sustainable economic recovery from the COVID-19 crisis through biodiversity-related business and investment opportunities.

Measures: To reach these goals, the Strategy calls for the full implementation of existing EU environmental legislation and the enhancement of the governance framework to fill remaining gaps. A key element is the commitment to protect a minimum of 30 % of the EU's land and sea, and to strictly protect at least a third of these, to build a coherent Trans-European Nature Network. The Biodiversity Strategy also announces the publication of an EU Nature Restoration Strategy with binding targets, a proposal for which is expected

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[11] When considering not only SACs and SPAs under the EU nature directives, but also those established under national designations and the Regional Sea Conventions, then the European MPA network covers approximately 12 % of Europe' seas (Agnesi *et al.*, 2020).

[12] If a Member State considers one or more of the proposed descriptors as not appropriate, they are not obliged to use it when determining GES. The decision needs to be justified to the Commission.

in 2021. It further specifies the aim of no deterioration in conservation trends and status of all protected habitats and species by 2030 and that at least 30 % of species and habitats not currently in a favourable status are in that category or show a strong positive trend by 2030. Regarding marine ecosystems, the Strategy calls for the full implementation of the MSFD, the Birds Directive and Habitats Directive and the Common Fisheries Policy, as well as for the application of the MSPD[13].

5.1.6 Maritime Spatial Planning Directive

Objectives: The MSPD (Directive 2014/89/EU) sets out that Member states develop maritime spatial plans which “consider economic, social and environmental aspects to support sustainable development and growth in the maritime sector, applying an ecosystem-based approach, and to promote the coexistence of relevant activities and uses.” The Directive specifically mentions the objectives of contributing to the sustainable development of energy sectors at sea, as well as increasing the resilience of marine sea areas to climate change impacts.

Measures: Member States decide on the design, format and content of their maritime spatial plans; the Directive does not impose any obligations on how to pursue sectoral policies in the areas of energy, transport, fisheries and the environment or on how to weigh different policy objectives. However, it sets out certain minimum requirements: plans must i) take into account land-sea interactions; ii) consider environmental, economic and social aspects, as well as safety aspects; iii) promote coherence between maritime spatial plans and other plans or processes; iv) ensure the involvement of stakeholders; v) use the best available data; vi) ensure transboundary cooperation with both EU Member States and third countries; and vii) apply an ecosystem-based approach. Maritime spatial plans are subject to a strategic environmental assessment under the Strategic Environmental Assessment Directive and to additional assessments as required by the Bird and Habitats Directives to ensure the protection of habitats and species.

5.1.7 Strategic Environmental Assessment Directive

Objectives: The Strategic Environmental Assessment Directive (Directive 2001/42/EC) prescribes the integration of environmental considerations into the preparation and adoption of public plans and programmes (Directive 2001/42/EC)[14]. Member States are required to carry out a strategic environmental assessment of any plans or programmes that are likely to have a significant environmental effect, explicitly mentioning plans/programmes in the policy areas energy, fisheries, and tourism, among others[15].

Measures: If a Strategic Environmental Assessment (SEA) is required for a specific plan or programme, the first step is the preparation of an environmental report that identifies, describes, and evaluates its likely effects of the environment and reasonable alternatives. The environmental report alongside the draft plan

[13] The Strategy mentions the importance of renewable energy to fight climate change and biodiversity loss and makes a brief reference to ocean energy and offshore wind. Further attention is however only paid to bioenergy. In addition, the Strategy proposes aims and actions regarding agriculture, soils, forest, freshwater ecosystems, pollution and invasive alien species.

[14] The EU Strategic Environmental Impact Directive is a transposition of the Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention).

[15] We do not include the Environmental Impact Directive in our review, as our focus is on EU and Member State policy, which are managed by the SEA Directive. The Environmental Impact Directive regulates reviews of individual projects; while therefore important for managing individual offshore energy projects, this makes it less relevant when considering environmental impacts of policies and plans (which are covered by the SEA).

or programme becomes available to national environmental authorities and the public for stakeholder consultations. If the plan or programme has environmental impacts beyond national borders, the report also becomes available to neighbouring countries for a transboundary consultation. The Directive sets out that the environmental reports and the results of the consultation shall be considered during the preparation of the plan or programme and before its adoption or submission to the legislative procedure. It moreover specifies that Member States shall give a statement summarising how environmental considerations have been considered in the adoption of the plan or programme. After the adoption, Member States are required to monitor the environmental effects of the implementation of plans and programmes and take remedial action when unforeseen adverse effects occur.

5.2 Synergies and trade-offs between policies

The policy overview presented in the previous section identified multiple objectives related to the development of offshore renewable energy and marine environmental protection. To investigate the potential for policy objective alignment or conflict, in this section, we categorise their objectives into three overarching policy aims: climate change mitigation, sustainable economic development, and marine environmental protection. For each of these overarching aims, we summarise the specific objectives set out in the Offshore Renewable Energy Strategy and relevant environmental policies, identifying synergies and potential conflicts. Because the directives and strategies we assess are issued at the European level, they only offer a first insight into the potential for conflict. What happens in practice depends on the actual transposition of the directives and the implementation of the policies at the national and local level; we analyse how environmental and offshore energy objectives are managed in maritime spatial plans in section 5.3.1. As summarised in Figure 18, our evaluation finds that in regard to the overarching aims of climate change mitigation and sustainable economic development, the assessed directives and strategies are generally aligned. However, there is the potential for conflict between the Offshore Renewable Energy and Sustainable Blue Economy Strategies and policies targeted at marine environmental protection.

Figure 18: Trade-offs and synergies between offshore energy and marine environmental protection policies

	Climate Change mitigation	Sustainable economic development	Marine environmental protection
Offshore Renewable Energy Strategy	Alignment	Alignment	Need to balance
Sustainable Blue Economy Strategy	Alignment	Alignment	Need to balance
Biodiversity Strategy for 2030	Alignment	Alignment	Alignment
Marine Strategy Framework Directive	Weak/ indirect alignment	Weak/ indirect alignment	Alignment
Nature directives	Weak/ indirect alignment	Not mentioned	Alignment

Colour legend

Alignment	Weak/ indirect alignment	Not mentioned	Need to balance

5.2.1 Climate change mitigation

Climate change mitigation refers to the EU objective of reducing greenhouse gas emissions and increasing sequestration of greenhouse gas emissions. Both the Offshore Renewable Energy Strategy and the Biodiversity Strategy for 2030 have the mitigation of climate change as a core objective. The Offshore Renewable Energy Strategy presents itself as key to achieving EU climate targets, because of the role that offshore renewable energy can play in decarbonisation. The Biodiversity Strategy specifically mentions that it is in line with the objectives of the Paris Agreement on Climate Change, promoting nature-based solutions for climate change mitigation. In addition, the success of the Biodiversity Strategy to halt and reverse biodiversity loss depends on effective climate action, because climate change is one of the five main drivers of biodiversity loss. The success of the Biodiversity Strategy is thus partially supported by the implementation of the Offshore Renewable Energy Strategy. The Biodiversity Strategy mentions that "sustainably sourced renewable energy will be essential to fight climate change and biodiversity loss" and specifically highlights solutions such as ocean energy and offshore wind. The Sustainable Blue Economy Strategy is aligned with the Offshore Renewable Energy Strategy and also proposes using EU funds to decarbonise ports and ships and support low-carbon short-sea shipping.

The MSFD and the nature directives make no mention of climate change mitigation. However, climate change is a threat to marine habitats and species and thus negatively impacts the EU's ability to reach GES in its marine waters and protect habitats and species[16]. Because the health of the marine environment is highly dependent on counteracting climate change, these directives are indirectly aligned with the climate change mitigation objectives of the Renewable Offshore Energy Strategy.

5.2.2 Sustainable economic development

Sustainable economic development refers to the EU objective of economic growth that is aligned with environmental and social sustainability. The Offshore Renewable Energy Strategy, the Biodiversity Strategy for 2030 and the Sustainable Blue Economy Strategy position themselves as contributors to sustainable economic development. The Offshore Renewable Energy Strategy notes that "decarbonising the energy system is critical for climate neutrality, as well as for the EU's recovery from the COVID-19 crisis and long-term prosperity". It focusses on the potential benefits in terms of jobs and growth from a development of ocean and wind energy, while the Biodiversity Strategy focuses on the business and investment opportunities connected to biodiversity. The Sustainable Blue Economy Strategy aims to create "tangible new opportunities for jobs and businesses" across the blue economy. The MSFD does not directly aim at sustainable economic development, but it holds that the Programmes of Measures developed in order to reach GES "shall give due consideration to sustainable development and, in particular, to the social and economic impacts of the measures envisaged". The nature directives do not contain any economic considerations.

5.2.3 Marine environmental protection

Marine environmental protection refers to the EU objective of reducing pressures on marine ecosystems and promoting ecosystem protection and restoration. There is potential for a need to manage trade-offs between the Offshore Renewable Energy Strategy and the Sustainable Blue Economy Strategy, on the one hand, and the MSFD, the EU Biodiversity Strategy for 2030 and the nature directives, on the other hand, about the protection of the marine environment. Unlike the other policies, the Offshore Renewable Energy Strategy does not have specific objectives with regard to the protection of the marine environment. It does however state that reaching the EU 2030 climate targets would require less than 3 % of the European sea space and can therefore be compatible with EU environmental legislation and the goals of the EU Biodiversity Strategy to 2030. The strategy thus advocates for the "sound coexistence between offshore installations and other uses of the sea space", including environmental protection. The Sustainable Blue Economy Strategy reiterates the importance of implementing the Offshore Renewable Energy Strategy, while also making references to protecting the marine environment.

[16] This alignment is identified by the EU Commission guidance on climate change and the Natura 2000 network, which highlights the effects of climate change, as well as the potential of the Natura 2000 sites for climate change mitigation and adaptation (European Commission, 2013).

However, it should be noted that using 3 % of the total European sea space for renewable offshore energy might represent a much larger proportion of certain habitat types. Not all sea areas are equally suitable for the construction of offshore wind power, because site selection depends on factors such as bathymetry, sea floor composition and average wind speeds. The Offshore Renewable Energy Strategy does not consider the impact of offshore renewable energy development on specific habitats and their biodiversity. And while it states that only 3 % of the sea would be required to reach 2030 climate goals, it gives no indication of the space needed for reaching the 2050 offshore energy generation targets. There is potential here for competition with the spatial objectives of the other policies, including the Biodiversity Strategy for 2030's commitment to designating 30 % of European marine space for marine protected areas, of which 10 % should be strictly protected.

Given the environmental risks associated with the construction and operation of offshore renewable energy, its further development needs to be considered alongside other objectives such as to reach GES of marine regions under the MSFD, protect Natura-2000 sites and species and halt and reverse biodiversity loss. The MSFD, EU Biodiversity Strategy and nature directives make many explicit references to protecting the marine environment. In addition to requiring 30 % of sea space to be protected and 10 % strictly protected under the Biodiversity Strategy by 2030, the policies include specific protections for threatened marine habitats and species and address human activities and their pressures on the marine environment.[17]

In order to prevent conflict between marine environmental protection and the development of offshore renewable energy, as well as other uses of the sea, both the Offshore Renewable Energy Strategy and the Sustainable Blue Economy Strategy highlight the importance of MSP in order to a realise multi-use approach to the sustainable development of maritime economic activities. Whether the potential for conflict between the Offshore Renewable Energy Strategy, the Sustainable Blue Economy Strategy and EU marine environmental policies can be successfully handled, and further deterioration of marine spaces prevented, depends not only on the implementation of the MSFD, the Biodiversity Strategy and the Nature Directives, but also on the implementation of maritime spatial planning and strategic environmental assessments in practice.

5.3 Introduction to Maritime Spatial Planning

The maritime space is increasingly crowded and interactions between different users and activities, as well as between the land and the sea, are becoming more frequent. In other words, the ocean is no longer a frontier but is instead becoming a "contact point and boundary object for a variety of political, economic and environmental interests and views" (Ehler et al., 2019). MSP is a tool for managing the resulting competition for sea space. Discussions around MSP in Europe began in earnest around 2000; the first sub-national maritime spatial plans were published by the German state of Mecklenburg-Vorpommern in 2005 (Ehler et al., 2019). Since then, an EU policy framework for MSP has developed, building on progress towards integrative approaches to EU environmental policy[18], and resulting in the adoption of the MSPD in 2014 (Directive, 2014/89/EU). A key driver behind many MSP initiatives in Europe was the increasing spatial demands of offshore wind energy (Quero García et al., 2019).

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[17] In 2020, the European Commission published a guidance document on wind energy developments and EU nature legislation, see European Commission. 2021. Communication C (2020) 7730 final on a guidance document on wind energy developments and EU nature legislation.

[18] See for example the EU Green Book, EU Blue Book, and the 2007 EU Action Plan (Ehler *et al.*, 2019).

The MSPD defines MSP[19] as a "process by which the relevant Member State's authorities analyse and organise human activities in marine areas to achieve ecological, economic and social objectives". In the EU, maritime spatial planning is primarily a legal requirement that Member States must fulfil, i.e., Member States shall submit maritime spatial plans to the European Commission. How these maritime spatial plans are created, and which form they take is up to the Member States.

The academic literature contains alternative interpretations of MSP, which are useful for understanding what is at stake in MSP processes. Ehler et al. (2019) do not focus on the required output, i.e., the maritime spatial plans, but instead highlight that MSP can be understood as a public choice process, which is based on democratic decision-making to manage the use of marine resources and space and avoid overexploitation. While they acknowledge that MSP processes follow pre-determined procedures, Ehler et al. (2019) remind us that MSP remains a highly social and political process. Accordingly, they underscore the need for equal representation of stakeholders in the process in order to ensure a balance of power.

As discussed, there is a need to address trade-offs and prevent conflict between marine conservation and offshore renewable energy (see Section 1). Both the EU Offshore Renewable Energy Strategy and the Sustainable Blue Economy Strategy point to maritime spatial planning as a tool for reaching energy and climate objectives while at the same time safeguarding the marine environment. Similarly, the academic literature has identified that MSP can facilitate the widespread deployment of offshore renewable energy by addressing various factors which are currently limiting its expansion, such as the negative environmental impact of offshore energy; its high spatial requirements; competition and diverging interests among maritime sectors; sectoral management of sea-based activities; difficulties in land-sea coordination; as well as institutional and management shortcomings in the governance of the European sea space (Quero García et al., 2019).

There are different ways of thinking about how MSP processes and the resulting plans can contribute to resolving the non-technical barriers:

- *Conflict prevention vs. conflict mitigation:* Conflict prevention seeks to avert spatial competition, for example through preventing those incompatible activities occur in the same space. This requires a degree of foresight concerning sectoral trends and future spatial pressures. Conflict mitigation seeks to soften the impacts of spatial competition, for example by means of compensatory measures. Mitigation is relevant for unavoidable conflicts resulting for example from past siting decisions (Gee et al. 2018).
- *Spatial vs. non-spatial solutions:* Both conflict prevention and mitigation can be achieved either through spatial and non-spatial solutions. Examples of spatial solutions are minimum distances, designation of corridors or seasonal closures, while non-spatial solutions could be encouraging mutual understanding between sectors, technical solutions to mitigate impacts or compensation schemes (Gee et al., 2018).
- *Area-based vs. criteria-based approach*: It is also possible to distinguish between an area-based vs. criteria-based approach to the management of maritime space. The former sets aside specific areas for activities, whereas the latter allows activities fulfilling certain criteria, for example complying with pre-determined environmental standards (Quero García et al., 2019).
- *MSP solutions vs non-MSP solutions*: Not all barriers can be overcome during the MSP process, because certain things require other actors or institutions. These solutions can, however, be negotiated in parallel with the MSP process, if they support the overall objective of the maritime

[19] The European Commission uses the term *maritime* spatial planning, while other actors, e.g., UNESCO, refer to *marine* spatial planning. While some use these terms interchangeably, it has been suggested that the European Commission (using the term *maritime*) focusses on minimising conflicts between sectors, while UNESCO (using the term *marine*) places emphasis on ecological and environmental issues (Ehler *et al.*, 2019).

spatial plan. Examples of regulations or actions which support plans, but need to be advanced outside of the official MSP process, include speed restrictions on shipping, promoting research and innovation in maritime sectors, or employing Particularly Sensitive Sea Area (PSSAs)[20] or other sectoral designations for MSP purposes (Gee et al., 2018). Thinking about both MSP and non-MSP solutions to maritime challenges in unison is important, because maritime spatial plans can and should not replace sectoral planning and programming (Ehler et al., 2019).

The MSPD gives limited guidance with regards to the required MSP process and outcome and many decisions rest with Member States[21]. As a result, the practice of MSP in the European Union is highly diverse. How MSP unfolds in practice depends on the degree of desired specificity of the maritime spatial plan, the integration and legal power of the plan, the scope and methods of stakeholder engagement, as well as on national planning culture and experience (Ehler et al., 2019). In addition, the physical characteristics of the sea space to be managed, the activities and prevailing uses of the sea area in question, the given regulatory and institutional framework, as well as the level of maturity of the offshore renewable industry and other maritime stakeholders exert an influence (Quero García et al., 2019). The European MSP Platform funded by the EU Directorate General for Maritime Affairs and Fisheries (DG MARE) offers guidance and information to EU Member States.[22] Also, the choice of competent authority for MSP may have implications for the integration of the maritime spatial plan with other policies, i.e., it matters whether a ministry of environment or a ministry of infrastructure leads the MSP process. The choice of MSP authority may also influence the prioritisation of different objectives throughout the planning process, for example influencing how shipping, environmental protection, or development of offshore energy are considered (Quero García et al., 2019). The final maritime spatial plan can take the form of an informative report, strategic guidance document or a binding law, depending on the national transposition of the MSPD and the national policy framework for MSP (Ehler et al., 2019).

While the final maritime spatial plan and its implementation are important, the process leading up to the adoption of the plan by a national government can be as, or even more important. The MSP process, often stretching over many years and ideally involving a broad range of stakeholders, can foster dialogue, build trusts between actors and secure a diverse engagement in the management of the maritime space for the long-term. It is more than mere administrative decision-making producing static outcomes. Ehler et al. (2019) posit that the practice of maritime spatial planning should be dynamic and process oriented, possibly involves the use of vision-based tools or scenarios and use the degree of mobilisation as a measure of success. In practice, some participatory MSP processes have been criticised for being limited to mere consultation meetings, being dominated by active or elite stakeholders, lacking inclusiveness, or aiming to legitimise management measures and policy decisions rather than facilitating meaningful participation (Steins et al., 2021). Besides meaningful stakeholder engagement, data and knowledge are crucial during the MSP process in order to allow for efficient and safe planning, ensure the protection of the marine environment and monitor progress (Quero García et al., 2019).

Ideally, MSP is a continuous process that is not completed with the publication of one maritime spatial plan. Demands and interests change over time, new data is collected, and plans should be developed and revised accordingly. The evaluation of MSP processes and plans by national governments may help in

[20] A Particularly Sensitive Sea Area (PSSA) is an area that needs special protection through action by the International Maritime Organisation (IMO).

[21] According to the MSPD, MSP processes need to take into account land-sea interactions; take into account environmental, economic and social aspects, as well as safety aspects; promote coherence between maritime spatial planning and the resulting plan or plans and other processes; ensure stakeholder involvement; use the best available data; and ensure transboundary cooperation and cooperation with third countries.

[22] https://maritime-spatial-planning.ec.europa.eu/msp-resources/msp-tools-and-guidance

identifying corrective measures and possible improvements, and thus play an important role in this continuous learning process. In addition, they can generate accountability, trust and legitimacy (Varjopuro, 2019).

5.3.1 Evaluation of maritime spatial plans

The directives and strategies introduced in section 5.1 are issued at the EU policy level, which makes it challenging to evaluate how they manage potential trade-offs between climate objectives, economic objectives, and other environmental objectives in practice at the national and local level. To evaluate how these different objectives are balanced on the ground, we look to recently published maritime spatial plans and accompanying documents. Given this report's focus on offshore renewable energy, we are especially interested in how maritime spatial plans balance potential trade-offs between the objectives of the EU Offshore Energy Strategy[23] and other marine environmental policies. The outcomes of this evaluation can help further improve MSP in Europe by providing cross-European evidence of alternative MSP processes, formats and outcomes, and highlighting how these address the potential trade-offs between offshore renewable energy and marine environmental protection.

The first step of the analysis was to identify available maritime spatial plans, environmental assessments and other relevant accompanying documents (see Table 11). Three criteria were applied to the selection of cases:

I. The maritime spatial plan has been established and has legal effect. Neither final maritime spatial plans awaiting approval nor draft plans were included in the analysis.

II. The maritime spatial plan has been established after 2018. This guarantees that plans were drafted in a comparable EU policy context regarding the development of offshore renewable energy.

III. The maritime spatial and environmental assessments, or at least a summary thereof, are available in English, French or Dutch.

According to the MSPD, Member States had to establish their updated or first maritime spatial plans no later than 31st March 2021. As of October 2021, most member states have adopted their plans, or have finalised draft plans that are pending for approval. Based on the availability at the start of writing this report (see Table 11), the maritime spatial plans by Belgium, Finland,[24] Ireland and Latvia were chosen for analysis (see Annex 4 for list of documents considered in the analysis). Poland's recent maritime spatial plan could not be considered due to language limitations.

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[23] The EU Offshore Renewable Energy Strategy was only adopted in 2020 and therefore not directly considered in the drafting of the maritime spatial plans discussed here. However, all countries investigated already had the objective to develop their offshore renewable energy sectors before, independently of the publication of the Strategy.
[24] This does not include analysis of the maritime spatial plan for the autonomous province of Åland Islands.

Table 11 Availability of maritime spatial plans (as of 14 July 2021)

Status	Total number	Country	Language of maritime spatial plan	Language of the environmental assessment(s)
Final maritime spatial plan approved	7	Belgium (2020)	English (Annexes only in Dutch and French)	Dutch, French
		Finland (2020)	English	English
		Latvia (2019)	English	Latvian (English summary only)
		Ireland (2021)	English	English
		Poland (2021)	Polish	Polish
		Portugal (2019)	Portuguese	Portuguese
		Malta (2015)	English	English
Final maritime spatial plan awaiting adoption	3	Sweden, Lithuania, Slovenia		
Draft maritime spatial plan available	8	Denmark, Bulgaria, Estonia, France, Germany, Spain, Netherlands*, Romania		
MSP process ongoing	4	Croatia, Cyprus, Greece, Italy		

**The Netherlands also has an approved maritime spatial plan from 2016.*

To evaluate the maritime spatial plans and environmental assessments, we iteratively developed an evaluation template to describe how they manage climate and environmental objectives in a structured and consistent way. The structure of the template and the criteria that were used to evaluate and describe the plans and environmental assessments within the template were identified by building on the policy evaluation and the MSP literature review (see Annex 3 for the template). The templates were used as working documents to record and organise relevant information from the maritime spatial plans and environmental assessments.

Following the completion of draft templates, we summarized the most relevant information, which is presented per Member State. These summaries describe the context, the MSP process and the final plan, and then focus on treatment of offshore energy/climate and broader environmental objectives, as well as how the maritime spatial plan manages trade-offs between these, as well as how plans will be implemented.

Cross-cutting analysis of the maritime spatial plans is presented in Table 11 and section 5.3.2. Table 11 summarises key attributes of the maritime spatial planning process and outcome, allowing comparison across the different plans assessed, while section 5.3.2 identifies conclusions from the MSP analysis.

Table 12 Comparative overview of maritime spatial plans[25]

Topic	Characteristics	Belgium (2020)	Finland (2020)	Ireland (2021)	Latvia (2019)
Context	Size of sea area (Economic Exclusive Zone; EEZ)	3,454 km²	83,210 km²	488,762 km²	28,500 km²
	Installed offshore renewable energy (ORE) capacity	2.2 GW	71 MW	30 MW	None
	% of EEZ covered by ORE	3.75 %	0.01 %	0.0006 %	n.a.
	ORE policy targets	4 GW offshore wind by 2030	No specific target, but development foreseen	5 GW offshore wind by 2030, 30 GW of offshore floating wind in the long term	800 MW of (onshore and offshore) wind by 2030, no specific offshore target
	% of sea area covered by marine protected areas	36 %	15 %	2.3 %	16 %
	Status of marine biodiversity	Mostly moderate, partially poor and bad	Mostly moderate, partially poor	Mostly moderate and partially poor near the shore, mostly good further offshore	Partially moderate, partially poor
Process	Governance level	National plan	Three regional plans	National plan	National plan
	Previous maritime spatial plan	2014	None	None	None
	Responsible agency	Minister of the North Sea, Marine Environment Service of the Federal Public Service for Health, Food Chain Safety and Environment	Finnish Regional Councils	Department of Housing, Local Government and Heritage	Ministry of Environmental Protection and Regional Development

[25] References are found in the corresponding country sections.

Topic	Characteristics	Belgium (2020)	Finland (2020)	Ireland (2021)	Latvia (2019)
	Stakeholder involvement	- 60-day public consultation in 2018 - 3 public stakeholder forums	- Two one-month electronic hearings in 2019 and 2020 - Stakeholder collaboration period from 2019-2020	- 3-month public consultation on the Baseline Report - 4.5-month public consultation on draft MSP 2019–2020 - Eleven stakeholder advisory group meetings in 2018–2021	- Two public consultations in 2015-2016 on the first draft MSP and 2018 on the second draft MSP - Four stakeholder meetings and two public hearing seminars between 2015 and 2017
Description	**Format**	Maritime spatial plan listing geographic coordinates of areas and permitted actions and/ or conditions for use + Annexes 1–4 (context and descriptions, vision document with principles and objectives for 2050, list of accepted and rejected actions for each marine use, maps) + SEA	Website containing three regional maritime spatial plans + Legislative framework, planning principles and process description + Three scenarios up to 2050 + Vision for the sustainable use of marine areas 2050 + Sector-specific roadmaps to 2030 + Impact assessment	Maritime spatial plan outlining Overarching Marine Planning Policies (OMPPs) and Sectoral Marine Planning Policies (SMPPs) + Appendices A-F (supporting actions, stakeholder engagement, upcoming spatial designation process, etc.) + Website with data and maps + SEA + Appropriate Assessment	Maritime spatial plan outlining strategic objectives, strategic priorities and zones for priority use of the sea + Annexes 1–3 (map, definition of priority uses, interests of neighbouring states) + SEA + Set of scenarios
	Zoning approach	Yes – legally binding	Yes – non-binding	No	Yes – non-binding
	Environmental assessments conducted	SEA	Impact assessment	SEA Appropriate Assessment	SEA
Offshore renewable energy (ORE)	**Additional ORE zones in maritime spatial plan**	Yes (7 % of sea area before, 15 % afterwards)	Yes (no exact % indicated)	n.a.	Yes (6 % of sea area allocated to potential wind park development)
	Explicit contribution of ORE to climate objectives	Yes	Yes	Yes	No

Topic	Characteristics	Belgium (2020)	Finland (2020)	Ireland (2021)	Latvia (2019)
	Consideration of ORE types	Explicit consideration of offshore wind, mention of other forms of ORE	Explicit consideration of offshore wind, mention of wave, solar, marine biomass and seawater for heating and cooling for long-term development	Explicit consideration of offshore wind (fixed and floating), mention of wave and tidal power for long-term development	Offshore wind
Marine environmental protection	**Additional environmental protection zones**	No	No (MPSs indicate ecologically significant marine underwater areas, without recommending their protection)	n.a.	Yes – potentially (maritime spatial plan indicates five investigation areas of nature values, where potential protected is investigated)
	Additional environmental measures (besides MPAs)	Principles	Principles for future development	Policies (eight environmental Overarching Marine Planning Policies, OMPPs)	Principles
Balancing of trade-offs	**Acknowledgement of trade-offs between ORE development and marine environmental protection**	Yes	Yes	Yes	Yes
	Process for managing trade-offs (besides existing regulation on environmental assessments)	- Principles - Requirement to consider climate impacts	- Consideration of environmental sensitivity, bird migratory routes and protected areas in indication of ORE zones	- Environmental OMPPs guide the development of ORE	- Priority of potential protected areas over wind power development - Consideration of environmental sensitivity in indication of ORE zones - Natura 2000 areas excluded from ORE development areas

Topic	Characteristics	Belgium (2020)	Finland (2020)	Ireland (2021)	Latvia (2019)
			- Natura 2000 areas excluded from ORE development areas		
	Objectives for multi-use/ co-existence	Yes – principle of "multiple use" to be the norm for all use of sea space	No	Yes – ambition to identify opportunities for multi-use between ORE and other activities	No
Implementation	**Implementation period**	2000–2026	2021–2030	2021–2030	2019–2030
	Monitoring and review	Ongoing monitoring and evaluation, review at least after six years	Ongoing monitoring and evaluation, review at least after ten years	Ongoing monitoring and evaluation, review at least after six years	Ongoing monitoring and evaluation, implementation report every six years

5.3.1.1 Belgium

Context: The total sea area of Belgium, its Exclusive Economic Zone (EEZ), covers 3,454 km², accounting for 0.5 % of the North Sea (European MSP Platform, 2021a). Up to 36 % of this area is designated as marine protected areas (MPA Atlas, 2021a)[26]. The biodiversity condition of the Belgian sea area is mostly moderate, although some zones are classified as poor or even bad (European Environment Agency, 2019)[27]. The maritime spatial plan allocates 15 % of the Belgian sea space to offshore energy[28]. There are currently six offshore wind farms in Belgian waters, with a total capacity of 2.2 GW (Belgian Offshore Platform, 2021). As of 2020, 3.75 % of the Belgian EEZ were covered by wind power farms (4C Offshore 2020)[29].

Process: The second Belgian maritime spatial plan ('Royal Decree establishing the marine spatial planning for the period 2020 to 2026 in the Belgian sea-areas') was adopted in May 2019 and came into force in March 2020. It is preceded by the first maritime spatial plan adopted in 2014, which was also legally binding. The authority on MSP is the Minister of the North Sea and the administrative authority rests with the Marine Environment Service of the Federal Public Service for Health, Food Chain Safety and Environment. The review process for the first Belgian maritime spatial plan began in 2017. Following informal consultation and feedback from the Belgian MSP Advisory Committee (made up of Belgian and regional government bodies), a draft plan was published in July 2018. This was followed by a 60-day consultation process, which included over 40,000 public responses. In addition, three public stakeholder forums were held. A SEA was published and open for consultation in parallel with the draft plan.

Description of plan: The Belgian maritime spatial plan was established through a legal instrument adopted by the government, a "Royal Decree", and is thus legally binding. The main body of the plan consists of short sections, each focused on a different marine use (e.g., research, nature conservation, energy/cables/pipelines, …). Each section lists geographic coordinates and a description of the activities that can occur in that area and/or conditions for activities operating in this area. In some cases, these also include justification for the area's proposed use. For example, text might state "Zones are delimited for the potential expansion of the ports of Ostend and Zeebrugge" with the condition that activity can only occur if it has obtained this Natura 2000-authorisation, justified by the fact that "the zone is important for the following species". The accompanying annexes provide background and additional detail and justification. Annex 1 provides context and descriptions, Annex 2 includes a vision document (with principles, 2050 objectives, and a section that details, for each marine use, the actions considered for the maritime spatial plan and justification for why or why not they were implemented), Annex 3 includes a list of supporting actions for the implementations of the plan, and Annex 4 consists of one map per marine use, and a combined map showing all uses.

Treatment of offshore energy and climate: Supporting documents to the maritime spatial plan identify that climate objectives are central to the MSP process and states that the "Belgian North Sea will make an important contribution to achieving the European target of 27 % renewable energy in the total energy

[26] Note the Belgian maritime spatial plan itself states that MPAs cover 33 % of the Belgian sea space, however, we use MPA Atlas as a consistent source across the Member States.

[27] This classification of biodiversity condition is based on the BEAT+ tool, which provides an assessment of the spatial variability of a range of biodiversity components by combining existing biodiversity indicators. The status of marine areas is evaluated in five classes, where High and Good are recognised as 'non-problem areas' and Moderate, Poor and Bad are recognised as 'problem areas (European Environment Agency, 2019).

[28] Note: all information comes from the maritime spatial plan and supporting documents, unless otherwise indicated.

[29] This figure only includes fully commissioned wind power farms. Those in the planning, construction or de-commissioning stage are not considered.

consumption of a Member State by 2030" (Annex 2). The first Belgian maritime spatial plan from 2014 allocated 7 % of the Belgian sea area (238 km^2) to renewable energy development. This number increased to a total of 15 % in the second maritime spatial plan. The plan supporting documents identify that if two or more projects are in competition to take up a certain zone, their respective climate impact is an important criterion in making a decision. Only wind energy is currently being considered, though plan supporting documents identify that other types of energy generation could also take place within the offshore energy zones. In addition, the further development of renewable energy is specified as one of the actions necessary to successfully implement the maritime spatial plan (Annex 3).

Treatment of broader environmental objectives: The maritime spatial plan sets several marine environment objectives, including achieving objectives of MSFD, WFD, and the nature directives. The 2050 vision document integrates ecosystem-based approaches throughout and promotes "working with nature" when introducing new uses in Belgian sea space. Broader environmental objectives are primarily managed in the maritime spatial plan through spatial closures such as MPAs or other spatial restrictions limiting particular activities. The plan maintains the current level of MPAs, which include Natura 2000 sites under the Birds and Habitats Directive, rejecting proposals to either shrink or extend these. In these areas, activities can only occur with a Natura 2000 authorisation (i.e., by default are banned). One of the MPAs includes time-based restrictions, with additional limits from December to March (e.g., no water sports, low-flying helicopters). Supporting documents make clear that the planners rejected a proposal to spatially delimit spawning, resting, breeding and foraging areas, or resting area of seals[30]. In addition to nature conservation areas, the maritime spatial plan includes three research areas with some fishing restrictions to assess the environmental impact of spatial closures (on Good Environmental Status according to MSFD). The plan includes some additional environmental restrictions beyond MPAs, e.g., for aquaculture, concessions will only be approved if they will decrease eutrophication, and for sites where there is overlap with nature conservation areas, concessions will only be approved if a Natura 2000 authorisation is given (i.e., other uses require additional approval). Interestingly, the area allocated to offshore energy is closed for fishing "due to the major safety risks".

Balancing of trade-offs: The supporting document to the Belgian maritime spatial plan acknowledges that offshore energy and marine environmental objectives can conflict and calls for testing of specific measures to promote biodiversity in renewable energy areas. These documents also set out the 2050 vision and principles, which should guide the managing of trade-offs. They include three core principles: 1. "Naturalness[31] is a basic precondition for the development of the Belgian North Sea in all its facets", 2. "The Belgian North Sea will continue to offer important functional uses in the future, to support social well-being", and 3. "In the future, the principle of multiple use of space will be the norm for all use of space within the Belgian North Sea." To achieve these objectives, the supporting documents call for activities to have ideally no or a positive impact on the environment. Environmental assessments are required, and sectors are to be accountable, and polluter pays principle applied. In terms of specific processes for balancing trade-offs, the maritime spatial plan supporting documents identify that if two or more projects are in competition to take up a certain zone, their respective climate impact is an important criterion in making a decision. There is some overlap between MPAs and the area allocated to offshore energy. The different MPAs have different restrictions: generally, offshore energy activities are permitted if they are

[30] The justification given was that this would not allow the most recent scientific evidence to be considered and that this issue was already considered by the Environment Minister before allowing activities in the relevant areas.

[31] "Naturalness is defined as an activity at a level that allows healthy economic development, without compromising current and future ecosystem services… The aim is not to create an ecosystem without human impact, but to ensure the sustainable management of the ecosystem."

"subjected to an appropriate assessment". An explicit allowance is made for energy storage sites, so long as "active marine management measures" are taken to minimise impact on protected species.

Implementation: The zoning provisions of the maritime spatial plan are legally binding and will be implemented by the Belgian Minister for the North Sea and the Marine Environment Service in the period 2020–2026. Given that "the sea is a dynamic environment and spatial requirements can change rapidly, the spatial planning process must strike a balance between flexibility and stability." Therefore, ongoing monitoring and evaluation of the choices made is advised and the plan will be revised every six years. It can also be adapted in the interim phase by the Minister of the North Sea if this alteration is approved by the Council of Ministers.

5.3.1.2 Finland

Context: The Finnish sea area, its EEZ, spans approximately 83,210 km², accounting for 20.9 % of the Baltic Sea (European MSP Platform, 2021b). Up to 15 % of the sea area is designated as a marine protected area (MPA Atlas, 2021b), contributing towards the EU's target of protecting 30 % of the EU's sea area by 2030 as outlined in the Biodiversity Strategy (European Commission, 2020c). The biodiversity condition of the Finnish sea area is mostly moderate, although some zones are classified as poor (European Environment Agency, 2019). Finland currently has three offshore wind farms that have a total capacity of 71 MW (WindPower, 2021)[32]. This includes the 42 MW Tahkoluoto wind farm opened in 2017, the World's first offshore wind farm built for icy conditions. As of 2020, 0.01 % of the Finnish EEZ was covered by fully commissioned wind energy installations (4C Offshore 2020). According to the Finish recovery and resilience plan, which the government submitted to the European Commission in May 2021, the development of offshore wind energy should continue. Specifically, the plan announced the support for a 6 GW offshore wind complex to be completed in the next 10–15 years (Rapacka, 2021).

Process: Finland has three regional maritime spatial plans for i) the Gulf of Finland, ii) the Archipelago Sea and southern Bothnian Sea, and iii) the Northern Bothnian Sea, Quark and Bothnian Bay, which were adopted in November-December 2020. The plans were prepared by the Regional Councils of the eight coastal regions,[33] while the Ministry of Environment was responsible for the general development and guidance of maritime spatial planning. Independent of this process, the autonomous territory of the Åland develops a maritime spatial plan under its own jurisdiction, which is not considered here. The MSP process began in 2017 with the preparation of a report on the current state of the Finnish sea areas, followed by the creation of three scenarios for the future of the Finnish seas up to 2050[34]. A one-month electronic hearing on the current state and the scenarios was held in 2019. In parallel, an interactive stakeholder collaboration period ran from 2019–2020. Next, a vision for 2050 and regional development visions and roadmaps for 2030 were created to determine the target state of the Finnish seas. After this vision phase, draft maritime spatial plans were prepared. Another one-month hearing was held on the draft plans in 2020, during which a total of 87 statements and 54 pieces of general feedback were received. An impact assessment on the draft plans was carried out in 2020, the results of which were used during the consultation phase.

Description of plan: The three Finnish maritime spatial plans are strategic development documents which describe the target status for the Finnish sea areas in 2030. They do not include legally binding maritime

[32] Note: The maritime spatial plan only mentions one offshore windfarm with a total capacity of 42 MW.

[33] Finland has 18 Regional Councils, which are statutory joint municipal authorities for its member municipalities. The autonomous province of Åland Islands does not have a Regional Council.

[34] The scenarios prepared are intended to develop the thinking on possible futures of Finnish maritime areas until 2050. Three different scenarios were created, focusing respectively on the Baltic Sea as a space for: 1. the development of economic opportunities; 2. for recreation and environmental protection; and 3. strategic geopolitical operations.

spatial zoning and their impact "arises by virtue of the planning process, in other words through the common understanding reached by the stakeholder groups, as well as through the commitment to the plan and the ownership experienced regarding it", as well as from the increased information about maritime areas it provides and from its links with national, regional and sectoral policies. The three regional plans are presented on a designated website available in Finnish, Swedish and English[35]. They indicate "areas of significance and with potential" with the aim to identify opportunities for multipurpose use and support the harmonisation of maritime operations between sectors in the future[36]. The zones do not reserve areas for a particular purpose. In addition to the three regional plans themselves, the website contains information on the legislative framework, planning principles and process description, the three scenarios up to 2050, a vision for the sustainable use of marine areas 2050, sector-specific visions and roadmaps to 2030, as well as the impact assessment.

Treatment of offshore energy and climate objectives: The sector-specific vision for the energy sector for 2030 developed as part of the MSP process states that Finland will "promote the transition to a low-carbon society by increasing offshore wind production. Energy will be produced cost-effectively in marine areas, taking sustainable development and safety into account." This round of MSP only considered offshore wind energy for the 2020´s, however it indicates that over the longer term also considers other forms of offshore renewable energy in the long term, including wave, solar, marine biomass and sea water for cooling and heating, will be considered. To this end, potential zones for energy production were identified in the three maritime spatial plans. The potential for the development of offshore renewable energy is regionally varied: Potential was mainly identified in the northern part of the Bothnian Sea and the open sea zones of the Bothnian Sea and Archipelago Sea. In the Gulf of Finland, on the other hand, the plan does not indicate any new potential areas for offshore wind power development due to the needs of the maritime transport sector, Finnish defence forces, Natura 2000 areas and other natural protection objectives.

Treatment of broader environmental objectives: The Finnish regional maritime spatial plans are set to contribute towards several marine environmental objectives, including those of the MSFD, the WFD and the Habitats and Birds Directives, as well as those of national legislation and international agreements. The vision for nature conservation and management envisions that "all operators impacting the marine environment take into account the ecological preconditions of the marine environment and safeguard marine biodiversity". This requires a set of actions outlined in the roadmap to 2030, including among others a clear definition of what can and must not be done in marine areas, sufficient protection areas, a review of nature conservation commitments, as well as the use of MSP as a tool for cooperation across sectors and industries. The three plans indicate 82 Finnish ecologically significant marine underwater areas across the three regions[37]. This indication is only descriptive, and they do not propose that these areas should be protected. The impact assessment points out that their identification may have a guiding effect on the future expansion of the protected areas network. The Finnish Sea area already has an extensive network of different types of protected areas, which have been considered in the planning process. However, the plans do not show existing Natura 2000 areas, national parks or other conservation areas whose protection and implementation is guided by other legislation.

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[35] https://meriskenaariot.info/merialuesuunnitelma/en/merialuesuunnitelma-english/

[36] The Finnish maritime spatial plan covers the following sectors: energy; maritime logistics; maritime industry; fisheries and aquaculture; tourism and recreation; cultural heritage; extractive sector; blue biotechnology; nature values and national defence.

[37] In the Gulf of Finland, 35 ecologically significant areas were marked, 16 areas in the Archipelago Sea and the Southern Bothnian Sea, and 31 areas in the Northern Bothnian Sea, Quark and Bothnian Bay.

Balancing of trade-offs: The long-term vision prepared as part of the MSP process identifies synergies and conflicts between the different maritime sectors. While it states that "clean renewable wind energy is generally good for nature and the climate", it also acknowledges that the "construction of offshore wind farms has a negative impact on ecosystems (construction, cables, maintenance visits, etc.)." The sector-specific roadmap for energy states that to mitigate these impacts, the consequences of construction and the status of the marine environment will be studied and taken into account in the planning. The MSP process for the three current plans paid attention to other conservation areas and natural values, as well as bird migration routes and the sensitivity of the marine environment when identifying potential areas of offshore renewable energy development. In addition, Natura 2000 areas were excluded, though allowed under national law and it is foreseen to build artificial reefs on the foundations of wind farms. Potential for offshore wind has mainly been identified in the open sea, where, according to the SEA and in the case of Finland, "area reservations are larger and adverse environmental and landscape impacts are smaller." The areas with potential for offshore wind power indicated in the maritime spatial plans are thus mainly located at least 10 km from the shore and at a depth of 10–50 meters. In the future, increased knowledge of marine nature values and their location will aid placing wind farms in the least sensitive areas.

Implementation: The Finnish maritime spatial plans offer strategic guidance for the development of the marine areas in 2021–2030. The monitoring and evaluation phase started immediately in 2021 and plans will be updated at least every 10 years.

5.3.1.3 Ireland

Context: Ireland has approximately 488,762 km^2 of EEZ (European MSP Platform, 2021c). Up to 2.3 % of the area are currently designated as marine protected areas (MPA Atlas, 2021c), requiring further effort towards reaching the EU's target of protecting 30 % of the EU's sea area by 2030 as outlined in the Biodiversity Strategy (European Commission, 2020c). The biodiversity condition of the Irish sea area is mostly moderate and partially poor near the shore, and mostly good further offshore (European Environment Agency, 2019). Currently, Ireland has 30 MW of installed offshore wind capacity (The WindPower 2021b). As of 2020, 0.0006 % of the Irish EEZ were covered by fully commissioned wind energy installations (4C Offshore 2020). In the future, the Irish government aims to develop 5 GW of offshore wind by 2030 and make use of a potential of 30 GW by 2050.

Process: The Irish Maritime Spatial Plan ('National Marine Planning Framework') was adopted by the Dáil (Irish Parliament) in May 2021. The planning process was conducted by the Ministry for Housing, Local Government and Heritage. The process of drafting the Irish maritime spatial plan began in 2017 with the publication of the National Marine Planning Framework (NMPF) Roadmap. A Baseline Report on the state of the Irish Sea and high-level MSP objectives was published for a three-month public consultation in September 2019. In November 2019, the government published the draft plan for public consultation[38]. From mid-November 2019 to late-April 2020, 3,500 comments from 225 submissions on the draft maritime spatial plan were received, which were subsequently considered in the preparation of the final plan. Parallel to the public consultation process, seven coastal regional events took place between November 2019 and March 2020 in person, plus one on-line event in April 2020. In addition, eleven stakeholder advisory group meetings were held between 2018 and 2021. A SEA and an Appropriate Assessment under the Nature directives were also published in 2019 and considered in the consultation. They were prepared using an integrated approach, for example sharing baseline data and mapping of sites. Updated versions of the SEA and the Appropriate Assessment have been published in 2021, containing chapters outlining

[38] On the same day, the Marine Planning Policy Statement was published, which underpins the MSP process as well as all other aspects of marine planning in Ireland.

the changes to the maritime spatial plan following the consultation. Ireland is committed to the preparation of regional or subnational plans in future MSP cycles.

Description of plan: The maritime spatial plan of Ireland does not include prescriptive zoning or siting provisions, but all public bodies involved in authorising maritime development and activities must ensure consistency with the plan when making decisions on leases, licenses and consents or introducing a new policy proposal. The maritime spatial plan outlines two types of policies: Firstly, it posits environmental, economic and social Overarching Marine Planning Policies (OMPPs). These will apply to all marine activities and development. Secondly, there are the Sectoral Marine Planning Policies (SMPPs), which will guide decision-makers in dealing with specific proposals (for example, offshore renewable energy, port development or aquaculture). Neither the OMPPs nor the SMPPs contain any spatial elements. Appendices A-F describe a system of spatial designation to be introduced under the Maritime Area Planning Bill 2021, stakeholder engagement, and actions taken in parallel to support the implementation of the plan, among other aspects[39]. A designated web portal with continuously updated data and maps as well as text from the plan will be set up[40].

Climate change and energy: One of the objectives of the Irish Maritime Spatial Plan is to “support the development of [offshore renewable energy] in Ireland as a driver to significantly reduce greenhouse gas emissions and accelerate the move to cleaner energy in line with national and EU policy.” The government aims to increase the share of electricity generated by renewable sources to 70 % by 2030, comprising at least 5 GW of offshore renewable energy in the shallower waters off Ireland’s eastern and southern coasts. In the medium to long term, Ireland additionally aims to take advantage of the potential of at least 30 GW of offshore floating wind power in the deeper waters off the southern and western coasts of Ireland, as well as develop wind and tidal power. In order to enable this development, the maritime spatial plan specifies eleven Sectoral Marine Planning Policies for renewable offshore energy. For example, any non-offshore renewable energy proposal must demonstrate that it avoids, minimises, mitigates, or justifies (in order or preference) adverse impacts on offshore renewable energy development, and plans and policies for ports must facilitate its development and related supply chain activities. The development of statutory marine planning guidelines on offshore renewable energy is mentioned as a supporting action to be revisited periodically as part of creating the marine planning system and implementing the maritime spatial plan (Annex F).

Treatment of broader environmental objectives: The Irish Maritime Spatial Plan sets out Overarching Marine Planning Policies (OMPPs) relating to eight environmental issues: biodiversity and protected marine sites; non-indigenous species; water quality; sea floor and water column integrity; marine litter; underwater noise; air quality; and climate change. Many of the environmental OMPPs specify that any proposal for the sea space needs to demonstrate that they will a) avoid, b) minimise or c) mitigate significant adverse impacts on the subject matter of the policy. The policies cover, among others, distribution and net extent of important habitats and species, the extension of the network of MPAs, or the protection of deep-sea habitats. The OMPPs under the plan are complementary to the existing policies, such as the binding environmental targets set up to achieve GES under the MSFD, as well as to other mechanisms in place relating to the conservation, protection and wider management of marine environmental matters.

[39] Appendix A: Public Bodies with Marine Responsibilities; Appendix B: Stakeholder Advisory Group Membership; Appendix C: Summary of Stakeholder Engagement to Date; Appendix D: Spatial Designation Process; Appendix E: Maps of Fish Spawning and Nursery Grounds; and Appendix F: Supporting Actions.
[40] See https://marineplan.ie (not yet available as of July 2021).

Balancing of trade-offs: Generally, the maritime spatial plan encourages the “effective use of space to support existing and future sustainable economic activity through co-existence, mitigation of conflicts and minimisation of the footprint of proposals”. It however acknowledges that renewable energy developments can have and potentially may produce adverse impacts on fish and mammals, which “must be managed in line with international obligations and best practice to support maximum social acceptance.” The plan points to requirements under existing legislation regarding the undertaking of any necessary environmental assessments to safeguard the marine environment. The environmental OMPPs guide the development of ORE. In addition, as a response to the Appropriate Assessment and SEA, the plan specifies the need to develop a “robust, effective transparent consenting process to ensure appropriate environmental protections are built-in” and to ensure “good regulatory practices in ORE installation and generation” according to international best practice. These assessments also called for the strategic assessment of zones for different activities to balance the trade-offs between offshore renewable energy development and marine environmental protection. The plan does indicate zones, but the requirement will be met through the development of Strategic Marine Activity Zones under the upcoming Marine Planning Area Bill.

Implementation: The Irish Maritime Spatial Plan does not include legally binding maritime spatial zones, in fact it includes no zoning at all. Instead, it provides an overarching framework for the development of the marine area from 2021–2030. Responsibility for the implementation of the plan rests with the Minister for Housing, Local Government and Heritage, which has “specific powers to direct a Public Body to adopt measures to implement or ensure compliance with the plan.” The Department takes an ongoing monitoring role and will carry out a review of the maritime spatial plan after no more than six years. The plan will be supported by the Maritime Area Planning Bill (MAP), an upcoming legislation which will modernise the Irish State’s marine planning system and designate Strategic Marine Activity Zones.

5.3.1.4 Latvia

Context: The total sea area under Latvian jurisdiction, its EEZ, spans 28,500 km^2, accounting for 7.2 % of the Baltic Sea (European MSP Platform, 2021d). 16 % of the area are designated as Marine Protected Areas (MPA Atlas, 2021d), contributing towards the EU’s target of protecting 30 % of the EU’s sea area by 2030 as outlined in the Biodiversity Strategy (European Commission, 2020c). The biodiversity condition of the Latvian sea area is partially classified as moderate, partially as poor (European Environment Agency, 2019). As of today, Latvia does not have any commercial offshore renewable energy installations in its waters. Latvia aims to increase its total (onshore and offshore) wind energy capacity to 800 MW by 2030 (Government of Latvia, 2020), partially by deploying offshore wind farms. In 2021, Estonia and Latvia have signed a Memorandum of Understanding to jointly develop an offshore wind farm with a capacity of 1 GW (Duracovic, 2020).

Process: The Latvian Maritime Spatial Plan (‘Maritime Spatial Plan 2030’) was adopted in May 2019 under the authority of the Ministry of Environmental Protection and Regional Development. The drafting of the maritime spatial plan began in 2015 with the elaboration of long-term visions and goals, as well as four alternative scenarios. A draft maritime spatial plan was published for public consultation in December 2019. The draft plan as was well as the first version of the plan were refined in 2016 and 2017. The second version of the plan was published for public consultation in August 2018, after which the final version was prepared. Four meetings with stakeholders as well as two regional public hearing seminars were organised throughout the process. The SEA has been launched simultaneously with the MSP process in 2019 and an environmental report was published on the first, second and final version of the maritime spatial plan.

Description of plan: The Latvian maritime spatial plan does not include legally binding zones for maritime activities, but “recommends the strategic and spatial development priorities with an outlook until 2030, as well as providing data and information regarding the marine environment status, ecosystem services and existing sea uses”. The plan shall be taken into account when granting licenses for new sea use. The plan has three parts: i) The explanatory part gives an overview of the current situation of the Latvian sea and various maritime sectors; ii) The strategic section outlines the long-term vision for the Latvian sea by defining three strategic objectives[41] and six strategic priorities; iii) The third section on MSP solutions defines the permitted uses of the sea. It defines zones for priority use (for example potential protected areas or wind park development areas) and details regulations for the existing uses and objects, as well as for the general use of the sea. Annex 1 contains a graphical representation of the maritime spatial plan, Annex 2 outlines how priority uses of sea space were determined, and Annex 3 describes the marine interests of neighbouring states.

Treatment of offshore energy and climate objectives: The maritime spatial plan envisions that "Latvia reasonably uses the renewable energy sources available in the sea, supporting the energy security of the country, while causing no damage to the environment, marine ecosystem or significant losses to other users of maritime resources and space." The plan refers to EU and Latvian climate change objectives, but no explicit link is made between these climate objectives and the development of offshore renewable energy. The use of marine renewable energy to support the energy security of Latvia is one of the six strategic priorities of the maritime spatial plan and both research areas for future wind park development and electricity cable corridors are defined as priority uses in the plan. Five areas totalling 1,766 km^2, or 6 % of the Latvian marine area, are allocated to wind energy development. The plan also includes a plan of 16 specific measures to reach the strategic objectives, including supporting offshore renewable energy demonstration projects by raising financial aid or State budgets by 2030. The only renewable energy type mentioned in the maritime spatial plan is offshore wind.

Treatment of broader environmental objectives: The maritime spatial plan sets out that the planning process is based on the conditions that "the use of the marine space must ensure the non-deterioration of the environmental conditions and ecological parameters and of the ability of the ecosystem to adapt, as well as create favourable conditions for improving the environmental condition and marine resources". A healthy marine environment and resilient ecosystem is one of the six strategic priorities of the Latvian plan. The plan envisions that this "will allow the provision of quality and diverse products and other ecosystem services, which serve for the welfare of people and form the basis of a sustainable economy." Currently, Latvia has seven MPAs, mostly located in the territorial sea (up to 12 nm from the coastline). These account for 15 % of Latvia's marine waters. Different rules and restrictions for the protection and utilisation of these MPAs have been adopted, for example the construction of wind power plants is prohibited in some zones of some of the MPAs. In addition to existing MPAs, the maritime spatial plan designates the priority use of five sea areas as investigation areas of nature values with a total area of around 1,350 km^2. If the upcoming investigation identifies areas with significant conservation value, this might lead to the establishment of new MPAs. If the survey does not confirm the conservation value of an area, licenses for new uses of the sea may be issued. In general, any use of the sea (including fishery, shipping, tourism and leisure, scientific research, etc.) must not cause significant negative impact to the marine environment and new uses of the sea need to obtain a license, which might require an Environmental Impact Assessment.

Balancing of trade-offs: The Latvian maritime spatial plan acknowledges the potential for conflict between wind energy production and the protection of birds and underwater biotopes and that there might be a need to "mitigate conflicts between offshore wind parks, other industries and existing uses". Among other

41 "SO1: Rational and balanced use of the marine space, preventing inter-sectoral conflicts and preserving free space for future needs and opportunities; SO2: The marine ecosystem and its ability to regenerate is preserved, ensuring the protection of biological diversity and averting excessive pressure from economic activities; SO3: Integrated use of marine and terrestrial areas by promoting development of maritime related businesses and the development of the required infrastructure."

criteria, the research areas for wind park development may not overlap with Natura 2000 sites or in areas designated for conservation of protected biotopes, where possible, wind power parks should be located outside of wintering grounds of migratory birds and their migration routes. The plan also states that construction of wind power plants must be in accordance with the existing regulatory framework regarding the protection of the marine environment and construction at sea, including the performance of an Environmental Impact Assessment. Three of the five investigation areas of nature values overlap with research areas for wind park development. The SEA states that this is "creating a potential conflict of interest." However, until the exploration of areas of nature values is completed, the issuing of licences for new uses, including offshore wind parks, wave energy stations, and other uses that could potentially endanger habitats and species, is not permitted. Investigation areas of potential nature value thus have priority over research areas for wind park development. The Latvian plan references the co-existence objective of the MSPD but does not elaborate on this general objective.

Implementation: The maritime spatial plan offers strategic guidance for the use of the Latvian see from 2019-2030. The main instrument for the coordination of sectoral interests for the implementation of maritime planning is the Maritime Planning Working Group, which will meet at least once a year. Once a year, the Ministry of Environmental Protection and Regional Development will review the actual use of the sea and update the geospatial data and maps of the plan and every six years submit a report on the implementation of the plan.

5.3.2 Key findings from maritime spatial plans

Maritime spatial planning takes place in diverse national contexts, which must be considered when evaluating maritime spatial plans. For example, Member States govern over sea areas of widely different sizes: Ireland's sea area is almost six times the size of its land area, while in Finland the sea area is only a quarter of its land area. There are also significant differences in existing offshore energy capacity and environmental protection provisions. Among the countries considered here, Belgium's offshore wind sector is most developed with 2.2 GW of installed capacity, limited capacity in Ireland and Finland, and none in Latvia. The coverage of protected areas ranges widely from 2.3 % (of 83,210 km²) in Ireland to 36 % (of 3,454 km²) in Belgium. There are some similarities across the assessed countries, such as that the current health of the marine environment in all states is currently mostly classified as moderate or worse. However, the identified differences and other contextual elements make direct comparisons of maritime spatial plans challenging.

The process, form and content of maritime spatial plans in different Member States vary widely. The MSPD only prescribes limited requirements for the final maritime spatial plans; most decisions regarding how to conduct maritime spatial planning remain with Member States. As a result, there are significant differences between the maritime spatial plans analysed. While Belgium, Latvia and Ireland decided to create plans at the national level, Finland opted for a regional approach and developed three plans under their national MSP jurisdiction. Member States can choose which authority to endow with the responsibility for MSP, which in return can determine the process from conception to publication of the plan. Similarly, the MSPD requires stakeholder engagement, but the respective national authority for MSP can decide how to implement it. The final plan and required environmental assessments can be accompanied by the publication of various additional materials, such as long-term visions, scenarios used during planning, GIS maps or interactive online maps targeted at the public, but this is not required by the MSPD.

Some maritime spatial plans are prescriptive, with specific zoning and siting provisions, whereas others only offer strategic guidance. The MSPD does not prescribe the legal status of resulting maritime spatial plans, it only requires that they are "established" at Member State level; this depends on how the EU Directive is transposed into national law. Whether a plan is very specific or only offers strategic guidance might affect its implementation as well as how effectively it can manage trade-offs between the development of offshore renewable energy and marine environmental protection. Belgium's maritime spatial plan is prescriptive with specific zoning provisions; it was adopted in the form of a 'royal decree'. This law is the result of a review of Belgium's first maritime spatial plan adopted in 2014. In all other cases examined, the maritime spatial plans are the first national plans and not legally binding. Instead, they offer strategic guidance to the future development of the sea areas. In Ireland, Latvia and Finland, maritime spatial plans have to be taken into account in future planning and licensing decisions, but they need not to be adhered to. Ireland and Latvia opted for presenting this guidance in the form of a report, whereas Finland created a website containing the three regional MSPs as well as supporting documents.

Maritime spatial plans can take a spatial approach or a policy approach. Latvia, Finland and Belgium all identify possible zones for different activities in their plans; only in Belgium are these zones legally binding. Geographic coordinates of zones are listed alongside a description of the activities that can occur in that area and/or conditions for activities operating in this area. While the Latvian and Finnish maritime spatial plans delineate zones for different activities, the zoning has no regulatory effect. The purpose of the zones in the Finnish plan is not to reserve sea areas for specific uses, but rather to identify opportunities for multipurpose use and support the harmonisation of activities between sectors. The Latvian plan identifies zones with potential for certain uses, such as the construction of wind parks or natural protection; these will be further investigated. Also, the Irish plan is not legally binding, instead aiming to provide guidance to the development of the Irish sea area, without identifying zones to this end. Instead, the Irish MSP planners opted for the formulation of a set of general, as well as sectoral policies to be considered by all public bodies involved in authorising maritime development and activities.

Maritime spatial plans are seen as tools to achieve climate and energy objectives through expansion of offshore wind energy. The maritime spatial plans of Latvia, Ireland, Belgium and Finland all support the development of offshore renewable energy. All except for Latvia's plan make an explicit connection between the need for offshore renewable energy and reaching climate objectives. In order to reach these objectives, the Belgian plan denotes legally binding zones for offshore renewable energy, increasing the area dedicated to this use from 7 % to 15 % compared to the plan from 2014. Latvia and Finland identified potential zones for offshore renewable energy production and Ireland drew up policies to facilitate growth of offshore renewable energy. All of them strive to expand offshore renewable energy in line with their national energy strategies and the physical conditions of their sea areas. The focus rests on offshore wind; other forms of ocean energy are only treated marginally. In Ireland, floating wind power is projected to play a large role, due to the large availability of sea space further offshore which is too deep for bottom-fixed turbines.

In addition to developing offshore energy, maritime spatial plans aspire to protect and improve the marine environment. All plans put forward principles for the stewardship of marine resources, such as that all activities should ideally have no or a positive impact on the environment (Belgium) or declaring a healthy and resilient marine environment a strategic priority (Latvia). The maritime spatial plans refrained or were unable to (due to their legal status) from introducing binding rules or designating new MPAs. Currently the level of MPA coverage between Latvia, Finland, Ireland and Belgium ranges from 2.3 % to 36 %. They thus contribute to different extents to the EU aim of reaching 30 % MPA coverage by 2030, as formulated in the Biodiversity Strategy. Given the non-binding nature of most maritime spatial plans, only the Belgian plan could have denoted new MPAs, but it did not to do so. Latvia denoted zones for the investigation of areas with nature values, which might lead to the establishment of protected zones upon further investigation. Finland only denoted zones of environmental values, without any indication of whether they will be protected in the future. There were only limited examples of maritime spatial plans going beyond principles or protected areas to deliver environmental protections. The Belgian plan made aquaculture concessions conditional on the proposed projects reducing eutrophication, for example, but generally maritime spatial plans refrained from additional protections within the plan, instead referring to other existing legislation to reduce negative environmental impacts (such as Natura 2000 authorisation or other national-level environmental impact assessment policies).

All maritime spatial plans explicitly acknowledge the need to balance trade-offs between the development of offshore renewable energy and marine environmental protection. To do so, these plans primarily reiterate their commitment to safeguarding the state of the marine environment during the construction, operation and decommissioning of offshore renewable energy installations, as well as considering environmental conditions during site selection. The plans also point to existing requirements for environmental assessments, which also apply to offshore energy installations. In addition, the Latvian maritime spatial plan gives priority to potential areas of natural value over areas for wind park development and Latvia and Finland excluded Natura 2000 areas from offshore renewable energy development. In Finland, areas with potential for offshore wind power are mainly located at least 10 km from the shore and at a depth of 10–50 meters, where negative environmental impacts are deemed smaller according to the Finnish maritime spatial plan.

Maritime spatial plans will be continuously monitored and evaluated and are in some cases embedded in larger policy processes. All maritime spatial plans will be continuously monitored and evaluated by a selected national authority. A review will take place after at least ten years in Finland (the minimum required under the MSPD), and at least after six years in the other countries considered. In some cases, such as in Ireland, the MSP is only a small part of a large marine policy process and can only be fully understood in the national political context. While the Irish MSP does not denote any zones for specific activities, for example, the upcoming 'Marine Area Planning Bill' will fulfil this function.

6 Discussion and conclusions

6.1 Environmental risks

When analysing the environmental impacts reported to be produced by renewable energy production infrastructures, it should be considered that the projects have gone through an EIA during the permitting process. EIA allow the identification and adoption of mitigation measures of potential impacts to the marine environment. In that sense, it is important to highlight the importance of having good baseline information of the environmental condition prior to the construction of a project, to understand the impacts produced by the project. In addition, early-stage environmental monitoring contributes to the reduction of uncertainty of environmental risks.

The rapid increase in the number and size of offshore wind farms means that the cumulative contribution from the many turbines may be considerable and should be included in SEA for MSP purposes as well as in EIAs of individual projects (Tougaard et al., 2020; Wilson et al., 2010). Offshore renewable energy industries should not be considered in isolation because the significance of environmental impacts depend on the full spectra of human activities in each area. MSP provides a platform for holistic assessments and may facilitate the establishment of ocean energy industries, as long as risk-related uncertainties are reduced (Hammar et al., 2017). Offshore renewable energy development should be also discussed from the economic, social point of view.

Environmental impacts must be evaluated on a project-by-project basis as these are site-specific. The results presented here are an integrated and up-to-date vision of the potential environmental impacts that are reported to be produced by different offshore energy production technologies.

The present work is not intended to question the expectations of offshore wind energy production as a source of clean and renewable energy, but to present the state-of-the-art of the present scientific knowledge regarding the ecological consequences that the expansion of this sector could cause on a local and, in some cases, also on a regional scale.

6.1.1 *Gaps in scientific knowledge and uncertainties on environmental impacts and risks*

In relation to the potential impacts and risks associated to offshore energy production, several gaps of scientific knowledge and uncertainties must be taken into account (Maclean et al., 2014). On the one hand, knowledge of some impacts depends on the marine environmental receptors and are very species specific, which means that there are difficulties in estimating the impacts on other species. A critical point here is that most of the studies are performed in northern countries and the impact of offshore renewable energy are assessed for northern species. If offshore renewable energy is going to expand to other regions, the specific effects on other species are still unknown (Galparsoro et al., 2021). Moreover, in this work we have not considered the life-cycle analysis of the impacts of energy devices, but only the potential environmental risks produced at the local site of production.

According to Wade et al. (2016) there is a greater uncertainty in data regarding displacement caused by vessels and/or helicopters and tidal races on seabirds, than in data regarding the percentage of flight overlapping wind farms and the level of displacement caused by structures, with varying uncertainty among species. In this sense, Grear et al. (2018) concluded that further work is needed on the likelihood of death or sublethal effects when a marine animal encounters a turbine, as well as the population-level risks associated with an encounter. Moreover, Sparling et al. (2020) reflected that even though efforts to characterize the risk of collision with single turbines are underway, there is little understanding of how animals might perceive large arrays of devices, making it difficult to extrapolate the information to other offshore renewable energy projects (Wilson et al., 2010). Furthermore, information is required on exact spatio-temporal migration routes, flight altitudes (especially during ascent and descent), and behavioural avoidance of turbines by birds to ascertain their risk. In the case of tidal energy, the potential for marine animals to encounter and collide with tidal turbines continues to present challenges for permitting developments due to the associated uncertainty and knowledge gaps related to collision risk (ORJIP Ocean Energy, 2017) (ORJIP, 2017).

There are also substantial gaps in the knowledge of impacts on benthos that include (Dannheim et al., 2019a; ICES, 2021):

- how the artificial reef and fisheries exclusion effects,
- how changes on hydrodynamic conditions produced by ORE potentially may change the food availability to filter-feeders,
- reduction of phytoplankton primary production due to an increase in turbidity,
- the way artificial structures could influence the colonization by non-indigenous species through new shipping activities related to OREs,
- the effects of shipping noise and vibration and the noise of construction and operation of OREs might induce avoidance behaviour and reduce fitness of sound-sensitive organisms, thereby potentially changing population structure and distribution pattern.

In general, most information exists for the construction and operational phases, while knowledge is poor on the effect pathways during decommissioning (Dannheim et al., 2019a). In most cases, prospective life cycle assessment has not been considered. The few available studies however indicate that the effects of decommissioning are likely to be comparable to the construction of marine renewable energy farms (Bergström et al., 2014).

Nelms et al. (2021) summarised knowledge gaps relating to these threats and recommend actions to resolve them: occurrence and behaviour of marine mammals using sites targeted for OREs and consequences of behavioural impacts of marine renewable energy infrastructures for marine mammals, in terms of fitness and population dynamics. According to Copping et al. (2020) displacement of animals due to the presence of ORE devices has not been examined for small numbers of devices; however, as larger arrays are deployed, there will be a need to examine whether migratory animals change their paths to avoid ORE projects, perhaps preventing them from reaching critical or preferred habitats. It has to be taken into account that the potential impacts of devices depends on the foundation design (ICF, 2020). Furthermore, significant gaps remain in understanding how pelagic species (mammals, fish) may react to dynamic cables suspended in the water column (Gill and Desender, 2020). Yet, the effects that wind farm structures have on fish populations remain unclear (Methratta and Dardick, 2019).

On the other hand, ecological impacts associated with submarine power cables can be considered weak or moderate, although many uncertainties remain, particularly concerning electromagnetic effects (Taormina et al., 2018). It is known that the levels of electromagnetic fields reported in many field and laboratory studies are much higher than those expected (Copping et al., 2020).

Some authors underline that there is a lack of reliable studies on the long term impacts of these technologies on the marine environment (uncertainty in the impact magnitude and extent, discrepancies in the understanding of positive and negative effects) and highlights the need for proper environmental and social impact assessments of these technologies (Ward et al., 2010), (Wilberforce et al., 2019). Furthermore, there are several difficulties to estimate the cumulative pressures and cumulative effects, depending on the individual device type, on the site selection, specific to the type of energy being harnessed, many potential impacts are unavoidable but measurable (Boehlert and Gill, 2010; Willsteed et al., 2017; Willsteed et al., 2018b). Caine (2020) concluded that the consenting processes for offshore renewables does not encourage full assessment of the cumulative and in-combination impacts of offshore renewable developments as required by European Union environmental impact assessment legislation. In this sense, some assumptions are adopted when producing environmental risk maps.

To allow for full biodiversity impacts to be assessed, there exists an urgent need for additional multi and inter-disciplinary research in this area ranging from engineering to policy. Whilst there are a number of factors to be considered, one of the key decisions facing current policy makers is where installations should be sited, and, dependent upon site, whether they should be designed to either minimize negative environmental impacts or as facilitators of ecosystem restoration (Inger et al., 2009). Developing standardised environmental impact assessment (EIA) practices would allow for potential impact concerns to the marine environment to be identified and mitigated early during project development (Scherelis et al., 2020a). Among others, it is important to know the baseline to understand the impacts of the project. Early-stage environmental monitoring can successfully provide baseline information about some ecosystem impacts (i.e., fish aggregation) thus reducing the uncertainty of risks for stakeholders of tidal energy developments.

6.1.2 Mitigation

The Environmental Impact Assessment (EIA) includes the project screening, the scoping (through to impact prediction) and monitoring. The EIA Directive[42] also claims to integrate mitigation and compensation measures into the EIA process. According to Lüdeke (2017), the mitigation hierarchy requires that environmental impacts must first be avoided in the first instance. If this is not possible, they are to be reduced or minimised.

[42] https://ec.europa.eu/environment/eia/eia-legalcontext.htm

Prior construction:

One of the measures that are applicable to MRE development and contribute to EIA is MSP which might help to accelerate permitting while protecting marine resources (Copping et al., 2014b).

Moreover, the deployment of MRE has the potential to cause conflict among interest groups including energy companies, the fishing sector and environmental groups. These conflicts could be minimized by integrating key stakeholders into the design, siting, construction and operational phases of the installations, and by providing clear evidence of their potential environmental benefits (Inger et al., 2009).

During construction:

Burial of cables and other measures such as placement of concrete mattresses are not considered to be effective ways to mitigate magnetic emissions into the marine environment, burial separates most sensitive species from the source of the emissions (Copping et al., 2016). However, as it was mentioned before, there is limited evidence that fish are influenced by the electromagnetic fields that underwater cables from wind turbines generate (Andersson et al., 2010a).

To reduce the underwater noise of pile driving several methods have been developed: the most developed noise mitigation method is the big bubble curtain, producing air bubbles around the construction site to form an air barrier. The sensitive area for potential injury could be reduced by more than 90 % (Nehls et al., 2016). Another method: small bubble curtain (which is used in the direct vicinity of a pile), hydro sound dampers (which are bubble curtains comprising air-filled balloons placed in the vicinity of piles), pile sleeves made of different materials or hollow steel tubes around the pile, as well as cofferdams (which are characterised by conducting the piling in the air rather than the water). Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises (Dähne et al., 2017). The Noise Mitigation System (NMS) is a new system to reduce noise during offshore pile driving, targeting specific low frequencies that produce most noise. This method is what distinguishes the NMS from other systems. The application of first-generation NMS thus reduced the effect range of pile driving and led to a lower decline of porpoise detections over all distances. However, NMS were still under development and did not always work with equal efficiency. As NMS have further developed since, future investigations are expected to show further reduction of disturbance effects (Brandt et al., 2018).

Furthermore, mitigation procedures that consisted of the application of scaring devices that aim to keep the animals out of a zone, where physical injury might occur, seem to have succeeded (Brandt et al., 2009).

During ORE device installation, the loss of benthic habitat caused by the footprint of anchors and foundations can be avoided or mitigated when vulnerable habitats have been identified and avoided during the siting process (Greaves and Iglesias, 2018).

During operation:

To reduce the collision risk for migrating birds, measures to adjust turbine operation, warn or deter birds, as well as fewer lights and lower light intensity are recommended, as an efficient “early warning system” (Hill et al., 2014; Lüdeke, 2017; May, 2015). It is not clear that a shutdown of wind turbines may help to mitigate the collision risk, showing higher avoidance of active turbines (Hill et al., 2014).

To reduce the underwater noise during the operational phase, a single 10 MW direct drive turbine is expected to cause behavioural response in marine mammals up to 1.4 km distance from the turbine, compared to 6.3 km for a turbine with a gear box (Stöber and Thomsen, 2021).

6.2 Risk maps

Limitations

The large spatial scale (raster cell size of 10*10 km) of the cumulative impact maps includes inherent limitations. Spatially small environmental impacts, such as effects around power cables, are impractical to include in a spatially large-scale analysis. Finer resolution maps can be created, though computing power requirements increase substantially.

Ecosystem components for animals were grouped into mammals, turtles, birds, invertebrates, and fish. These are quite broad categories and not all species within one group necessarily react the same way to stressors caused by offshore renewable energy production sites. With more information on how stressors affect specific species, subgroups with their own sensitivity scores could be created. Further research on the ecological stressors caused by offshore renewable energy sites can also help produce more advanced indices.

The analysis does not consider potential benefits that offshore renewable energy installations might have on some ecosystem components. Positive effects could be considered in future analyses but estimating how a positive effect compensates a negative effect might prove a complex problem.

The results from an EcoImpactMapper analysis are relative to the stressors and ecosystem components included and should be viewed with this context in mind.

Utility

Using EcoImpactMapper to produce cumulative impact maps is a relatively straightforward and flexible method. Sensitivity scores can quickly be modified, and stressors and ecosystem components can easily be added or removed, enabling the user to experiment with or analyse different types of scenarios, each with their own variables. EcoImpactMapper also has integrated functions for normalising and logarithmically transforming input data. Typically, the program is capable of quickly calculating and exporting results. Although the pre-processing of stressor and ecosystem data requires GIS knowledge, using EcoImpactMapper itself requires little to no experience with GIS. EcoImpactMapper is open source and freely available from the software development hosting site GitHub (www.github.com).

The cumulative impact maps can be used to identify areas where stressors from offshore energy installations and ecosystem components that are affected by said stressors overlap (Willsteed et al., 2018a). Such information can be used in MSP and by decision makers to minimize or reduce negative ecological effects of new offshore renewable energy installations, facilitating effective ecosystem-based management and achieving MSFD goals of good environmental status for the European marine environment. The ecological sensitivity maps can be used in a similar fashion, identifying areas where offshore renewable energy installations might have a minimal negative ecological effect.

The indices are not meant to be the definite answer to where ecosystems are most affected by offshore renewable energy installations, rather they can function as support for decision making, further research, and advancing the methodology for producing cumulative impact maps further.

6.3 Policy framework

The development of offshore renewable energy is necessary to reach EU climate targets and expand the Sustainable Blue Economy. At the same time, marine ecosystems in Europe are in a fragile state, which may be aggravated by the construction, operation, and decommissioning of offshore energy installations. Our policy review in section 5.1 and 5.2 identified that recent EU policies related to offshore renewable energy and marine environmental protection are aligned on climate change mitigation and sustainable economic development. However, there is a potential for conflict between these objectives and marine environmental protection. Both the Offshore Renewable Energy Strategy and Sustainable Blue Economy Strategy identified MSP as a tool that could be used to manage the potential trade-offs arising from diverse – and possibly conflicting – interests and objectives.

Our literature review of MSP in section 5.3 concluded that MSP did indeed hold promise as a tool to balance the increasing, sometimes competing demands on sea space. The literature identified that the initial MSP process should consider all current and planned uses of the sea space, as well as climate, environmental, economic, and social objectives and reconcile them, if necessary. By doing so, MSP ideally prevents conflicts from arising in the first place, or otherwise can aim to mitigate already ongoing conflicts resulting from past siting decisions or uses. MSP is a flexible process that achieves this goal of conflict mitigation and strategic planning both through the process and through the resulting plan. The literature identified that MSP is a collaborative process between authorities and different stakeholders which establishes connections between users of the sea, enabling them to coordinate their activities in the future. The maritime spatial plan itself, which often includes spatial zones allocated to particular uses, can also establish rules and regulations that reduce conflict and promote use of the sea space aligned with societal goals. Maritime spatial plans need not exclusively use area-based regulations, the literature also identified that plans may establish criteria-based management of activities at sea (e.g., only allowing fishing in areas where fish stocks exceed set standards) or include rules and regulations that manage how the use of the marine area is carried out.

Another conclusion from the literature is that MSP processes cannot be considered in a vacuum, but that they depend on – and may even facilitate – the parallel negotiation of solutions beyond the scope of MSP (e.g., agreements on shipping speed reductions). MSP is not a replacement of sectoral planning and regulation, but should frame and accompany it, and also encourages cross-sectoral management. A final key conclusion of the literature review was that while the final maritime spatial plan is important, it is equally important to understand the MSP process, especially the involvement of different stakeholders, as well as how a plan will be implemented and reviewed. MSP should be a continuous process, which does not end with the publication of a final plan, and instead evolves as new information becomes available, interests and activities change, and choices are reviewed accordingly.

To better understand how MSP balances potential trade-offs between the development of offshore renewable energy and marine environmental protection, in section 5.3.1, we reviewed four recently finalised maritime spatial plans by Belgium, Ireland, Finland, and Latvia. As determined in the MSPD, EU Member States had to establish maritime spatial plans by 31st March 2021. The review showed that MSP processes, form and content, as well as the national context in which plans were created differ widely. Only the Belgian plan is legally binding, whereas others offer strategic, non-binding guidance. Some plans identified spatial zones for specific activities, while others also or alternatively formulated policies to steer economic activities and the protection of the sea. These differences between the contexts and form and format, and our lack of analysis of the MSP process or the maritime spatial plans' future implementation, make direct comparisons of the plans challenging.

These differences aside, we found that all maritime spatial plans strive to facilitate the development of offshore renewable energy in national waters, while at the same time protecting and improving the marine environment. All plans explicitly acknowledge the need to balance potential trade-offs between these two objectives. To do so, the maritime spatial plans primarily rely on commitments to safeguarding the state of the marine environment when expanding offshore renewable energy, along with requirements to consider environmental conditions when selecting sites. The plans also refer to existing regulations requiring environmental assessments, and in some cases pose additional constraints on the development of offshore energy installations, such as excluding Natura 2000 areas or giving priority to the protection of especially valuable natural sites. In all maritime spatial plans, short-term offshore energy development focussed on wind energy (predominantly fixed turbines except for Ireland, who also targeted floating wind in deeper waters) with mentions but few plans for wave or tidal energy. The Belgian plan – the only plan with a legally binding zoning plan assessed in our study – was the only to increase the area available for offshore renewable energy; the other maritime spatial plans only identified areas with potential, as they were limited by the non-legally binding status.

Our literature review and analysis of maritime spatial plans suggests that even non-legally binding plans are valuable for balancing environmental and other objectives. MSP processes set in motion long-term planning processes, create relations between different stakeholder groups, clarify interests and objectives, and increase the information available about the sea areas. Especially the latter point should not be underestimated, because information about the ecological state of the seas as well as about its different users is often scarce. Understanding the baseline is a precondition for eventually being able to denote binding regulations and specify zones for activities. The first round of MSP also offers an opportunity to formulate medium- and long-term objectives, as well as actions and measures necessary to reach them; it can thus be regarded as a sort of stocktaking of where a country stands and where it needs to go. The plans of Latvia, Ireland and Finland should thus not be seen as ends, but rather the start of a process that includes monitoring and review, as well as ongoing development.

In terms of future research, our evaluation showed that it can be challenging to understand trade-offs between offshore energy and marine environment objectives by evaluating maritime spatial plans. A key gap is understanding the MSP process: the resulting plan does not reveal whether and where exactly conflicts occurred during the MSP development and implementation process. It also does not make explicit the influence of concurrent environmental assessments, the relations and power balance between different stakeholders, or how and whether conflicts were resolved. Moreover, from the plans and accompanying documents alone it is difficult to gauge how trade-offs will be balanced in the implementation phase. In future analysis, it could be insightful to go beyond evaluating the maritime spatial plans, and also assess the MSP process and its subsequent implementation.

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Annex 1 Search terms and strings used for searching scientific publications related to environmental impacts of offshore renewable energy

Table A1 Search terms and strings used for the query of scientific publication databases related to offshore wind farms

Search term or string	Nº of publications	Search term or string	Nº of publications
"wind farm*"	25,177	"wind turbine*"	67,571
"offshore windfarm*"	312	**"offshore wind turbine*"**	**5,601**
"offshore wind farm*"	**5,178**	**"marine wind turbine*"**	**8**
"marine windfarm*"	4		
"marine wind farm*"	10		
"offshore wind farm*" AND "pressure*"	163	"offshore wind turbine*" AND "pressure*"	378
"offshore wind farm*" AND "impact*"	986	"offshore wind turbine*" AND "impact*"	700
"offshore wind farm*" AND "environmental impact*"	**215**	"offshore wind turbine*" AND "environmental impact*"	72
"offshore wind farm*" AND "ecological impact*"	40	"offshore wind turbine*" AND "ecological impact*"	7
"offshore wind farm*" AND "environmental risk*"	9	"offshore wind turbine*" AND "environmental risk*"	4
"offshore wind farm*" AND "ecological risk*"	3	"offshore wind turbine*" AND "ecological risk*"	0
"offshore windfarm*" AND "pressure*"	12		
"offshore windfarm*" AND "impact*"	64		
"offshore windfarm*" AND "environmental impact*"	**24**		
"offshore windfarm*" AND "ecological impact*"	4		
"offshore windfarm*" AND "environmental risk*"	1		
"offshore windfarm*" AND "ecological risk*"	0		
"marine wind farm*" AND "pressure*"	3	"marine wind turbine*" AND "pressure*"	1

Search term or string	Nº of publications	Search term or string	Nº of publications
"marine wind farm*" AND "impact*"	7	"marine wind turbine*" AND "impact*"	1
"marine wind farm*" AND "environmental impact*"	**4**	"marine wind turbine*" AND "environmental impact*"	0
"marine wind farm*" AND "ecological impact*"	2	"marine wind turbine*" AND "ecological impact*"	0
"marine wind farm*" AND "environmental risk*"	0	"marine wind turbine*" AND "environmental risk*"	0
"marine wind farm*" AND "ecological risk*"	0	"marine wind turbine*" AND "ecological risk*"	0
"marine windfarm*" AND "pressure*"	0		
"marine windfarm*" AND "impact*"	2		
"marine windfarm*" AND "environmental impact*"	**1**		
"marine windfarm*" AND "ecological impact*"	0		
"marine windfarm*" AND "environmental risk*"	0		
"marine windfarm*" AND "ecological risk*"	0		

Table A2 Search terms and strings used for the query of scientific publication databases related to offshore current and tidal farms. WoS: Web of Science

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
Tidal energy	12,553		
Current energy	440,676		
"current energy"	5,095		
marine "current energy"	348		
offshore "current energy"	128		
marine "tidal energy"	568		
offshore "tidal energy"	276		
marine AND "current energy" AND "environmental impact"	24	9	753
offshore AND "current energy" AND "environmental impact"	5	5	742
marine AND "tidal energy" AND "environmental impact"	72	44	884
offshore AND "tidal energy" AND "environmental impact"	22	22	781
marine AND "current energy" AND "ecological impact"	3	1	84
offshore AND "current energy" AND "ecological impact"	1	1	76
marine AND "tidal energy" AND "ecological impact"	10	5	156
offshore AND "tidal energy" AND "ecological impact"	2	1	117
marine AND "current energy" AND "environmental risk"	2	2	84

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
offshore AND "current energy" AND "environmental risk"	0	1	83
marine AND "tidal energy" AND "environmental risk"	4	2	93
offshore AND "tidal energy" AND "environmental risk"	3	1	90
marine AND "current energy" AND "ecological risk"	0	0	12
offshore AND "current energy" AND "ecological risk"	0	0	14
marine AND "tidal energy" AND "ecological risk"	0	1	24
offshore AND "tidal energy" AND "ecological risk"	0	0	16
TOTAL	**148**	**95**	**4,009**
Fusion	**243**		
Duplicated references removal	**135**		
Incomplete references removal	**131**		
Conference proceedings removal	**101**		

Table A3 Search terms and strings used for the query of scientific publication databases related to offshore wave energy farms. WoS: Web of Science

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
wave energy	21,461	25965	32,548
wave energy converter	4,307	2697	2,579
wave energy converter AND environmental impact	69	33	536
wave energy converter AND ecological impact	2	0	52
wave energy converter AND environmental risk	3	0	51
wave energy converter AND ecological risk	1	0	3
wave energy AND environmental impact	239	90	2,236
wave energy AND ecological impact	17	1	376
wave energy AND environmental risk	12	2	208
wave energy AND ecological risk	3	0	62
	271	93	2882
Fusion	364		
Duplicated references removal	273		
Incomplete references removal	265		
Conference proceedings removal	184		
Additional publications (ResearchGate)	8		

Table A4 Search terms and strings used for the query of scientific publication databases related to photovoltaic farms. WoS: Web of Science

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
photovoltaic			
marine AND photovoltaic			
"marine photovoltaic"	8	6	9
offshore AND photovoltaic	309	240	5,410
"offshore photovoltaic"	13	10	35
Solar			
marine AND solar	4,148	6621	49,925
offshore AND solar	1,260	769	20,038
marine AND photovoltaic AND "environmental impact"	24	14	2,045
"marine photovoltaic" AND "environmental impact"	0	0	4
marine AND photovoltaic AND "environmental risk"	0	1	240
"marine photovoltaic" AND "environmental risk"	0	0	0
marine AND photovoltaic AND "ecological impact"	0	0	166
"marine photovoltaic" AND "ecological impact"	0	0	0
marine AND photovoltaic AND "ecological risk"	0	0	54
"marine photovoltaic" AND "ecological risk"	0	0	0
offshore AND photovoltaic AND "environmental impact"	12	7	2,008
"offshore photovoltaic" AND "environmental impact"	0	1	12

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
offshore AND photovoltaic AND "environmental risk"	1	0	180
"offshore photovoltaic" AND "environmental risk"	0	0	3
offshore AND photovoltaic AND "ecological impact"	0	0	146
"offshore photovoltaic" AND "ecological impact"	0	0	0
offshore AND photovoltaic AND "ecological risk"	0	0	42
"offshore photovoltaic" AND "ecological risk"	0	0	0
marine AND solar AND "environmental impact"	122	78	6,839
"marine solar" AND "environmental impact"	0	0	10
marine AND solar AND "environmental risk"	10	9	1,127
"marine solar" AND "environmental risk"	0	0	0
marine AND solar AND "ecological impact"	12	5	1,007
"marine solar" AND "ecological impact"	0	0	1
marine AND solar AND "ecological risk"	3	5	457
"marine solar" AND "ecological risk"	0	0	0
offshore AND solar AND "environmental impact"	55	20	4,381
"offshore solar" AND "environmental impact"	1	1	48
offshore AND solar AND "environmental risk"	7	2	6,885
"offshore solar" AND "environmental risk"	0	0	3
offshore AND solar AND "ecological impact"	4	0	481
"offshore solar" AND "ecological impact"	0	0	3

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
offshore AND solar AND "ecological risk"	1	1	118
"offshore solar" AND "ecological risk"	0	0	0
TOTAL	**130**	**66**	**26,260**
Fusion	**196**		
Duplicated references removal	128		
Incomplete references removal	122		
Conference proceedings removal	93		

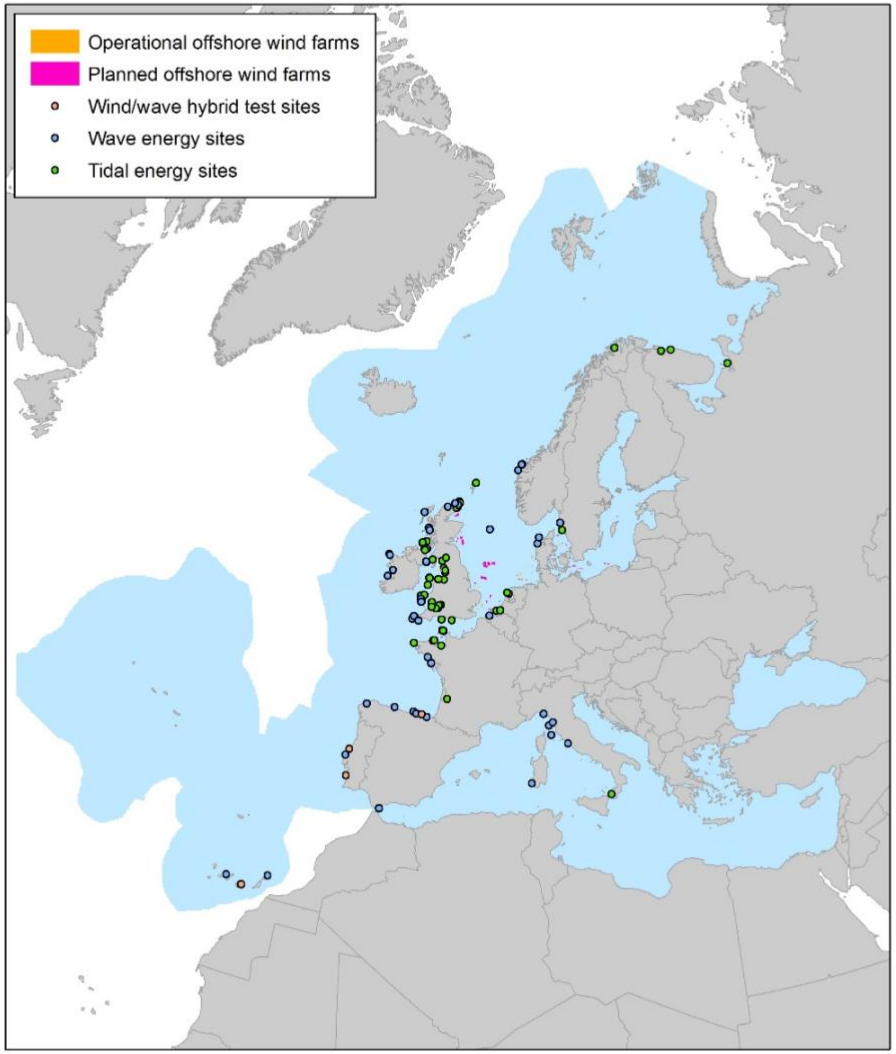
Table A5 Search terms and strings used for the query of scientific publication databases related to thermal gradient farms. WoS: Web of Science

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
thermal gradient	77,019		
"thermal gradient"	24,997		
marine AND "thermal gradient"	352	322	6,565
offshore AND "thermal gradient"	206	47	2,750
marine AND "salinity gradient"			
offshore AND "salinity gradient"			
"ocean thermal energy"	**1,964**	**772**	**2,345**
"renewable energy" AND offshore AND "thermal gradient"	3	2	278
"renewable energy" AND marine AND "thermal gradient"	11	10	349
"ocean thermal energy" AND "environmental impact"	87	19	678
marine AND "thermal gradient" AND "environmental impact"	11	4	415
offshore AND "thermal gradient" AND "environmental impact"	2	1	302
"renewable energy" AND offshore AND "thermal gradient" AND "environmental impact"	0	1	151
"renewable energy" AND marine AND "thermal gradient" AND "environmental impact"	5	2	170
"ocean thermal energy" AND "ecological impact"	4	0	62
marine AND "thermal gradient" AND "ecological impact"	0	0	74
offshore AND "thermal gradient" AND "ecological impact"	0	0	50

Search terms	Nº of papers		
	Scopus	WoS	ScienceDirect
"renewable energy" AND offshore AND "thermal gradient" AND "ecological impact"	0	0	24
"renewable energy" AND marine AND "thermal gradient" AND "ecological impact"	0	0	23
"ocean thermal energy" AND "environmental risk"	2	0	52
marine AND "thermal gradient" AND "environmental risk"	0	0	60
offshore AND "thermal gradient" AND "environmental risk"	0	0	37
"renewable energy" AND offshore AND "thermal gradient" AND "environmental risk"	0	0	26
"renewable energy" AND marine AND "thermal gradient" AND "environmental risk"	0	0	29
"ocean thermal energy" AND "ecological risk"	1	0	10
marine AND "thermal gradient" AND "ecological risk"	0	0	16
offshore AND "thermal gradient" AND "ecological risk"	0	0	7
"renewable energy" AND offshore AND "thermal gradient" AND "ecological risk"	0	0	3
"renewable energy" AND marine AND "thermal gradient" AND "ecological risk"	0	0	3
TOTAL	**112**	**27**	**2,192**
Fusion		**139**	
Duplicated references removal		**113**	
Incomplete references removal		**109**	
Conference proceedings removal		**68**	

Annex 2 Risk maps input data

Figure A1: Combined EMODnet and 4C data used to create stressor layers for the environmental risk maps production



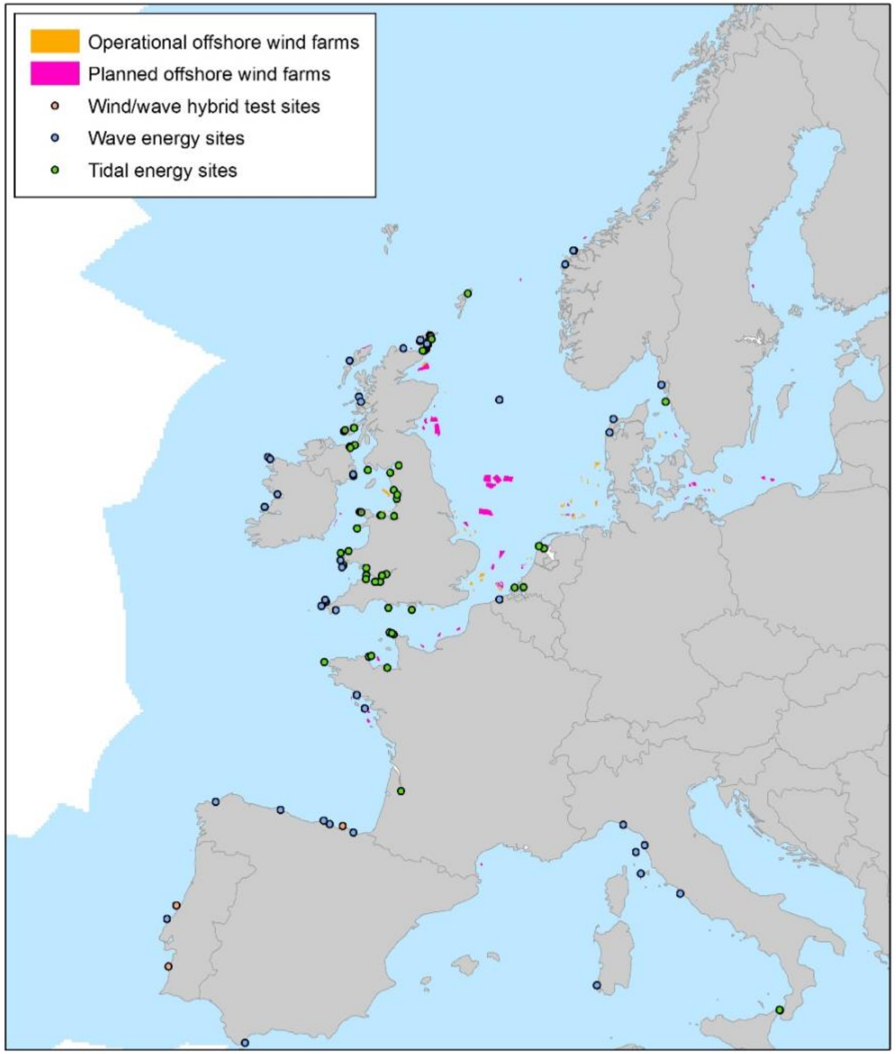


Table A6 Ecosystem components sensitivity scores for wind, tidal and wave energy stressors

Wind power stressor	Seabed	Invertebrates	Fish	Birds	Wind conditions	Phytoplankton	Mammals	Turtles	Ecosys. structure
Operational: structures	0.00	3.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00
Operational: barrier effect	0.00	0.00	0.00	3.25	2.00	0.00	0.00	0.00	0.00
Operational: Mechanical disturbance	0.00	0.00	0.00	0.00	0.00	5.00	0.00	0.00	0.00
Under construction: Noise	0.00	0.00	5.00	0.00	0.00	0.00	5.00	0.00	0.00
Under construction: Mortality/alteration through sediment removal	0.00	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tidal power stressor	**Seabed**	**Invertebrates**	**Fish**	**Birds**	**Wind conditions**	**Phytoplankton**	**Mammals**	**Turtles**	**Ecosys. Structure**
Antifouling	0.00	0.00	0.50	1.00	0.00	0.00	1.00	0.00	0.00
Electromagnetic fields	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
Noise	0.00	0.00	2.20	1.00	0.00	0.00	3.50	0.00	0.00
Physical disturbance	3.00	0.00	0.50	2.00	0.00	0.00	3.00	0.00	2.20
Wave power stressor	**Seabed**	**Invertebrates**	**Fish**	**Birds**	**Wind conditions**	**Phytoplankton**	**Mammals**	**Turtles**	**Ecosys. structure**
Antifouling	0.00	0.00	0.00	1.00	0.00	0.00	0.50	1.00	0.00
Hydrological changes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.70
Noise	0.00	0.00	2.50	0.50	0.00	0.00	2.00	1.00	0.00
Physical disturbance	5.00	1.00	5.00	2.00	0.00	0.00	3.00	3.50	3.00
Physical loss	0.00	0.00	0.00	1.20	0.00	0.00	0.00	0.00	0.00
Electromagnetic fields	0.00	0.00	1.75	0.50	0.00	0.00	0.50	3.00	0.00

Annex 3 Template for the analysis of maritime spatial plans

Contextual information	
Size and location of sea space	
Status of the marine environment	
Status of MPAs	
Status of offshore renewable energy	
Involvement in MSP related projects during MSP process	
Relevant regional organisations	
Structure/ Form	
Language	
English title	
Current status and, if relevant, date adopted	
Maritime spatial plan version	
General description	
Maps	
Mode of presentation	
Accompanying documents	
Environmental assessments	
Type of assessment	
Date published	
English title	
General description	
Responsible agency	
Timeline	
Key principles and methodology	
Assessment of the trade-offs between ORE development and marine environmental protection	
Influence of environmental assessment on MSP	
Process	
Timeline	
Planning process	
Coherence between MSP and other processes	
Stakeholder involvement	
Use of best available data	
Transboundary cooperation and cooperation with third countries	

Cooperation with third countries	
Ecosystem-based management	
Guiding principles/ core values	
Process for balancing competing objectives	
Content	
Definition of MSP	
General functioning of maritime spatial plan	
Climate objectives	
Offshore renewable energy objectives	
Marine environmental objectives	
Multi-use/ co-existence objectives	
Identification of interactions between ORE development and marine environmental objectives	
Implementation	
Authority of maritime spatial plan	
Implementing agency	
Implementation process	
Monitoring and review	

Annex 4 Overview of sources used in the evaluation of maritime spatial plans

Belgium

All documents are available on the website of the Federal Public Service for Health, Food Chain Safety and Environment under https://www.health.belgium.be/en/marinespatialplan.be, last accessed on 27 August 2021.

- Royal Decree establishing the marine spatial planning for the period 2020 to 2026 in the Belgian sea-areas, 2020 – *unofficial English translation*
    - Annex 1: Spatial analysis of sea areas (Ruimtelijke analyse van de zeegebieden) – *official Dutch version as well as unofficial English translation of relevant experts*
    - Annex 2: Long-term vision, objectives and indicators, and spatial policy choices (Langetermijnvisie, doelstellingen en indicatoren, en ruimtelijke beleidskeuzes) – *official Dutch version as well as unofficial English translation of relevant experts*
    - Annex 3: Actions for the implementation of the MSP (Acties tot uitvoering van het marien ruimtelijk plan) – *official Dutch version*
    - Annex 4: Maps (Karten) – *official Dutch version*
- Strategic Environmental Assessment of the MSP (Strategische Milieubeoordeling van het Ontwerp Marien Ruimtelijk Plan), 2018 – *official Dutch* version.

Finland

The Finish maritime spatial plan and accompanying documents are available on the designated website https://meriskenaariot.info/merialuesuunnitelma/, last accessed on 27 August 2021.

- Maritime spatial plan for Finland 2030, 2020 – *official website in English*
    - Legislative framework, planning principles and process description
    - Potential and alternative scenarios for the future of marine areas up to 2050
    - Vision for the sustainable use of marine areas 2050, and sector-specific roadmaps 2030
    - Maritime spatial plans for Finland's three planning areas
- Impact assessment of the Finnish Maritime Spatial Plan, 2020 – *English version.*

Ireland

All documents are available on the website of the Department of Housing, Local Government and Heritage under https://www.gov.ie/en/publication/60e57-national-marine-planning-framework, last accessed on 27 August 2021.

- National Marine Planning Framework including appendixes A–F, 2021
- National Marine Planning Framework: Post Consultation Natura Impact Statement (NIS), 2021
- National Marine Planning Framework: Strategic Environmental Assessment (SEA) Statement, 2021.

Latvia

All documents are available on the website of the Ministry of Environmental Protection and Regional Development under https://www.varam.gov.lv/en/maritime-spatial-planning, last accessed on 27 August 2021.

- Maritime Spatial Plan 2030: The Maritime Spatial Plan for the Marine Inland Waters, Territorial Sea and Exclusive Economic Zone Waters of the Republic of Latvia, 2019 – *unofficial English translation*
    - Annex 1: Map
    - Annex 2: Criteria for defining priority uses of the marine space – *unofficial English translation*
    - Annex 3: Interests of the neighbouring states in the marine space – *unofficial English translation*
- Maritime Spatial Plan 2030: Environmental report (Final version), 2019 – English summary.

European Topic Centre European Topic Centre on Inland, Coastal and Marine waters (ETC/ICM)
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