Enduring sectoral challenges

Ainhoa González and Fatemeh Rezaei

19th June 2026

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Deliverable Information Sheet

Version	
Grant Agreement Number	**101235376**
Project Acronym	**SUSTAINOW**
Project Title	**SUSTAINABLE OFFSHORE WIND**
Project Call	**HORIZON-CL5-2024-D3-02**
Project Duration	**36 months**
Deliverable Number	D3.1
Deliverable Title	Enduring sectoral challenges
Deliverable Type	Report
Deliverable Dissemination Level	Public
Work Package	WP3
Lead Partner	Prof. Ainhoa González
Authors	Ainhoa González, Fatemeh Rezaei
Contributing Partners	UCD, AAU, DTU
Reviewers	Lone Kørnøv, David Philip Rudolph
Official Due Date	30th June 2026
Delivery Date	19th June 2026

History of changes

Version	Date	Description	Author(s)
0.1	04.05.2026	Draft 1	Ainhoa González
0.2	06.05.2026	Draft 2	Fatemeh Rezaei
0.3	22.05.2026	Draft 3	Ainhoa González
	27.05.2026	Draft 4	Fatemeh Rezaei
0.4	29.05.2026	Finalise draft for review	Ainhoa González, Fatemeh Rezaei
0.5	02.06.2026	Review	Lone Kørnøv, David Philip Rudolph
1.0	19.06.2026	Submission	

List of Acronyms

Acronym	Full term	Description
AA	Appropriate Assessment	Assessment of the potential effects, including in-combination effects, on designated Natura2000 protected areas and species required under the European Habitats Directive 92/43/EEC.
CEA	Cumulative Effects Assessment	Assessment of the combined effects of multiple plans, projects and activities on multiple environmental and social receptors over space and time, regulated by the SEA, EIA and AA Directives.

Funded by the European Union

EIA	Environmental Impact Assessment	Project-level assessment of significant environmental effects, including cumulative effects, regulated through the EIA Directive 2014/52/EU.
EIAR	Environmental Impact Assessment Report	Report that describes the assessment of significant environmental effects as per the EIA Directive 2014/52/EU, and provides recommendations to avoid, mitigate or compensate identified potential significant effects.
EEZ	Economic Exclusion Zone	A maritime area (extending up to 200 nautical miles from the coast) where the state possesses sovereign rights to explore, exploit, conserve, and manage natural resources - including marine life, oil, gas, and wind or tidal energy.
GIS	Geographic Information Systems	Software for the creation, gathering, analysis and visual display of spatial (or geographically-specific) data.
GPS	Global Positioning Systems	A global navigational satellite system that provides precise positioning, navigation, and timing services to users worldwide.
MPA	Marine Protected Area	A designated geographical region of the ocean or coastal waters where human activities are regulated and managed to achieve or maintain long-term good environmental status; they are key spatial protection measures under the MSFD 2008/56/EC.
MSFD	Marine Spatial Planning Directive	European Directive establishing a framework for community action in the field of marine environmental policy.
MSP	Marine Spatial Planning	A public process for analysing and organising human activities in marine spaces with the aim to achieve ecological, economic; regulated by the MSP Directive 2014/89/EU.
SEA	Strategic Environmental Assessment	Assessment of significant environmental effects, including cumulative effects, applied to plans and programmes, regulated through the SEA Directive 2001/42/EC.
SEA ER	Strategic Environmental Assessment Environmental Report	Report that describes the assessment of significant environmental effects as per the SEA Directive 2001/42/EC, and provides recommendations to avoid, mitigate or compensate identified potential significant effects.
WP	Work Package	Thematic research groups underpinning the research tasks and objectives of the project.

List of Tables

Keywords list

- Challenges
- Cumulative effects
- Cumulative Effects Assessment (CEA)
- Current practice
- Environmental Impact Assessment (EIA)
- Environmental risks
- Expert consultation
- In-combination effects
- Literature review
- Methods
- Offshore wind
- Report Review
- Strategic Environmental Assessment (SEA)
- Social risks

Funded by
the European Union

Disclaimer

This document reflects the views of the author(s) and does not necessarily reflect the views or policy of the European Commission. Whilst efforts have been made to ensure the accuracy and completeness of this document, the European Commission is not responsible for any use that may be made of the information it contains nor for any errors or omissions, however caused.

Executive Summary

Purpose and scope

This deliverable (D3.1) presents a comprehensive qualitative register of prevailing practical challenges in Cumulative Effects Assessment (CEA) practice, as well as key (cumulative) socio-environmental risks within the offshore wind energy sector. The content of the report is informed by an extensive review of international scientific literature, a review of a selected number of Strategic Environmental Assessment (SEA) and Environmental Impact Assessment (EIA) reports, and consultation with expert representatives from the European wind energy sector, including consenting authorities, impact assessment practitioners, researchers, plan-makers, and developers.

By outlining prevailing CEA challenges and socio-environmental risks, the objective is twofold: 1) to establish a shared understanding of current practice issues that need to be addressed to improve the assessment of cumulative effects; and 2) to identify critical pressures/receptors that need to be prioritised in cumulative (and transboundary) assessments. It is anticipated that the outcomes of these objectives provide a robust foundation for developing a CEA framework and inform the development of decision-support tools in subsequent Work Packages (WPs).

Current practice challenges

Despite significant advancements, the implementation of CEA continues to face significant challenges in current practice. These challenges are characterised by procedural shortcomings, analytical complexities, data limitations and lack of knowledge. The findings of the reviews of international scientific literature and environmental reports, and expert opinion render most challenges as procedural, and they coincide in the following **procedural shortcomings:**

- **Assessment type:** There is a predominance of qualitative CEA approaches, largely based in expert judgements, which can entail a degree of professional subjectivity or bias and influence replicability of assessments and transferability of outputs. Quantitative approaches are only applied at project level and for certain pressures/receptors (e.g. noise and marine mammals, physical presence of turbines and bird collision).
- **Methods:** Significant variations are observed in CEA methods (e.g. spatial analysis, modelling, expert judgement, field observations), with particular differences between assessments levels (SEA versus EIA), but also across a given assessment level and across jurisdictions. Such inconsistencies lead to non-comparable CEA outcomes and recommendations.
- **Spatial extent:** The spatial extent or geographic area of CEA varies across assessments: from the plan area boundary, to project 'zones of influence', to entire sea basins. The 'zones

of influence' also vary across and within receptors (e.g. from 300 meters through to 750 meters from the development site, to the entire Economic Exclusion Zone for noise sensitive receptors). These disparities also apply to monitoring, affecting coherent and coordinated ecosystem-wide assessments.

- **Temporal scope:** CEAs are typically bounded by plan/project timelines (e.g. 25 to 30 years), which are not necessarily aligned with the long-term, delayed, and often non-linear ecological responses characteristic of marine ecosystems. Importantly, CEAs capture a snapshot in time and they do not meaningfully capture effects over time due to shifting baselines; every assessment starts with the 'current' baseline thus not capturing previous effects or not accounting for climate change effects or system recovery times.

Additional significant procedural challenges include: Discrepancies in **assessment scope** (e.g. consideration of plans/programmes, planning stages, effect types, methods and spatio-temporal extents) which influence effect significance (or impact) determinations; **effect types** with cumulative effects typically treated as simple aggregations of individual effects, and synergistic and antagonistic effects rarely being considered; lack of **guidance** which leads to assessment inconsistencies that affect comparability; different **interpretations** of CEA, also induced by the lack of guidance, which influence what is included - or excluded - from assessments; and lack of **thresholds** for determining what constitutes an acceptable level of cumulative social and/or environmental change over time and space.

Concurred **analytical complexities** entail:

- **Aggregation:** The absence of agreed approaches for aggregating multiple assessment indicators, pressure-receptor relationships and model outputs into a single, transparent, and scientifically defensible cumulative effect index. This can affect comparability of assessment as well as communicating assessment outcomes, and thus the capacity of decision-makers to understand overall cumulative effect implications.
- **Dynamic nature:** The dynamic and highly complex nature of marine ecosystems creates substantial uncertainty in assessing cumulative effects, as well as a risk that findings become rapidly outdated in evolving marine environments.
- **Uncertainties:** Uncertainties arise when accurate and complete socio-environmental information are missing, as well as a result of limited understanding on how cumulative effects vary across geographic contexts, ecosystem conditions, and exposure pathways over time. This affects the accuracy and reliability of assessment outcomes.
- **Significance:** Effect significance or impact judgements are complex and highly dependent on the conceptual interpretation of cumulative effects, assessment scope, thresholds agreed upon, and the spatial and temporal extents considered. They are also influenced by planning phases considered and, importantly, by data and knowledge gaps. Consequently, different assessments of similar activities or pressures may reach substantially different conclusions regarding whether cumulative effects are considered acceptable, manageable, or ecologically significant.

Funded by the European Union

Validation of model outputs is also an important analytical challenge. Predictive **modelling** is increasingly used, particularly at project assessment level, and are essential for forecasting potential (cumulative) effects, but they often lack long-term, post-construction empirical validation. Without ground-truthing models risk compounding initial hypothesis and propagating uncertainties into broad quantification biases or inaccurate effect predictions.

The critical **data limitations** and **knowledge gaps** identified in all three sources (i.e. literature, environmental reports and expert input) are:

- **Centralisation:** The absence of centralised, accessible, and interoperable systems for storing and sharing socio-environmental data is a significant constraint for CEA. It means that practitioners (and decision-makers) face substantial difficulties in accessing available baseline data, which in turn affects the adoption of comparable evidence-basis and can affect the comprehensiveness of assessments.
- **Gaps:** Missing, incomplete, outdated, inconsistent, inaccessible, or insufficiently reliable data limits the ability to accurately identify, predict, evaluate, monitor and/or manage the cumulative effects of offshore wind energy plans and projects on socio-environmental receptors, as well as determine effect significance.
- **Planning phases:** There is limited understanding of how different project development phases (e.g. construction, operation, and decommissioning) interact across wide marine geographical areas, and how these interactions contribute to cumulative effects over time. Moreover, current project level CEAs frequently emphasise construction and operational activities; **decommissioning** is rarely included in assessments due to the absence of empirical data.
- **Social effects:** These are typically understudied, and their inclusion is commonly limited to the fisheries sector with regards to co-existence conflicts and to tourism in coastal communities with regards to visual effects and seascape changes. Broader social (e.g. job creation), cultural (e.g. identify), health (e.g. noise), and well-being effects (e.g. stress from industrialisation of the seascape) on coastal communities are rarely examined, limiting the comprehensiveness of CEAs.

Data quality (affecting the veracity and reliability of CEA outcomes) and **comparability** (different units and formats in socio-economic data, significance thresholds, etc. affecting the extent to which CEA outcomes can be compared across sectors and jurisdictions and taken into consideration int future assessments) are compounded by **data collection** (lack of methodological across different plan and/or project proponents and research institutions, as well as monitoring frameworks). These create major obstacles for integrating datasets across projects, sectors, and jurisdictions, ultimately limiting the reliability of CEAs outcomes. In addition, restricted **access** to proprietary, confidential, or commercially sensitive datasets complicates data gathering processes, and can result in spatial and taxonomic data gaps that weaken confidence in assessment outcome. Data limitations are magnified by knowledge gaps, particularly with regards to **pressure-receptor interactions:** lack of data and understanding of how specific environmental pressures affect ecological or social receptors cumulatively across space and time, and how these receptors may recover (e.g. post-construction or after decommissioning) leads to incomplete and potentially incorrect assessments.

Environmental risks

Cumulative environmental effects of wind farms vary across their planning stages. They are characterised by a temporal split: intense, short-term disturbances during construction and long-term, chronic shifts during operational phases. Decommissioning effects remain understudied.

Risks can be positive or adverse, and largely relate to species-specific responses based on sensitivity and/or tolerance. In all cases, such risks should be jointly considered, as appropriate to the marine area and plan/project context. Existing challenges with regards to data and knowledge limitations may affect the extent to which some of these risks may be effectively considered.

The main risks during construction are those derived from underwater noise pressures from pre-piling vessel activity; high-intensity impulse noise from pile-driving. It affects **bats, birds, fish and marine mammals**, creating **permanent or temporary disturbance** (in movement and/or breeding patterns) **and displacement** (e.g. from habitats and/or migratory routes). It can also cause a **reduction in recruitment (in fish) and subsequent reproductive success (in birds)** through trophic level connections. For **marine mammals**, it can lead **to temporary or permanent auditory injury and behavioural changes** (e.g. reduction in foraging vocalisations or echolocation) which can lead to **potential starvation** (lethal threat). Habitat change pressures during construction (e.g. removal of natural habitat; introduction of hard surfaces and artificial reefs) can also affect benthic and fish communities, and **alter predator-prey dynamics** due, for example, to **increase/decrease in benthos and fish recruitment**.

During operation, physical structures and barriers associated with the presence of wind turbines and foundations, can increase **collision and mortality risk for birds** as well as **displacement from their habitats and migratory routes**. For **benthos, decapods, epifauna, and fish**, physical structures can lead to **changes in species interactions** through food supply. Turbine foundations can also create **changes in marine physical processes and hydrodynamics** (e.g. waves and currents around foundations, including changes in grain size distribution) and subsequently influence **changes in habitats and food supply**. The positive effect of the existence of wind farms is the potential for biodiversity conservation as a result of removal of fishing and shipping activities (i.e. wind farms acting as marine protected areas). Additional environmental pressures during operation include the introduction of non-native species (through vessel activity and colonisation of turbine foundations) resulting in **ecosystem changes** at the expense of native soft-bottom communities. There is also the positive or antagonistic reef effect (i.e. hard substrate from foundations and scour protection)

Funded by the European Union

leading to **changes in species composition** such as benthos and epifauna and benefiting fish in particular, through **increased food supply and spawning connectivity**.

Decommissioning is understudies but the partial or full removal of physical structures can have the risk of detrimental **effects on habitats and species richness**. Organic enrichment and turbidity can also affect habitats and species during infrastructure removal.

Social risks

Cumulative social risks are understudied when compared to environmental risks, despite them often being most contentious. The fisheries-conservation-offshore wind nexus is the primary area of cumulative social friction, entailing competing values, subjective data, and various risk factors (including cultural, identify and economic ones) for local communities.

The presence of physical structures and barriers represents the main pressure, affecting significantly the fisheries sector by creating the risk of **marine use conflicts** (e.g. spatial squeeze that forces fishermen to less favourable conditions, and increased competition), which also create **navigation safety risks** for the shipping industry. They also present a risk to the viability of the tourism sector as a result of **visual intrusion** and **seascape changes** reducing the value of coastal tourism destinations. Such risks can equally affect the **wellbeing** of coastal communities. Additional pressures relate to governance frameworks, which can create a risk for local **public opposition** to renewable energy development if local communities are not engaged in planning and decision-making. A potential **positive 'risk'** is that of **conservation** (by removing fishing from wind farm sites and the creation of reef effects) with the subsequent spillover of adult fish into grounds adjacent to wind farm sites, increasing catchment for fishermen.

Basis for further work

The CEA challenges and socio-environmental risks presented in this deliverable provide the basis for a shared understanding of practical issues and pressure-receptor priorities that need to be considered in subsequent project activities. They will inform the development of a CEA framework with the intention to tackle as many as the identified challenges as it is practically possible. This, in turn, will influence the development of a tool for supporting informed and sustainable offshore wind farm sitting decisions. Similarly, the identified environmental and social risks will be considered in the CEA framework, as well as in the data collection processes and the development of the shared data space.

Table of Contents

1. Introduction

1.1. Background and rationale

The global transition toward decarbonised energy systems has positioned offshore wind farms as a cornerstone of marine renewable energy strategies. As nations strive to meet the Paris Agreement targets (UN, 2015) and regional mandates, such as the European Green Deal (EU, 2019) and the Renewable Energy Directive (EU, 2015), the scale and density of offshore development zonings and project deployments have increased exponentially. Such rapid industrialisation of the marine environment introduces complex socio-environmental pressures. Identifying, assessing and mitigating these pressures requires robust assessments that address multiple pressures and varying receptor sensitivities in the marine environment. Cumulative Effects Assessment (CEA) enables this by systematically evaluating socio-environmental changes resulting from the additive, synergistic, or antagonistic[1] effects of multiple plans and projects simultaneously on different natural processes, species or habitats (Borja et al., 2024; Morejón and González Del Campo, 2026; Pinkau and Schiele, 2021).

CEA is a mandatory requirement under Directives 2001/42/EC on Strategic Environmental Assessment (SEA - EC, 2001) and 2014/52/EU on Environmental Impact Assessment (EIA - EU, 2014a). These legislative tools aim to anticipate and mitigate significant (cumulative) environmental and social effects/impacts[2] arising from the implementation of plans and programmes (SEA), and projects (EIA) in order to promote sustainable development. Similarly, the Habitats Directive (EC, 1992) requires the assessment and mitigation of in-combination effects on designated Natura 2000 conservation sites. In addition, CEA requirements are also embedded into marine-specific legislation, including the Marine Strategy Framework Directive (MSFD), and the Maritime Spatial Planning (MSP) Directive (EC, 2008; EU, 2014b). Despite its legal mandate and pivotal role, CEA has long faced challenges in practice, both onshore and offshore (Blakley, 2021; Declerck *et al.*, 2022; Duinker *et al*. 2013; Gunn and Noble 2011; Joseph *et al.*, 2023; Noble *et al.*, 2017; Willsteed *et al.*, 2018). Key reported CEA challenges include insufficient guidance, and poor methodologies and data/knowledge limitations compounded by uncertainty (e.g. Blakley, 2021; Bragagnolo *et al.,* 2021; Joseph *et al.*, 2023). Much of the international literature on CEA focuses onshore, with limited published studies in the marine environment. Perhaps more importantly, empirical research reviewing multiple case studies,

[1] Cumulative effects are additive when the combined effect equals the sum of individual effects; synergistic when the combined effect is greater than the sum; and antagonistic when the combined effect is less than the sum (e.g. one effect offsets another).

[2] The SEA and EIA Directives place clear emphasis on the identification of environmental effects, with limited references to identifying impacts. While acknowledging that 'impact' is commonly used in SEA and EIA practice, the term 'effect' is adopted in this report, as the general consensus is that effects are defined as the consequences of an action (e.g. plan, project) while impacts relate to the severity of the effect.

Funded by
the European Union

and associate multiple pressures and receptors simultaneously, remains notably sparse (Kannen, 2014; Depellegrin *et al*., 2024; Ferguson *et al*., 2025).

Authoritative CEA guidance/guidelines are also limited (e.g. CEAA, 2018; EPA, 2020; IFC, 2013; NERC, 2013; UK Government, 2024); with only one specific to offshore wind farms (i.e. NERC, 2013), although a very limited number of topic-specific CEA guidance also exist (e.g. on cumulative visual and bird effects - NatureScot, 2021; 2025). The recommendations in these guidance documents remain largely broad, and focus on: a) setting up appropriate spatial and temporal assessment scales; b) identifying pressures from existing, planned and future plans and developments within a zone of influence; c) identifying receptors (often referred to as valued environmental components); d) establishing either limits from environmental standards/legislation or effect/impact thresholds; e) assessing changes in receptors as a result of identified pressures; and f) determining effect significance (i.e. impact). Impact is typically a result of the magnitude of effect (taking into account its type, duration and extent) versus the sensitivity of the receptor and its capacity to absorb change. The CEA FasTips of the International Association for Impact assessment (IAIA, 2017) imply similar considerations. In some of these guidance documents (e.g. UK Government, 2024), it is recognised that spatial scales may need to be receptor-specific (e.g. cumulative effects manifest over larger geographical areas for migratory birds and mammals than for benthos), but no advice is provided on how to define these. Similarly, no recommendations are provided for the prioritisation of pressures and/or receptors – the only guidance in this regard is contained in Annex III of the MSFD which provides an indicative list of characteristics, pressures and impacts (EC, 2008). Broadly, existing guidance recommend adopting a source-pathway-receptor model, together with the use of Geographic Information Systems (GIS) to determine spatio-temporal overlaps between multiple pressures and receptors; as well as the application of professional judgement to determine effect significance or impact, particularly in data poor contexts.

The MSFD and MSP Directives (EC, 2008; EU, 2014b) are driving significant research efforts towards a better assessment and understanding of accumulated socio-environmental effects in the marine environment across space and time (e.g. Ansong *et al*., 2017; Borja *et al*., 2024; Halpern *et al*., 2008; Hammar *et al*. 2020; Morejón and González Del Campo, 2026; Piet *et al*. 2023, Willsteed *et al*., 2018). While these research advancements enable a more comprehensive and quantifiable approach to CEA, it has been argued that environmental assessment researchers often lament that “practice frequently disappoints” by not living up to research ideals and innovations when aiming to improve its real-world conduct (Bonnell, 2025: 1).

Despite existing guidance and research-driven methodological advancements, there is a dearth of research on how CEA is currently executed in practice, with a specific lack of cross-project meta-analyses. As a result, there is a lack of understanding on what are the enduring CEA practice challenges. There is limited comparative evidence synthesising insights from scientific literature, impact assessment practice, and practitioner experience across multiple

Funded by the European Union

jurisdictions. This limits understanding of which challenges persist despite methodological advancements. The lack of understanding on how CEA is implemented, also leads to a lack of knowledge on what socio-environmental issues are being prioritised and subsequently to a lack of awareness of what aspects, if any, are being overlooked. A better understanding of these considerations is pressing to improve CEA effectiveness and develop comprehensive assessments in the offshore wind energy sector, particularly in light of the growing number of marine spatial plans and the proliferation of offshore wind energy projects across the world.

1.2. Objectives and scope

The overall objective of Deliverable D3.1 is twofold: 1) to establish a shared understanding, among the SUSTAINOW consortium (and the wider impact assessment and offshore wind energy communities of research and practice), of current practice challenges that need to be addressed to improve the assessment of cumulative effects; and 2) to identify critical socio-environmental effects that need to be prioritised in cumulative (and cross-boundary) assessments.

More specifically, the deliverable aims to:

- Review scientific and grey literature on state-of-the-art methods and models for CEA and critical socio-environmental risks within the offshore renewable energy sector.
- Review SEA and EIA reports for offshore wind to determine, among other things, CEA methods and limitations.
- Consult stakeholders, through semi-structured interviews, on current CEA practice and challenges.

The scope of the deliverable is limited to CEA specific to offshore wind, and to environmental reports and expertise within the countries partnering in the SUSTAINOW project (i.e. Denmark, Estonia, Germany, Ireland, Portugal, Spain, and the United Kingdom - UK).

Based on the findings from the reviews and consultation outlined above, a comprehensive qualitative register of prevailing practical challenges in CEA practice, as well as key (cumulative) socio-environmental risks within the offshore wind energy sector are presented and discussed. It is anticipated that this register provides a robust foundation for developing a CEA framework envisaged in this Work Package (WP3), which will form the basis for the development of a decision-support tool for sustainable offshore renewable energy planning and sitting decisions as part of WP6, as well as inform data requirements and the development of s shared data space in WP2.

1.3. Structure of the deliverable

Section 2 presents the CEA practice challenges in the form of a qualitative register of prevailing practical issues. Section 3 outlines the environmental risks of offshore wind development, and Section 4 the social risks.

The research supporting Sections 2 to 4 is summarised in Annexes A to C. Annex A presents the findings of a scientific literature review on CEA methods, and principal cumulative social and environmental effects (and thus associated risks) in the offshore renewable energy sector. Annex B discusses the outcomes of a review of SEA and EIA reports, highlighting identified practical and methodological challenges in current practice. And Annex C examines the CEA methods, challenges and priority socio-environmental risks identified by the consulted experts.

1.4. Risks, effects, impacts

In the context of enduring CEA challenges, the growing expansion of offshore wind energy plans and projects and the uncertainties associated with these in relation to when and where they will materialise, as well as to the dynamic nature of marine environments and the complexities of pressure-effect interactions, requires a clear distinction between risks, effects and impacts. Risks are understood as the possibility or potential for current or future offshore wind farm plans or projects to cause effects or impacts. For clarity, effect is the change caused or accrued on environmental receptors from one or various (offshore wind development) pressures, while impact is characterised by the significance (e.g. importance with regards to predetermined standards or threshold) or magnitude (e.g. extent, amount, intensity) of the effect; in other words, the impact is the severity of the effect. As impacts, particularly cumulative impacts, are very difficult to accurately determine, the word effect is typically used in this report.

2. Current Practice Challenges

The implementation of CEA continues to face significant challenges in current practice. These challenges are characterised by procedural shortcomings, analytical complexities, data limitations and lack of knowledge. The challenges have been categorised under these four main categories, and are presented alphabetically in the form of a glossary in Table 1.

Table 1. Glossary of enduring current practice challenges. *These are presented in alphabetical order for each category. The coloured symbols indicate the source of the identified challenge, where ■ refers to international scientific literature (Annex A); ■ to environmental reports (Annex B); and ■ to expert input (Annex C). Terms highlighted in bold in the narrative refer to additional challenges and can be cross-referenced. The text in light blue provides contextual information and explanations.*

Procedural shortcomings	
■	**Assessment integration** The consistent integration of CEA in impact assessment practice remains a fundamental challenge. SEAs and EIAs do not always include CEA despite the mandatory requirement to assess cumulative effects. When they do, CEA commonly is presented in a dedicated chapter; but at times, cumulative effects are dispersedly and inconsistently addressed within relevant environmental topic chapters. The systematic incorporation of CEA in SEAs and EIAs is a mandatory requirement under the European SEA and EIA Directives[3]. CEA requirements are also embedded into the MSFD Directive (EC, 2008). Nevertheless, there are no specifications in the legislation about the ***scope, level*** or ***methods*** for CEA, and ***guidance*** is also limited.
■ ■	**Assessment scope** Discrepancies exist between the consideration of plans/programmes, development phases, ***effect types***, ***methods*** and ***spatial extents*** in CEAs at strategic planning (SEA) and project (EIA) levels as detailed below. Such discrepancies ultimately influence effect ***significance*** determinations. • At SEA level, CEAs tend to pertain site suitability assessment, although they can also entail the assessment of regional development scenarios, multiple projects, or policy measures. In-combination effects with other plans/programmes are also considered, as mandated by SEA legislation. In the context of ***transboundary cumulative effects,*** the consideration of other projects is hampered, particularly by limitations with accessing data for other countries. • At EIA level, CEAs centre on assessing how other projects (offshore wind, but also mineral and gas extraction sites, pipelines, telecommunication cables, etc.) may lead to cumulative effects in-combination with the proposed project. Project detail ***data gaps*** and ***data access*** often hinder assessment effectiveness. Moreover,

[3] The SEA Directive (EC, 2001) states that the "cumulative nature of the effects" should be considered when determining the likely significance of effects. The EIA Directive (EU, 2014a) requires having regard to "the cumulation of the impact with the impact of other existing and/or approved projects" when assessing likely significant effects. The MSFD (EC, 2008) requires an analysis of the predominant pressures and impacts, including human activity, on the environmental status of marine waters that "covers the main cumulative and synergetic effects".

Funded by the European Union

	some assessments consider within project cumulative effects only, and in-combination effects with other plans/programmes are rarely considered. • CEAs at EIA level typically encompass the construction, operation, maintenance and decommissioning phases, but it is uncommon for the ***decommissioning*** phase to be effectively integrated due to the significant time gap and ***lack of knowledge*** about the potential risks and effects of this phase. These project phases are often difficult to integrate at SEA level due to ***lack of*** easily accessible ***data*** on project development phases. The assessment scope (i.e. purpose and analytical boundaries of the assessment) is typically distinct at SEA and EIA levels due to their nature as well as degree of location and development specificity (e.g. strategic planning implies larger geographical areas, and marine use zonings or policies, while projects have smaller delimitations and detailed layout and design). Despite these considerations, the SEA and EIA Directives require a consistent consideration of plans/programmes and projects respectively.
	Assessment type Assessments can be qualitative, quantitative or both. There is a reliance on predominantly qualitative CEA approaches. CEAs at SEA level, in particular, are broadly qualitative, and rely on professional judgement for interpreting existing data, GIS mapping and spatial analysis, and expert consultation outputs. At EIA level, expert judgments prevail, but GIS-based analyses are typically complemented with more quantitative approaches through predictive modelling (e.g. underwater noise effects on marine mammals, bird collision risk) and field surveys for site-specific data ***collection***. Qualitative assessments can have a degree of professional subjectivity or bias, and influence replicability of assessments and transferability of outputs. The assessment level (i.e. SEA versus EIA) determines the assessment types (or extent and specificity), but it is often data limitations and available resources and know-how that determine the application of qualitative and/or quantitative ***methods***.
	Effect types In SEA Environmental Reports (SEA ERs) and EIA Reports (EIARs), cumulative effects are typically treated as simple aggregations of individual effects, while complex interactions between pressures and receptors are often overlooked, which leads to synergistic and antagonistic effects rarely being identified, examined and discussed. The European SEA and EIA Directives (EC, 2001; EU, 2014a) require that the identification of likely significant effects include secondary, cumulative, synergistic, short, medium and long-term permanent and temporary, positive and negative effects.
	Expert input A key limitation in CEA ***reporting*** is the frequent absence of a clear “statement of authority” identifying the competent experts, specialists, and sectoral contributors involved in the assessment process. This can reduce the credibility, accountability, and traceability of professional judgement underpinning cumulative effects evaluations. The multidisciplinary nature of CEAs requires both environmental assessment generalists who can bring an ecosystem perspective, as well as topic specialists providing pressure- or receptor-specific expertise. Acknowledging the qualifications, experience, and specific inputs of contributing experts, advisory groups and

Funded by the European Union

	stakeholders is necessary to contribute towards the requirement for transparency and accountability in decision-making required in the SEA and EIA Directives (EC, 2001; EU, 2014a).
■ ■	**Guidance** There is no European or international guidance and very limited national guidance on CEA, particularly specific to offshore wind[4]. There is also a lack of receptor-specific guidance. This results in ***inconsistencies***, and affects both know-how and comparability of assessments that enable an ecosystem-wide understanding of cumulative effects. The recommendations in these guidance documents remain largely broad, and focus on: setting up appropriate ***spatial extents, temporal coverage,*** as well as ***assessment scope*** (e.g. identifying pressures from existing, planned and future plans and developments within a zone of influence); identifying receptors (often referred to as valued environmental components); establishing either limits from environmental standards/legislation or impact thresholds for these; assessing changes in receptors as a result of identified pressures (typically applying models, particularly at project level); and determining effect significance (or impact) by interpreting available data/model outputs and using expert judgement. Broadly speaking, these guidance documents also establish that effect significance is often a result of the magnitude of the effect (taking into account its type, duration and extent) versus the sensitivity of the receptor and its capacity to absorb change. Adopting a source-pathway-receptor model is recommended, together with the use of GIS to determine spatio-temporal overlaps between multiple pressures and receptors; as well as the application of professional judgement to determine effect significance, particularly in data-poor contexts.
■	**Governance** Fragmented institutional and regulatory responsibilities, combined with inconsistent standards and ***methods,*** and ***data comparability*** and ***access*** limitations present a major challenge to effective CEA. This leads to assessments that are often siloed, reactive, and insufficient for long-term regional planning. These issues are magnified when undertaking transboundary assessments, as different governance frameworks across jurisdictions can exacerbate inconsistencies in assessment ***spatio-temporal extents*** and ***methods***, and influence data limitations with regards to data ***collection***, ***access*** (including ***planning phases***) and ***comparability***. An unified framework or centralised institutional oversight across European marine waters can facilitate data sharing, knowledge exchange and more consistent cross-jurisdictional assessments.
■	**Categorisation of pressures/receptors** An important confounding factor in CEA and marine spatial planning is the lack of harmonised classification of pressures and stressors across regional sea basins and governance frameworks. Different institutions and assessments frequently apply divergent definitions, categorisations, and conceptual approaches to pressures and

[4] These include: CEAA, 2018; EPA, 2020; IFC, 2013; NERC, 2013; UK Government, 2024, but only one is specific to offshore wind (i.e. NERC, 2013). A limited number of topic specific guidance also exists (e.g. on cumulative visual and bird impacts - NatureScot, 2021; 2025).

Funded by
the European Union

	receptors. The problem is particularly significant because pressure/receptor classifications form the conceptual foundation of CEA. Categorisation inconsistencies create substantial difficulties when developing coherent cumulative effect assessment frameworks. For example, the European Commission-supported Tools4MSP[5] modelling framework adopts the pressure categories established under the MSFD[6]. In contrast, other regional marine governance frameworks such as the OSPAR Commission[7] apply different categorisations for operationalising environmental pressures. Such variations in terminology and pressure hierarchies (as well as ecosystem component classifications and indicators) affect ***comparability*** and can hinder trust in environmental governance.
■ ■	**Interpretation** There are different understandings of CEA, which influence what is included - or excluded - from assessments, particularly with regards to ***assessment scope,*** choice of ***methods****, and agreement on* ***thresholds****,* as well as ***categorisation of pressure/receptor*** and the extent to which ***effect types*** are considered. Practitioners and regulators may interpret cumulative effects differently, ranging from in-combination effects of multiple projects/pressures on a single receptor, to broader ecosystem-level interactions (e.g. ecosystem-based assessments that encompass both multiple pressures and multiple receptors). Using different assumptions, pressure/receptor categorisations, thresholds, and methodological approaches hinders comparability of assessments, confuse statutory authorities and can confound regulatory effectiveness reviews (e.g. European REFIT[8]).
■ ■ ■	**Methods** Significant variations are observed in CEA *methods* (e.g. *spatial analysis, modelling, expert judgement, field observations),* with particular differences between *assessment levels* (SEA versus EIA – largely driven by the scale and specificity of assessment requirements), but also across a given assessment level and across jurisdictions (see ***governance***). Such inconsistencies lead to non-comparable CEA outcomes and recommendations. Five overarching methods commonly support CEAs – one or several of these methods can be applied in any one assessment: • Spatial analysis through GIS is typically applied for identifying or sieving plans/projects and pressures-receptors overlapping over time and space, and for developing optimum zoning and siting solutions that avoid or reduce cumulative effects.

[5] Data and Tools Supporting Marine Spatial Planning. See: http://data.tools4msp.eu/
[6] Annex III of the MSFD (EC, 2008) lists the pressures that need to be considered when assessing environmental status of marine environments including physical loss, physical disturbance, and interference with hydrological processes.
[7] European Union cooperation initiative to protect the marine environment of the North-East Atlantic. See: https://www.ospar.org/
[8] European Union REFIT stands for the Regulatory Fitness and Performance programme. Details on the SEA REFIT can be found here: https://environment.ec.europa.eu/law-and-governance/environmental-assessments/strategic-environmental-assessment-sea_en

	• Models (e.g. ecological or ecosystem modelling) are applied to anticipate (often long-term and large-scale) effects of certain pressures (e.g. noise, collision) for certain receptors (e.g. marine mammals, birds, shipping) and thus inform sitting decision. • Field observations (e.g. Global Positioning Systems (GPS) tracking, visual annotations, diving and sampling) seem to be used only when data ***gaps*** exist (or as part of monitoring), to improve the baseline or to ground-truth or ***validate*** models. • Stakeholder, expert and/or public consultation (e.g. interviews, workshops) are used in data poor context to fill in data gaps and determine pressure-receptor interactions. • Expert or professional judgements are commonly used to interpret the available data, fill data gaps, address complexities and, ultimately, categorise interactions and determine (cumulative) effect significance or impact[2].
■ ■	**Reporting of context** There is limited reporting of critical spatial contextualization details in scientific publications, as well as in some assessment reports, such as plan area delimitations or turbine dimensions and footprint, distance from shore, and water depth. This contributes to ***data gaps***. Spatial contextualisation details (e.g. zoned area, turbine size/number/footprint, distance from shore and water depth) are essential for understanding assessment findings such as spatial squeeze dynamics, or links between receptor sensitivity to turbine location and scale.
■	**Reporting on CEA limitations** CEA shortcomings, assumptions, and methodological limitations are not always explicitly documented in environmental assessment reports. This affects interpretation of assessment results, reduces transparency, limits comparability across studies, and hinder the development of more robust and consistent future CEAs. The SEA and EIA Directives (EC, 2001; EU, 2014a) require a description of "how the assessment was undertaken including any difficulties (such as technical deficiencies or lack of know-how)" and "details of difficulties (for example technical deficiencies or lack of knowledge) encountered" respectively. These requirements are also applicable to CEA.
■	**Research informed** While marine spatial planning and assessment research has significantly advanced CEA methods and modelling tools[9], their application is almost non-existent in practice. Time and resource limitations, lack of know-how for the effective implementation of research advancements, the experimental nature of research-based approaches, and political agendas represent some of the barriers to the integration of research-driven CEA methods intro practice.

[9] For a comprehensive review of latest research advancements in marine CEA approaches and methods, refer to Morejón *et al.* (2025).

Funded by
the European Union

■ ■ ■	**Spatial extent** The spatial extent or geographic area of CEA varies across assessments: from the plan area boundary to entire maritime areas (e.g. Exclusive Economic Zones - EEZ) at strategic planning or SEA level; and, at project or EIA level, from marine 'zones of influence'[10] only to the inclusion of onshore zones of influence that account for effects resulting from elements aground (e.g. substation, grid connection, road widening works). 'Zones of influence' also vary significantly across and within receptors (e.g. they span from 300 meters through to 750 meters from the development site, to the entire EEZ for noise sensitive receptors). Spatial extents are expanded when considering transboundary effects – this also vary significantly, entailing the adoption of a fixed or lax buffer area (e.g. specifically 10Km versus the wider marine area, without specified limitations other than country names). These disparities then transfer to ***monitoring*** frameworks and future CEAs, affecting coherent and coordinated ecosystem-wide assessments. Both the SEA and EIA Directives require taking into account the spatial extent when identifying significant effects, which includes the transboundary nature of the effects – relevant considerations also when defining monitoring measures. However, there are no criteria for the definition of spatial extents in the legislation. Nevertheless, there is a common understanding that this should be proportionate and reflective of the plan/project being assessed, and the potential to affect adjacent jurisdictions. 'Zones of influence' for pressure-receptor interactions typically take into account effect pathways, including dispersal of pressures and sensitivity of receptors. In all cases, coordinated approaches to determining 'zones of influence' could provide a more comprehensive and comparable account and understanding of cumulative effects.
■ ■ ■	**Temporal scope** CEAs are typically bounded by plan and project timelines (e.g. 25 to 30 years), which are not necessarily aligned with the long-term, delayed, and often non-linear ecological responses characteristic of marine ecosystems, and often entail hypothetical scenarios. This is compounded by the fact that site investigation studies, which tend to inform assessment baselines, are short (e.g. capped at 12/24 months), and ***monitoring*** of different offshore wind projects in the same sea basin may be undertaken in different periods/seasons affecting comparability. Importantly, CEAs relate to a snapshot in time, and they do not meaningfully capture effects over time due to shifting baselines; every assessment starts with the 'current' baseline and thus does not capture previous effects as these have already been accounted for in previous assessments. Cumulative effects can occur not only when pressures and receptors coincide spatially, but also when temporally separated disturbances collectively alter ecosystem state; ecological responses vary substantially across different development phases and time, spanning several decades. Meaningful temporal scopes need to distinguish offshore wind plan/project effects from natural processes and fluctuations and thus imply consideration of ***climate change*** scenarios and/or ecosystem recovery timeframes in ***data collection*** methods and ***monitoring*** frameworks.

[10] This can be defined as geographic areas within which a plan or project, or an associated environmental pressure may directly or indirectly affect environmental or social receptors.

Funded by the European Union

■	**Theory versus practice** There is a dearth of published empirical evidence, with the majority of the scientific literature presenting theoretical studies, hypothetical scenario analysis or modelling applications. This is partially due ***monitoring*** limitations and data ***gaps***, but importantly to data ***access*** (due to confidentiality) impeding dissemination of real world studies and application of empirical data. These issues are compounded by the lack of ***validation*** and suggest that current academic understanding of offshore wind socio-environmental effects relies heavily on theoretical assumptions rather than observed real-world outcomes.
■ ■	**Thresholds** A major challenge in CEA is the lack of clearly defined thresholds (e.g. species resilience thresholds or ecological tipping points[11]) for determining what constitutes an acceptable level of cumulative environmental change over time and space. This arises from: lack of regulatory limits for pressures and receptors; analytical complexities (e.g. dynamic marine environments and non-linear pressure-receptor responses); limited baseline and monitoring data (hindering identification of trends and carrying capacity); and reliance on qualitative assessments (professional interpretations can affect consistency and comparability). The absence of robust thresholds can hinder effect ***significance*** determinations, weaken decision-making, hinder effective mitigation, and increase the risk of incremental environmental degradation going undetected until impacts become severe or irreversible. While individual project impacts may appear minor or manageable in isolation, their combined effects can progressively exceed ecological, social, or regulatory limits if a clear mechanism for identifying when unacceptable conditions have been reached is not available or agreed upon.
■ ■	**Monitoring** A key procedural challenge relates to monitoring frameworks (for systematically observing, measuring, and reassessing socio-environmental conditions), as these often fail to specifically include measures to follow up on cumulative effects. While these frameworks may capture individual effects/impacts or isolated environmental changes, they frequently fail to account for the combined, long-term, and interacting effects of multiple activities and associated pressures across ecosystems and species. Moreover, existing monitoring frameworks are often fragmented and inconsistent: they rarely adopt coherent, coordinated and standardised approaches for addressing persistent data and knowledge limitations (e.g. ***data gaps*** and ***access***) with regards to cumulative effects. This hinders the improvement of the evidence base and future CEAs. Monitoring is a requirement of the SEA and EIA Directives[12], as well as of project licensing consent. However, there is a lack of coordination between regulatory authorities, plan

[11] A tipping point is a critical threshold where a gradual change in an ecosystem's conditions triggers a self-perpetuating shift to an entirely new, degraded state.
[12] The SEA Directive (EC, 2001) mandates that Member States "monitor the significant environmental effects of the implementation of plans and programmes". The EIA Directive (EU, 2014a) requires Member States to ensure that

Funded by the European Union

	proponents and project developers with regards to ***spatial*** and ***temporal extents***, types of data to be collected, data ***collection*** methods, the implementation of shared high-tech solutions (e.g. radio telemetry, GPS tracking, thermal imaging, surveillance radar) that can facilitate and improve monitoring, and ***monitoring data centralisation***. This perpetuates geographical area, data type and data sharing silos.
Analytical Complexities	
■ ■ ■	**Aggregation** A persistent analytical challenge in CEA is the absence of agreed approaches for aggregating multiple assessment indicators, pressure-receptor relationships and model outputs into a single, transparent, and scientifically defensible cumulative effect index. Aggregation requires combining heterogeneous data types (e.g. species responses, habitat condition indicators, social variables) into a unified index. However, there is little consensus regarding how these data types should be homogenised, how ***threshold*** should be applied to prioritise indicator weights, or how ***uncertainty*** should be accounted for. As a result, CEAs often remain fragmented, assessing (certain) pressures-receptor interactions in isolation. This hinders comparability and affects communication of assessment outcomes, which can affect the capacity of decision-makers to understand the overall implications of cumulative effects. Environmental reports frequently evaluate individual pressures, receptors, or indicators separately, yet few establish rigorous methods for integrating these results into an overall measure of cumulative environmental effect or risk; when they do, this entails an expert-based qualitative categorisation of overall cumulative effect (e.g. low, moderate, high). A few research studies have attempted to develop overall cumulative effect indexes, supported by GIS[13].
■	**Assessment criteria** There is an important absence of systematic and scientifically robust criteria for systematically evaluating cumulative effects on certain ecological receptors, particularly highly sensitive and mobile species such as bats, birds or marine mammals. Criteria may encompass mortality, displacement or behavioural change, for example, but the lack of agreed indicators and ***thresholds*** and their resulting inconsistent application in assessments leads to data and knowledge silos, as well as ***comparability*** limitations. Existing CEA ***methods*** vary across plans and projects, and often rely on inconsistent indicators, resulting in considerable variability in how cumulative effects (and, ultimately, impacts) are identified, measured, and interpreted across spatial and temporal scales.
■ ■ ■	**Dynamic nature** A major analytical challenge in CEA arises from the dynamic and highly complex nature of marine ecosystems, where mobile receptors (e.g. birds and marine mammals), interconnected food web interactions, and changing environmental conditions (including ***climatic variables***) create substantial ***uncertainty*** in assessing cumulative

"appropriate procedures are determined regarding the monitoring of significant adverse effects on the environment resulting from the construction and operation of a project".

[13] See, for example, Halpern et al. (2008) on globally mapping cumulative human impact across 20 ocean ecosystem types.

Funded by the European Union

	effects. This is exacerbated by ***data limitations***, including commonly available static datasets (e.g. once-off surveys), and the absence of long-term longitudinal ***monitoring:*** assessments often provide only a snapshot of environmental conditions and associated effects, creating a risk that findings become rapidly outdated in evolving marine environments. The movement of species such as birds and marine mammals across large spatial scales, combined with multi-pathway pressure-receptor interactions, complicates the prediction of how effects/impacts accumulate, interact, and propagate through ecosystems over space and time. This complexity is further intensified by temporal variability across the different phases of offshore wind developments (including construction, operation, and decommissioning) during which environmental conditions and receptor sensitivities may change significantly.
■ ■	**Climatic variables** Offshore wind CEAs tend to assess development-related pressures in isolation, with limited consideration of how these pressures interact cumulatively or synergistically with broader climate change stressors (e.g. sea warming, ocean acidification, shifting prey distribution, and changing habitat conditions). This fragmented approach can underestimate the significance of cumulative effects (i.e. impacts) on marine ecosystems. In practice, offshore wind CEAs often focus on localised plan or project-specific pressures (e.g. underwater noise, introduction of hard surfaces) and effects (e.g. displacement, collision) without adequately accounting for how climate-driven environmental change may magnify receptor vulnerability or alter ecosystem resilience over time. This is compounded by the ***temporal extent*** of assessments. Climate-induced shifts in species distribution and migration patterns can change exposure pathways and cumulative interactions in ways not captured by current assessments.
■ ■	**Consultation** Consultation in CEA is typically limited to expert input (e.g. topic specialists, advisory groups). Broader stakeholder and public consultation are limited to SEA/EIA procedural requirements and insufficiently integrated into CEA frameworks. As a result, local knowledge, community concerns, and stakeholder perspectives are frequently underrepresented in the identification, evaluation, and management of cumulative effects. This can undermine public trust in decisions and environmental governance. Importantly, effective engagement with diverse stakeholders and publics, to gather multiple perspectives and facilitate agreement on social effect ***significance*** presents its own procedural and analytical complexities. Social perspectives, indicators and effects are often dynamic, subjective, and influenced by cultural and political contexts. Therefore, they require interdisciplinary and participatory approaches for gathering and integrating qualitative social data (e.g. on health and well-being) into CEAs. These approaches can be supported by the mandatory requirement for stakeholder and public consultation under the SEA and EIA Directives[14].

[14] The SEA Directive (EC, 2001) requires that "opinions expressed by the relevant authorities and the public, as well as the results of any transboundary consultation, should be taken into account during the preparation of the plan".

■	**Modelling** Models are increasingly used to anticipate (cumulative) effects and fill in ***knowledge gaps***. However, model assumptions, parameters and ***data gaps*** can propagate ***uncertainties***. In addition, the frequent use of different models in both research and practice, and the lack of interoperability between the models and model results, their evolving and often proprietary nature, compromise their systematic and consistent application. Predictive models are essential for forecasting potential cumulative effects; they play a central role in translating complex environmental processes into decision-support tools. However, many of the models used in practice are highly specialised and often developed in isolation. As a result, they are difficult to seamlessly implement in practice. Even when model outputs are made available, the underlying assessment framework assumptions and parameters are often inaccessible, hindering integration across CEAs.
■ ■ ■	**Uncertainties** There is a high degree of scientific uncertainty associated with understanding how cumulative effects vary across geographic contexts, ecosystem conditions, seasonal dynamics, and long-term exposure pathways, as well as on multiple ***pressure-receptor interactions*** and system recovery times. Cumulative effects are highly context-dependent and often difficult to effectively predict because ecological responses differ substantially between regions, habitats, species assemblages, temporal scales, and recoverability. These uncertainties are further intensified by persistent ***data*** and ***knowledge gaps.*** The ***dynamic nature*** of marine environments implies that cumulative effects are not linear nor spatially or temporally uniform. The same pressure may produce different ecological outcomes for different species, depending on local environmental conditions, types of other interacting pressures, trophic interactions, or habitat connectivity. For example, marine ecosystems exposed to similar levels of underwater noise or habitat disturbance may respond differently depending on species composition or oceanographic conditions. As a result, CEAs often struggle to transfer findings across regions, or to establish universally applicable significance ***thresholds***.
■ ■ ■	**Significance** There is a lack of scientific and professional consensus in determining the significance of (cumulative) environmental effects. Significance judgements are complex and highly dependent on the conceptual ***interpretation*** of cumulative effects, ***assessment scope***, ***thresholds*** agreed upon, and the ***spatial*** and ***temporal extents*** considered. They are also influenced by ***planning phases*** considered and, importantly, ***data*** and ***knowledge gaps***. Consequently, different assessments of similar activities or pressures may reach substantially different conclusions regarding whether cumulative impacts are considered acceptable, manageable, or ecologically significant. Some CEAs adopt relatively narrow and project-focused approaches that evaluate effects and resulting impacts primarily as localised, additive effects occurring within

The EIA Directive (EU, 2014a) states that "the main reasons and considerations on which the decision is based, including information about the public participation process. This also includes the summary of the results of the consultations (...)".

	defined spatial and temporal boundaries. Under this interpretation, cumulative significance may be judged acceptable if individual impacts remain below regulatory ***thresholds*** or appear minor when assessed independently. In contrast, other assessments apply broader ecosystem-based or precautionary approaches that consider synergistic pressures, habitat connectivity, long-term ecological interactions, and ecosystem resilience. These broader interpretations often identify higher levels of cumulative ecological risk, even when individual project effects appear limited in isolation, as thus may be more significant.
■ ■	**Validation** ***Modelling*** is essential for forecasting potential cumulative effects, but predictive models often lack long-term, post-construction empirical validation. Without ground-truthing (e.g. systematic verification against observed environmental outcomes over time), models risk compounding initial hypothesis and propagating ***uncertainties*** into broad quantification biases or inaccurate effect predictions. This issue can be magnified by ***monitoring*** shortcomings, ***data access*** restrictions and ***data quality***. Ecological responses may differ substantially from modelled expectations due to the ***dynamic nature*** of marine environments and resulting changing environmental conditions, species adaptation, indirect interactions, or unforeseen cumulative pressures and effects. Sufficient empirical evidence is needed to validate their accuracy.
Data Limitations	
■ ■ ■	**Access** Restricted access to proprietary, confidential or commercially sensitive datasets that are necessary for robust assessment and decision-making is a significant challenge to CEA effectiveness. Scientific literature consistently identifies data accessibility as a critical limitation affecting the comprehensiveness and reliability of CEAs. Experts highlight that while marine data availability is growing, datasets are frequently dispersed across institutions and subject to different data-sharing policies (see ***governance***) and thus varying access restrictions. This complicates data gathering processes and can result in spatial and taxonomic ***data gaps*** that weaken confidence in assessment outcomes (particularly in transboundary contexts). CEAs rely on large volumes of spatio-temporal data on the distribution of activities and associated pressures, ecological processes and receptor sensitivities, and socio-economic variables. These datasets are typically collected by multiple actors, including governmental departments, private industry, research institutions, and environmental consultancies. However, many datasets remain inaccessible because of commercial confidentiality, intellectual property restrictions, licensing limitations, national security considerations, or fragmented governance arrangements affecting ***centralisation*** of data. This creates substantial barriers to effective CEA, as practitioners are often unable to integrate all relevant pressures and receptors, baseline conditions, or monitoring results into a unified analytical framework.
■ ■ ■	**Centralisation** The absence of centralised, accessible, and interoperable systems for storing and sharing socio-environmental data is a significant constraint for CEA. The issue is magnified by inconsistencies in ***monitoring*** frameworks that prevent data from being published and/or shared. This lack of public data centralisation means that practitioners (and decision-makers) face substantial difficulties in seamlessly accessing available

	baseline data, which in turn affects the adoption of comparable evidence-basis and the comprehensiveness of assessments. Although regulatory licensing processes (including SEA and EIA) often require plan-proponents and developers to collect and submit ***monitoring*** results to competent authorities, these datasets are frequently fragmented across institutions, retained within project-specific repositories, or subject to restricted access arrangements. As a result, monitoring information generated through previous plans and projects is often not systematically centralised or made publicly available to support future assessments.
■ ■	**Collection** The lack of methodological consistency in data collection across different plans, projects and/or jurisdictions (by e.g. proponents, regulatory authorities, and research institutions) means that data are often collected using varying sampling and analytical methods, ***monitoring*** frameworks, ***spatial extents*** and resolutions, temporal frequencies, and reporting standards. These inconsistencies also apply to ***monitoring*** frameworks. They affect data ***comparability*** and create major obstacles for integrating datasets across projects, sectors, and jurisdictions, ultimately limiting the reliability of CEAs outcomes. Differences in survey timing, species detection methods, habitat classifications or pressure and effect indicators can produce inconsistent results even within similar ecosystems. As a consequence, CEAs may struggle to distinguish cumulative effects from natural variability, or to compare findings across plans/projects and time periods.
■ ■	**Comparability** Jointly considering heterogenous socio-environmental datasets, obtained from different sources is problematic in CEA. Data are presented in different measurement units and formats (e.g. qualitative versus quantitative, numerical versus spatial), making it difficult to harmonise and/or ***aggregate***. This is magnified by variations in data ***collection*** and ***monitoring*** frameworks often resulting in non-comparable datasets (e.g. due to different methods and spatio-temporal scales), which can constraint their integration – this is particularly problematic in transboundary assessment contexts. In addition, practitioners often apply different definitions of effects/impacts, baselines, scales, and significance thresholds, resulting in CEA outcomes that are difficult to compare across sectors and jurisdictions and take into consideration in future assessments. CEAs rely on the ability to seamlessly combine socio-environmental information from multiple sources. Typically, social indicators are qualitative while environmental indicators tend to be quantitative. Importantly, they are all collected using disparate methods and standards (e.g. resolution, temporal extent, attribute types, etc.). Metadata[15] can help determine their fitness for use and fitness for purpose, as well as inform potential ways for harmonisation.
■	**Gaps**

[15] Metadata can be defined as data about data: it describes the content and quality of the data, and helps interpret the information. The European Statistics Code of Practice (EC, 2017) states that data should always be made available with supporting metadata. Similarly, metadata is at the heart of the European INSPIRE Directive (EC, 2007) on an interoperable spatial data infrastructure for environmental policies.

Funded by the European Union

	Data gaps are a significant challenge in CEA, affecting their comprehensiveness, accuracy and reliability. Missing, incomplete, outdated, inconsistent, inaccessible, or insufficiently reliable information limits the ability to accurately identify, predict, evaluate, monitor and/or manage cumulative effects of offshore wind energy plans and projects on socio-environmental receptors. Gaps typically relate to environmental baseline conditions, ***spatial*** *and* ***temporal extents***, but also *to* information on other plans/projects. They often derive from **data *access, collection*** as well as ***monitoring*** limitations. • Baseline data gaps imply missing or inadequate information describing existing social or environmental conditions before plan/project activities or disturbances occur. This particularly affects SEAs as these assessments rely on available data, while baseline surveys are often undertaken at project or EIA level. Reported baseline data gaps vary across marine regions and jurisdictions but typically include migratory routes of birds and mammals, bats, and fishing vessels less than 12 metres in length (refer to Annexes A to C for more detail). Project level data on specific habitat and species effects (as opposed to environmental conditions) is also missing. • Information on plans/projects is rarely publicly or readily accessible, particularly across jurisdictions. The lack of immediate access to details on location, scale, distribution and development phase of existing and future plans or projects results in incomplete assessments, that fail to account for different pressure intensities over time within the study area. Effective CEAs require comprehensive understanding of the location, timing, scale, and pressure intensity of multiple overlapping activities and receptors. However, data on offshore energy developments, shipping, fisheries, dredging, military activities, and other marine uses is often fragmented, inconsistently reported, or difficult to ***access*** publicly. Similarly, varying ***data gaps*** on receptors are observed across jurisdictions (e.g. seasonal movement patterns and behavioural responses of seabirds, marine mammals, and bats), even for the same pressures/receptors (e.g. for birds: collision risk, breeding/wintering bird species movements, or lack of knowledge on the extent displaced birds can find sufficient alternative food sources).
	Quality Data quality can significantly affect the veracity and reliability of CEA outcomes. Data quality is influenced by ***collection*** and ***monitoring*** frameworks, by their ***spatio-temporal extents*** and ***resolution, modelling*** approaches and, most importantly, by ***uncertainties***. Data availability is exponentially increasing, yet data assurance and quality control procedures are lacking. While research institutions and governmental organisations may cross-check the data, ***validation*** (specially of modelling results) is often lacking, and verification procedures are underdeveloped. Metadata[14] can help determine quality by outlining its fitness for use and fitness for purpose.
	Resolution There is a mismatch between the spatial resolution of project-level (EIA) social and environmental data and the broader regional-scale information required to evaluate cumulative effects in SEA and capture ecosystem-level effects.

	Developers typically collect highly detailed data (i.e. high resolution) within and immediately surrounding their individual project footprints in order to satisfy project-specific regulatory and monitoring requirements. These datasets support exhaustive local CEAs, but they are often inadequate for understanding cumulative effects that emerge across larger ecological systems and multiple interacting developments. Regional lower resolution surveys are therefore necessary to understand the bigger picture and consider the overall ecosystem.
■ ■	**Taxonomic bias** There seems to be a persistent taxonomic bias in the selection of ecological receptors and indicators used to evaluate environmental change. Scientific literature and environmental report reviews consistently show that marine studies and CEAs disproportionately prioritise megafauna (e.g. marine mammals, seabirds, and commercially important fish species), while comparatively little attention is given to less visible or lower trophic-level organisms (e.g. bats, benthos, cephalopods, plankton and phytoplankton). The bias is also observed in taxa, where certain species receive disproportionate assessment resources and consideration (e.g. divers such as gannets, gulls and terns among birds; cetaceans such as porpoises, whales and dolphins among marine mammals). ***Data*** and ***knowledge gaps*** can magnify such biases. In all cases, these imbalances can substantially influence assessment outcomes, ecological interpretations, and ultimately environmental management and planning decisions. Species that are more publicly visible, economically important, legally protected, or easier to monitor tend to dominate environmental assessments, whereas ecologically important but less conspicuous taxa are frequently underrepresented or excluded. These include lower trophic-level organisms such as plankton and phytoplankton, but also pinnipeds (e.g. seals, sea lions) and certain bird species (e.g. auks, cormorants, shags and shorebirds). This is partially a result of better data and knowledge availability for the 'important' or protected species. However, the omission of certain species can lead to overlooking effects that may propagate through trophic levels. Taxonomic biases and simplification in CEAs, and associated uneven data coverage across receptor groups, can lead to failure to adequately capture ecosystem-wide responses to cumulative pressures, or to identify cumulative effects on critical ecological processes such as trophic interactions or habitat functioning.
Knowledge limitations	
■ ■ ■	**Decommissioning** This phase remains insufficiently studied and indeed incorporated into CEAs and environmental assessments more broadly – this is partially due to the limited number of wind farms decommissioned to date. As a result, CEAs risk underestimating long-term cumulative effects and overlooking important ecological trade-offs associated with infrastructure retirement and ecosystem transformation. Removing offshore wind foundations may result in significant environmental effects (e.g. due to the sudden loss of the established artificial reef biodiversity), and the removal of infrastructure (e.g. blades, cables) may lead to additional secondary effects (e.g. from non-recyclable materials). The trade-offs between full and partial infrastructure removal strategies (e.g. preserving artificial reefs) remain poorly understood and represent a significant scientific ***knowledge gap*** and governance challenge.

■	**Local expertise** Some regions lack expertise on offshore wind effects. This is often due to the absence or lack of maturity of the wind energy sector in local marine waters as well as to limited local experience and/or ***data gaps***. Scientific and technical experts may have substantial theoretical knowledge and access to generalised datasets or studies from other regions, but they often lack sustained, in-situ observational experience within the specific marine environments where new developments are being assessed. This creates ***uncertainty*** in understanding how local environmental conditions (e.g. currents, sediment transport processes, and ecological communities) respond to offshore wind installations over time.
■ ■ ■	**Planning phases** There is limited understanding of how different project development phases (e.g. construction, operation, and decommissioning) interact across wide marine geographical areas, and how these interactions contribute to cumulative effects over time. The lack of ready access to information on other project phases, particularly across jurisdictions (see ***governance***), adds to this knowledge gap. Moreover, current project level or EIA-based CEAs frequently emphasize construction and operational activities; ***decommissioning*** is rarely included in assessments due to the absence of empirical data. Effective CEAs need to consider not only the effects of multiple plans and projects within an analytical temporal extent, but also the variation of environmental and social effects across different plan/project phases. Limitations on ready ***data access*** to project phases across sectors and jurisdictions, as well as ***knowledge gaps*** on different phase interactions creates substantial ***uncertainty*** in determining the intensity as well as ***significance*** of cumulative effects.
■ ■	**Pressure-receptor interactions** Critical knowledge gaps remain relating to pressure-receptor interactions, affecting understanding of how specific activity pressures affect ecological or social receptors cumulatively across space and time, and how these receptors may recover (e.g. post-construction or after decommissioning). Despite advancements in ***modelling*** and ***monitoring***, incomplete knowledge and data on pressure-receptor pathways and associated interactions persists. Cumulative effects are often non-linear, context-dependent, and characterised by interactions among pressures and receptors. Many habitats and species in the marine environment are exposed simultaneously to multiple pressures. Yet scientific studies and environmental assessments typically evaluate pressures individually (e.g. combined underwater noise from multiple developments) and distinctively for different species. Nevertheless, different accumulated pressures (e.g. noise and sediment changes) may lead different cumulative effects (e.g. synergistic or antagonistic). The ***dynamic-nature*** of marine environments and enduring ***data gaps*** adds complexity to these interactions and can magnify ***uncertainties*** in assessments.
■	**Range of effects** Current studies and ***modelling*** focus on specific pressures (e.g. noise, physical change) and receptors (e.g. marine mammals, birds and fish), overlooking other potentially important effects (e.g. changes in hydrodynamics) and receptors (e.g. plankton),

	hindering the understanding of the full range of effects. This narrowing of analytical focus can lead to systematic blind spots in CEAs and environmental assessments more broadly. They also impinge upon improving our understanding of ***pressure-receptor interactions***. Effective CEAs rely on a comprehensive account of pressure-receptor pathways across trophic levels. Yet current practice focus on a limited subset of pressures and receptors, and rarely account for effect propagation across the food chain. For example, noise effects largely focus on sound pressure on marine mammals, yet the majority of fish, invertebrates and benthos primarily detect particle motion and substrate vibration, aspects that are invisible to current standard acoustic monitors. This may overlook potential small fish displacement effects on higher trophic levels. Without incorporating the full spectrum of biologically relevant exposure pathways CEAs risks providing incomplete or biased results.
■ ■ ■	**Social effects** Social effects of offshore wind are typically understudied, and their inclusion in CEAs is commonly limited to the fisheries sector with regards to co-existence conflicts and to tourism in coastal communities with regards to visual effects and seascape changes (refer to Annexes A and C for more detail). Broader social (e.g. job creation), cultural (e.g. identity), health (e.g. noise), and well-being effects (e.g. stress from industrialisation of the seascape) on coastal communities are rarely examined. Public/stakeholder ***consultation*** to gather, understand and incorporate local concerns presents its own challenges. CEAs are intended to evaluate cumulative interactions across ecological, economic, and social systems, but the social dimension remains comparatively underdeveloped in both research and practice. Yet socio-economic transformations due to competing sectoral uses of the marine space can significantly affect local livelihoods, and changes in landscape and seascape character can influence emotional attachment, sense of place, and perceived quality of life among coastal residents. These effects can be dynamic, subjective, and influenced by cultural and political context, and therefore require participative approaches for their identification and integration into assessments.
■	**Technology type** There is an uneven scientific understanding of (cumulative) environmental effects associated with fixed-bottom versus floating offshore wind technologies. Existing knowledge, ***monitoring*** frameworks, and CEA methodologies are heavily concentrated on fixed-bottom turbines, while the environmental effects of floating offshore wind technologies remain comparatively underexplored. This relative disparity in knowledge across technologies reflects their historical evolution, and therefore current status of the industry: most operational offshore wind farms are located in shallow to mid-depth water depths and use fixed foundations. As a result, fixed-bottom wind farms have relatively mature environmental monitoring protocols, and better data and knowledge on effects than floating turbines.

Funded by the European Union

3. Environmental Risks

Cumulative environmental effects of wind farms vary across their planning stages. They are characterised by a temporal split: intense, short-term disturbances during construction and long-term, chronic shifts during operation and maintenance phases. Decommissioning effects remain understudied (see Section 2).

This section presents key environmental risks associated with each development phase to clearly link pressures to receptors (Table 2). Such risks can be cumulatively positive (e.g. increase in benthic habitats or biodiversity conservation) or adverse (e.g. species displacement, habitat loss), and largely relate to species-specific responses based on sensitivity and/or tolerance. In all cases, such risks should be jointly considered in CEAs, as appropriate to the marine area and plan/project context. Assessing effects/impacts both within a site and in-combination with other plans and projects is necessary for the meaningful identification of cumulative effects. Existing challenges with regards to data and knowledge limitations, among other things, may affect the extent to which some of these risks may be effectively considered.

Table 2. Glossary of key environmental risks. *These are presented in alphabetical order for each phase. The coloured symbols indicate the source of the identified risk, where ■ refers to international scientific literature (Annex A); and ■ to expert input (Annex C).*

Construction			
	Pressure	**Receptor(s)**	**Risks**
■	**Habitat change** Removal of natural habitat; introduction of hard surfaces and artificial reefs.	Benthos	• Increase of benthic communities in hard surfaces and artificial reefs. • Permanent habitat loss resulting in the demise or reduction of established benthic communities. • Predator-prey dynamics can be influenced by ecosystem changes associated with increase/decrease in benthos as, for example, increased biomass could support fish recruitment.
■		Fish	• Increase/decrease in fish distribution, affecting spawning, and catch rates. • Permanent habitat loss resulting in the demise or reduction of established fish communities. • Predator-prey dynamics can be influenced by ecosystem changes associated with increase/decrease in fish as, for example, increased fish recruitment could enhance food web links for other species such as marine mammals, as well as enhance fisheries catch.

■ (orange)	**Marine litter** From construction materials and operational degradation.	Habitats and species	• Water quality changes resulting from the accumulation of wind farm debris and pollution.
■ (blue)	**Noise (underwater)** Pre-piling vessel activity; high-intensity impulse noise from pile-driving.	Bats	• Temporary state of disturbance entailing short-term stress and disturbance of their seasonal offshore movements.
■ (blue) ■ (orange)		Birds	• Displacement from their normal habitat or migratory routes to avoid physical structures. • Rapid energy depletion potential (lethal threat) due to displacement. • Reduction if reproductive success due to a decrease in fish recruitment through trophic levels.
■ (blue)		Fish	• Chronic state of disturbance entailing long-term stress and resulting in disruption to movements, spawning, feeding and growth. • Fish recruitment reduction, referring to a decrease in the number of juvenile fish that grow large enough to join a fish stock or breeding population. • Permanent displacement from their normal habitat or migratory routes, resulting in loss of local fish populations and/or disruption of breeding and feeding patterns.
■ (blue) ■ (orange)		Marine mammals (e.g. dolphins, porpoises, seals, whales)	• Chronic state of disturbance entailing long-term stress and resulting in disruption to movements, breeding, feeding and growth. • Temporary behavioural changes (e.g. reduction in foraging vocalisations or echolocation) which can lead to potential starvation (lethal threat). • Temporary or permanent auditory injury (e.g. hearing damage in Harbour porpoise). • Temporary or permanent displacement due to long-distance avoidance with the potential for rapid energy depletion and potential starvation (lethal threat).
■ (blue)	**Suspended sediment** From cable lying and turbine foundation construction.	Fish	• Clogged gills affecting the breathing and feeding apparatus of filter feeders (e.g. Atlantic herring). • Impaired hunting efficiency of visual predators as a result in water turbidity (e.g. Atlantic salmon, Northern pike).

Funded by the European Union

■		Marine mammals	• Impaired hunting efficiency of visual predators as a result in water turbidity (e.g. Harbour seal).
Operation/Maintenance			
	Pressure	**Receptor(s)**	**Risks**
■	**Electromagnetic fields** From subsea cables.	Fish	• Altered orientation and hunting efficiency in elasmobranchs (e.g. sharks, rays).
■ ■	**Non-native species** Introduction through vessel activity; creation of new (hard substrate) habitats.	Epifauna, decapods	• Changes in species composition due to colonisation of turbine foundations at the expense of native soft-bottom communities.
■ ■	**Physical structures and barriers** Associated with the presence of wind turbines (e.g. pylons, blades, foundations).	Birds	• Collision and mortality risk associated with the presence of pylons and moving turbine blades. This is particularly relevant for certain species such as bats, kittiwakes, gannets and gulls due to their attraction to wind farms for foraging, perching or roosting. • Habitat displacement of certain species (e.g. divers, scoters and migratory birds) due to avoidance, affecting their foraging habits, reproductive success and energy budgets (e.g. from reduced forage availability), contributing to their mortality risk. • Migratory patterns may be altered as a result of turbines interfering with flying paths; adjustments to migratory routes (particularly in the context of multiple wind farms along the route) can lead to energy depletion, reduced breeding capacity and, ultimately, mortality risk.
■		Fish, benthos, decapods, epifauna	• Changes in marine physical processes (e.g. waves and currents around foundations, including changes in grain size distribution) influence changes in habitats and food supply. • Changes in species interactions resulting from changes in food supply, resulting in, for example, increased predatory pressure.
■ ■		Habitats and species	• Biodiversity conservation as a result of removal of fishing and shipping activities (potential to act as marine protected areas).

■ ■		Hydrodynamics	• Changes in water regimes as a result of the stratification and mixing of the water column (e.g. wake effect). • Changes in sediment dynamics as a result of changes in water regimes, with potential habitat change effects.
■ ■	**Reef effect (habitat change)** Hard substrate from foundations and scour protection.	Fish, benthos, epifauna	• Changes in species composition and local biomass, due to an increase in epifauna (e.g. mussels, anemones) which displace soft-bottom taxa and attracts predatory fish and decapods (e.g. crabs). • Enhanced spawning connectivity for species with pelagic larvae by linking natural and artificial hard substrates (e.g. cod, flatfish). • Shifts in foraging habits (e.g. dietary shifts) due to changes in species composition.
Decommissioning			
	Pressure	**Receptor(s)**	**Risks**
■ ■	**Removal of physical structures and barriers** Associated with the (partial or full) removal of wind turbines.	Habitats and species	• Habitat change/loss due to organic enrichment and turbidity. • Changes in species richness associated with habitat changes.

4. Social Risks

Social risks are understudied when compared to environmental risks, despite them often being most contentious. The fisheries-conservation-offshore wind nexus is the primary area of cumulative social friction, entailing competing values, subjective data, and various risk factors (including cultural, identify and economic ones) for local communities. However, positive cumulative social risks are also possible, such as fish stock spillover effect benefitting the fisheries sector in areas adjacent to offshore wind farm sites, and the potential for diversification in the sector. Table 3 presents key social risks, but significant uncertainties remain on these due to lack of data, and individual and changing perceptions that impede robust evidence-based assessments.

Table 3. Glossary of key social risks. *These are presented in alphabetical order. The coloured symbols indicate the source of the identified risk, where ■ refers to international scientific literature (Annex A); and ■ to expert input (Annex C).*

	Pressure	Receptor(s)	Risks
■	**Habitat changes** Removal of natural habitat; introduction of hard surfaces and artificial reefs.	Commercial fisheries/local fisheries	• Spillover of adult fish (as a result of the reef effect, enhancement of spawning beds, fishing removal within wind farm sites) into adjacent grounds creating increased production/catchment areas.
■ ■	**Governance** Top-down marine planning approaches.	Commercial fisheries/local fisheries/ Coastal communities/ Tourism sector	• Opposition to renewable energy planning and development when marginalised from decision relevant to sea spaces.
■ ■	**Physical structures and barriers** Associated with the presence of wind turbines (e.g. pylons, blades, foundations, cables, anchors, etc.).	Commercial fisheries	• Spatial squeeze forcing fishermen to travel further offshore into less favourable conditions (in search of alternative fishing grounds particularly for trawling). • Increased competition in remaining open areas, which can result in social conflicts. • Forced 'gear transition' (e.g. from trawling to potting inside the farm), and associated potential for diversification and innovation within the sector.
■ ■		Local fisheries	• Loss of traditional fishing grounds affecting their livelihoods (e.g. cultural identity and economic viability). • Increased competition for other local grounds, which can result in social conflicts and safety risks due to fatigue and longer periods at sea.

Funded by the European Union

			• Potential for diversification and innovation within the sector (e.g. monitoring of offshore wind farm sites).
■ ■		Coastal communities	• Seascape changes (as a result of overlapping offshore wind developments) can alter perceptions of local maritime identify and cultural value (particularly for small fishing villages). • Aesthetic changes and visual intrusion can affect mental health and wellbeing for coastal communities. • Increase/decrease in local employment (e.g. increase in local offshore wind farm maintenance jobs, decrease in tourism).
■ ■		Tourism sector	• Visual intrusion and seascape changes as a result of multiple offshore wind views overlapping can alter perceptions of the tourism value and restorative nature of the seascape.
■		Shipping	• Changes in vessel navigation patterns due to conflicts in maritime spatial use. • Navigational safety and operational efficiency issues close to offshore wind development sites.

5. Concluding Remarks

The research leading to this report aimed, among other things, at identifying and developing a shared understanding enduring challenges limiting the effectiveness of CEA. These challenges are characterised by procedural shortcomings, analytical complexities, data limitations and lack of knowledge. Many of the challenges identified (e.g. methodological differences, data and knowledge gaps, uncertainty, absence of agreed thresholds) converge in the process of determining whether cumulative effects are significant. It should be therefore noted that significance is not only an assessment outcome, but also a reflection of methodological choices, available evidence and professional judgement. Such challenges are amplified in transboundary contexts, particularly due to inconsistencies in assessment boundaries and methods, and poor data governance and sharing arrangements – all of which, as noted above, affect significance determinations. Given the transboundary nature of marine ecosystems and the transboundary risk implications of offshore wind development, cross-jurisdictional coordination is a remaining prerequisite for effective CEA.

While the identified challenges need to be addressed to enhance assessments, it is beyond this stage in the project to provide specific recommendations to that effect. Nevertheless, it is acknowledged that some of the identified challenges are currently being addressed in research and practice (e.g. dedicated surveys to fill in data gaps, multi-disciplinary research to strengthen knowledge on pressure-receptor interactions or setting up mechanism to centralise monitoring data). The glossary of challenges is intended to impulse their (joint) consideration throughout the subsequent stages of the project in order to develop a comprehensive and effective CEA framework (the ultimate aim of Work Package 3) that tackles as many as these challenges as it is practically possible. This CEA framework will form the basis of the offshore wind sitting decision tools envisaged in WP6.

The identified environmental and social risks are envisioned as priority aspects to consider in the CEA framework, as well as in the data collection process and the development of the data sharing portal as part of Work Package 2, recognising that other risks (e.g. social effects identified in Work Package 4) may also be relevant.

It is worth noting that the review suggests that current CEA practice remains strongly oriented towards identifying and mitigating negative cumulative effects. Comparatively, limited attention is given to potential cumulative benefits and enhancement opportunities, such as biodiversity gains, fish stock spillover, or local socio-economic development. This represents a potential area for future methodological development - and aligned with the ambition of SUSTAINOW regarding enhancement of offshore wind planning and development.

Annex A. Cumulative effects assessment and socio-environmental risks in the scientific literature

A keyword search on methods for CEA, cumulative environmental effects and cumulative social effects was undertaken in the Scopus and Web of Science (WOS) authoritative scientific literature databases. The identified publications were screened to ensure they specifically relate to CEA of offshore wind, and 185 relevant manuscripts were ultimately identified as relevant and included in the review. These were subsequently compiled into three distinct review databases to separately examine contemporary literature on: a) methods; b) environmental issues/risks; and c) social issues/risks. The publications were manually reviewed and categorised using short-hand codes (e.g. for methods, whether GIS or predictive modelling or multi-criteria analysis were used, for example, a related code was applied – i.e. MET-GIS, MET-MOD, MET-MCA). This helped structure the review and standardise vocabulary, ensuring that different authors describing the same phenomenon (e.g. "acoustic disturbance" vs. "noise pollution") were captured under a single code (e.g. environmental effect - noise levels = EN-NL). It also enabled subsequently analysing the frequency of the findings to determine priority methods and/or risks. In addition, other parameters were captured in the review, such as plan/project details (e.g. footprint, distance from shore, water depth), technology type (e.g. fixed versus floating turbines), scale of assessment (national versus local), identified pressures, and type of assessment (e.g. theoretical versus empirical). The complete review table can be provided upon request.

A1.Cumulative effect assessment methods

Significant variations are observed in CEA methods, with particular differences between assessments at plan (SEA) and project (EIA) levels – largely driven by the scale and specificity of assessment requirements (Table A1). Nevertheless, there is a strong consensus among authors on the need to integrate CEA into SEA and EIA (which is, in fact, a mandatory requirement under European legislation).

Predictive modelling is the most prevalent methodological category identified in the reviewed literature (45% or 37 of 83 manuscripts), particularly for the assessment of offshore wind projects. Models are typically used for long-term and large-scale effects, such as collision risks for birds and underwater noise propagation (Brabant *et al.*, 2015; Goodale and Milman, 2020; Benhemma-Le Gall *et al.*, 2023; Williams *et al.*, 2024). This is particularly the cases where real-time data are scarce. For example, studies on harbour porpoise often rely on models to predict population-level declines when empirical tracking is limited (King *et al.*, 2015).

Spatial analysis and mapping were used in 38% (32 of 83) of the reviewed manuscripts, with particular relevance at planning (SEA) level. Such spatial approaches are essential for site selection, habitat suitability mapping and visual assessments. In this context, nearly 25% of regional-scale studies apply GIS to identify site configurations that minimise a cumulative effect metric. Sophisticated spatial analysis tools such as Marxan or the InVEST Habitat Risk Assessment model are commonly used for visualising the spatial squeeze and trade-offs between offshore wind farms, fisheries, and conservation zones (Ferguson *et al.*, 2025; Stephenson and Hobday, 2024; Trifonova *et al.*, 2025).

Interestingly, field observations were employed only in 29% (24 of 83) of the manuscripts. This is relevant when considering that field methods, such as passive acoustic monitoring and visual observations, provide the "ground truth" necessary to define baselines and calibrate models (Benhemma-Le Gall *et al.*, 2021; Odríguez *et al.*, 2012; Siddagangaiah *et al.*, 2022; Welcker and Nehls, 2016). Similarly, expert consultation (e.g. interviews, workshops) is less common, and identified in 19% (16 of 83) of the reviewed manuscripts. This qualitative approach is vital for managing scientific complexity, addressing data gaps, and establishing common vocabularies among multidisciplinary experts. Approximately 18% of these studies specifically employ expert elicitation and stakeholder engagement to co-create guiding CEA principles and identify assessment priorities that balance ecological health with socio-economic development.

Table A1. Overarching methods identified in the literature review, their main purpose and application.

Predictive modelling - Ecosystem models such as SCAIRM; Food web models such as Ecopath, Ecosim and Ecospace; Stochastic population models.			
Main purpose	**Main application**	**References**	**Frequency**
To assess long-term and large-scale effects (e.g. bird collision risks, underwater noise propagation and marine mammal displacement, sediment changes and benthos); allowing for causal links between activity/pressure and long-term changes/trends in receptors. Some models are quantitative (e.g. Ecopath, which examines trophic interactions and ecosystem-wide effects) while others are qualitative and/or risk-based (e.g. SCAIRM).	SEA and (mainly) EIA. Risk-based models are typically applied at SEA level (e.g. for identifying hotspots where high-intensity human activities overlap with sensitive receptors, or for assessing species survival risks), while quantitative models (e.g. noise propagation, bird collision, trophic interactions due to the reef effect) are applied at EIA level.	Brabant *et al.*, 2015; Benhemma-Le Gall *et al.*, 2023; Bisinicu *et al.*, 2024; Gil-García *et al.*, 2022; Goodale and Milman, 2020; King *et al.*, 2015; Nogues et al., 2021; Noorollahi *et al.*, 2016; Rezaei *et al.*, 2023; Turrell, 2026. Vasileiou *et al.*, 2017a; Williams *et al.*, 2024.	45% (37 of 83)
Spatial analysis tools – Spatial overlays in Geographic Information Systems (GIS); GIS and multi-criteria analysis tools such as Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS); Marxan; InVEST Habitat Risk Assessment.			

Main purpose	Main application	References	Frequency
To identify overlapping pressures and sensitivities, and to determine suitable sites or optimum sitting locations based on pre-defined criteria. Some approaches (e.g. Marxan or InVEST) focus on examining the threats to conservation areas and sensitive receptors to help identify most suitable uses for different areas.	Both SEA and EIA, particularly for identifying spatio-temporal overlaps between projects/plans (i.e. pressure-receptor interactions), and for zoning conflict resolution (e.g. through area configurations that minimise cumulative effects for habitats and species, or fishing).	Azzellino *et al.*, 2019; Baig and Ahmed, 2025; Díaz and Guedes-Soares, 2020; Goodale and Milman, 2016; Guşatu *et al.*, 2022; Harvey and Dew, 2016; Huang *et al.*, 2025; Isaksson *et al.*, 2025; Kannen, 2014; Li *et al.*, 2023; Muñoz *et al.*, 2018; Peters et al., 2020; Pine *et al.*, 2014; Sahoo *et al.*, 2025; Sarnocińska *et al.*, 2020; Vasileiou *et al.*, 2017b.	38% (32 of 83)
Field observations - Passive acoustic monitoring; Visual observations; Remote observations (e.g. aerial surveys, Global Positioning Systems (GPS) tracking, and radar monitoring); Sampling (e.g. scientific diving, grab sampling, and experimental fishing).			
Main purpose	**Main application**	**References**	**Frequency**
Field observations and sampling methods are used to gather empirical evidence of how wildlife and habitats respond to the presence and construction of offshore wind farms. These methods enable calibration of models and bridge data gaps in predictive models and also provide baselines for CEA.	SEA and EIA. Satellite, radar and aerial surveys for measuring displacement range and bird flight height for collision models. GPS/telemetry for mapping flyways and identifying high-use areas for site avoidance. Visual observations for monitoring behavioural changes and validating species vulnerability. Sampling for studying the reef effect and changes in benthos/fish biomass. Acoustic monitoring for assessing disturbance on marine mammals from vessels and piling.	Benhemma-Le Gall *et al.*, 2021; Croll *et al.*, 2022; Goodale and Milman, 2016; Heinänen *et al.*, 2020; Hooker *et al.*, 2025; Huang *et al.*, 2025; Odríguez *et al.*, 2012; Peschko *et al.*, 2024; Popper *et al.*, 2022; Roach *et al.*, 2018; Schröder *et al.*, 2006; Siddagangaiah *et al.*, 2022; Welcker and Nehls, 2016; Williams *et al.*, 2024.	29% (24 of 83)
Consultation – Expert or stakeholder interviews; Focus groups; Public consultation.			
Main purpose	**Main application**	**References**	**Frequency**
These methods are critical for navigating scientific	Both SEA and EIA, particularly for public	Baig and Ahmed, 2025; Goddijn-	9% (16 of 83)

Funded by the European Union

uncertainty, establishing regulatory frameworks, and integrating socio-economic values into offshore wind planning. In data-poor scenarios, expert-elicited values are used to build frameworks for assessing population-level consequences of disturbance. In addition, stakeholder consultation improves transparency in consenting processes and identifying co-use opportunities.	acceptance, of plans/projects, fisheries or shipping conflicts. Interviews and focus groups are used to identify and/or rank environmental issues (e.g. identifying key potential cumulative effects, and underwater noise as top concerns).	Murphy, 2026a, 2006b; Isaksson *et al.*, 2025; Nie *et al.*, 2024; Pine *et al.*, 2014; Sahoo *et al.*, 2025; Sarnocińska *et al.*, 2020.	

Table A1 provides a snapshot of overarching methodological approaches for assessing cumulative effects. Specific methods and models, based on these four approaches (i.e. predictive modelling, spatial analysis, field observations, and consultation) will be examined in depth in subsequent WP3 tasks.

A1.1. Methodological challenges

A reflection on the review findings, including the methods and the parameters extracted from the literature, enables the identification of key barriers for the effective implementation of CEA methods. Overall, the reviewed literature characterises current research and analytical efforts as data-rich but information-poor. While the volume of data is increasing, the ability to translate it into cumulative effects knowledge faces the following challenges (presented in alphabetical order):

- **Data gaps**: A significant portion of the reviewed manuscripts acknowledge data gaps. These are most prominent regarding mortality rates (approximately 90%), followed by gaps in empirical data (79%), and gaps in temporal (67%) and spatial (50%) context. This may be a result of the limitation above on most publications entailing theoretical studies rather than empirical ones. While more empirical studies are needed and monitoring can help fill some of the existing critical data gaps, adopting multi-criteria assessments (MCA) and risk based approaches such as SCAIRM (that qualify rather than quantify effects - Bisinicu *et al.*, 2024; Piet *et al.*, 2023) and consulting experts to effectively implement these methods (Baig and Ahmed, 2025; Sahoo *et al.*, 2025) can also contribute to addressing some of the existing data gaps.
- **Dynamic environment and limited real-time monitoring:** Most assessments treat offshore wind development pressures in isolation, overlooking the effects of climate change, which are projected to outweigh localised offshore effects on fish community traits by 2060 (Rehren *et al.*, 2025). In addition, most studies (57% of the studies that report

on temporal scope) are capped at 24 months, which is insufficient to capture indirect or synergistic effects that manifest only after a decade of operation (e.g. changes in primary production or sediment grain size - Rezaei *et al.,* 2023). Moreover, for highly mobile receptors (i.e. birds and mammals), static data are insufficient (Goodale and Milman, 2019). Therefore, high-tech solutions such as 'passive acoustic monitoring', radio telemetry, GPS tracking, thermal imaging, or surveillance radar are needed (Benhemma-Le Gall et al., 2021, 2023; Croll et al., 2022; Goodale and Milman, 2019; Heinänen et al., 2020; Hooker et al., 2025). The challenge, however, is that these technologies are expensive and often project-specific (Howell et al., 2021), leading to geographical area and data sharing silos where the information is not made available due to its commercial value. By mandating the contribution of both once-off and real-time monitoring data to open-access repositories, the sector can move beyond fragmented information to a collective evidence base that captures environmental effects manifesting over decades of operation.

- **Empirical versus theoretical studies**: Only 22% (16 of 74) manuscripts reviewed are empirical. In contrast, literature reviews account for 25% (or 19) of the reviewed manuscripts, while modelling and theoretical studies represent 28% and 13%, respectively. This significant lack of published empirical evidence is partially a result of research-dominated scientific literature (as opposed to practice) but also suggests that current understanding of wind farm socio-environmental effects is driven by theoretical assumptions rather than observed real-world outcomes. Accordingly, environmental assessments and decisions may be based on models and assumptions, rather than on site-specific knowledge and variables. Publication of case studies and ground-truth data from existing wind farms is needed to expand knowledge and understanding; the implementation of effective monitoring measures (a mandatory requirement within SEA and EIA – EU, 2001; 2014) can help address this issue.
- **Geographical coverage**: A significant minority of the manuscripts (39% or 32 of 83) focus on evaluating cumulative effects of wind farms in isolation (e.g. by looking at the effects of a wind farm through the stages of construction, operation and decommissioning, or by examining interactions with other renewable energy plans/projects but within their zones of influence). This limits the understanding of cumulative effects on the entire sea basin. The adoption of spatial boundaries that enable the assessment of marine ecosystems would provide a more comprehensive account and understanding of cumulative effects.
- **Historical baselines**: The most frequently cited data gap (20% or15 of 74 manuscripts), is for historical baseline data; many projects begin monitoring only *after* the site has been selected, missing the pre-industrial state of the ecosystem. Yet long-term ranging data (e.g. 1906-2021 for birds and fish spawning areas or fishing volumes - Critchley *et al.*, 2025) are necessary to distinguish offshore wind effects from natural population fluctuations. The inclusion of long-term monitoring measures into the licensing and management of sites would present a good first step towards longitudinal data availability.
- **Methodological inconsistencies**: The prevalence of methodological inconsistencies (Table 1) is a significant obstacle in the field. The lack of technical standards or

specifications in regulatory frameworks or guidance tends to result in non-comparable CEA methods. For example, Serpetti *et al*. (2021) and Raoux *et al*. (2017) both apply the Ecopath model to calculate cumulative effects, but with different indices rendering different results. This lack of methodological standardisation makes it difficult to aggregate data across different plans/projects or timeframes effectively (Durning and Broderick, 2019; King *et al.*, 2009). Developing methodological guidance, or guidelines on ways to enhance comparability of assessment outcomes, is key to move towards systematic, consistent and comparable results and decisions. It has also been argued that a standardised metric for cumulative effects (e.g. a unified "cumulative pressure index" that combines different environmental effects) could be helpful for establishing thresholds and consolidate assessment findings (Azzellino *et al.*, 2019).

- **Planning stage coverage**: Decommissioning is the least represented stage (5% of the manuscripts), suggesting an important knowledge gap. Removing foundations may lead to significant effects through, for example, the sudden loss of the established artificial reef biodiversity (Brignon *et al.,* 2022), and trade-offs between full infrastructure removal and partial removal (e.g. preserving artificial reefs) require urgent experimental validation. Decommissioning studies should be published as they become available so that the industry more meaningfully considers this planning stage in future CEAs.
- **Reporting limitations**: The review of the literature unveiled that approximately half (i.e. 48%) of the manuscripts reported on specific project location (e.g. distance from the shore), 44% on water depth, and 46% specified project footprint. Such spatial contextualisation details are essential for understanding spatial squeeze dynamics and for linking receptor sensitivity to turbine location and scale. These parameters should be reported in both scientific publications and grey literature studies, in a similar way to EIA reports, to facilitate a more informed and better interpretation of assessment results, as well as comparability across findings.
- **Sensory mismatches:** The assessment of (cumulative) effects also favours certain species, exacerbating the taxonomic bias. For example, 71% of acoustic studies focus on sound pressure (and its effects on marine mammals), neglecting particle motion and substrate vibration, which are the primary sensory cues for the majority of fish and invertebrates (Popper *et al.*, 2022; Williams *et al.*, 2024).
- **Social effects**: The scarcity of published empirical studies on cumulative social effects (33% or 36 of 108 manuscripts) leads to knowledge limitations with regards to marine use conflicts and co-existence opportunities between marine sectors but also with coastal communities (e.g. fisheries, tourism). To address this, public and stakeholder consultation should be integrated into pre-planning stages to identify local concerns and propose solutions (i.e. mitigation), and incorporate these into assessments (as noted in 14% of the papers). In addition, social CEAs should be more widely published and associated data shared to contribute to the knowledge base.
- **Spatially specific approaches**: 38% (32 of 83) reviewed manuscripts include the application of GIS. According to the reviewed international literature, careful spatial

planning currently remains the most effective tool for mitigating negative effects on sensitive receptors (e.g. Bailey *et al.,* 2014; Krabbe and Argüello, 2025). By identifying and avoiding high-sensitivity "hotspots" during the SEA phase, through spatial analysis methods, the potential for cumulative effects, such as displacement or collision, can be reduced before individual projects are subject to further mitigation through EIA.

- **Taxonomic bias**: There is a significant knowledge gap regarding ichthyofauna (fish) and benthic sensitivity, for example (with only 5% of the manuscripts covering these) compared to megafauna (i.e. mammals and birds) (65% of manuscripts). Similarly, phytoplankton and plankton, the foundation of the food web, are addressed in only 5% of studies. There is also a tendency across the literature to focus on gannets, gulls and terns (i.e., 11% or 9 manuscripts) while auks, cormorants, shags and shorebirds (i.e., 7% or 6 manuscripts), as well as bats (8%) appear much less studied. Porpoises (24%, 20 out of 83 manuscript), whales (30%) and dolphins (28%) also get most attention among marine mammals; and cephalopods (8.4%) are rarely studied. This creates a skewed risk-based prioritization where charismatic species receive disproportionate assessment resources and, ultimately, consideration in decisions (Dannheim *et al*., 2025; Li *et al*., 2023; Serpetti *et al.,* 2021). Future research should investigate the short- and long-term effects of offshore wind on understudied groups, including bats, cephalopods, plankton, and sea turtles.
- **Technology coverage:** 89% (74 of 83) manuscripts specifically focus on fixed turbines, while 30% (25 of 83) discuss floating turbines. This reflects the status of the industry, where fixed foundations in shallow to mid-depth waters represent the vast majority of operational projects and established environmental monitoring protocols. However, this leads to a limited understanding and knowledge exchange on floating turbine effects. Wider dissemination of floating technology effects (and their inclusion in theoretical studies and models) could help address this gap.
- **Validation gap**: Predictive models (applied in 46% or 37 of 83 manuscripts) are essential for forecasting, but they often lack long-term, post-construction empirical validation (Brabant *et al*., 2015; Benhemma-Le Gall *et al*., 2023; Goodale and Milman, 2020; Williams *et al*., 2024). Without "ground-truthing" these models risk compounding initial hypothesis and uncertainties into broad quantification biases (Huang *et al.*, 2025). To fully understand the environmental and social limits of marine ecosystems, systematic field observations need to be undertaken over time (e.g. through SEA/EIA monitoring).

A2. Cumulative environmental risks

The literature underlines that cumulative environmental effects of wind farms vary across their planning stages. They are characterised by a temporal split: intense, short-term disturbances during construction and long-term, chronic shifts during the operational phase.

A2.1. Construction and installation stage

Based on the literature review analysis, **noise** level remains the most cited environmental cumulative pressure (78% of the reviewed manuscripts) during the construction/installation phase (e.g. high-intensity impulse noise from pile-driving). This pressure can create a chronic state of disturbance that can lead to permanent displacement of marine mammals and fish from high-quality feeding grounds (Benhemma-Le Gall *et al.,* 2021; Popper *et al.,* 2022). Furthermore, pile-driving activity generates high-intensity impulse noise that can cause temporary or permanent hearing damage in marine mammals such as Harbour Porpoise *(Phocoena phocoena)* (e.g. Benhemma-Le Gall *et al*., 2023; Goodale and Milman, 2016; Rezaei *et al.,* 2023). 'Passive acoustic monitoring' methods have shown that Harbour Porpoise population can decline by up to 33% during pre-piling vessel activity even before the first pile is struck; this is associated with increased levels of vessel and pre-piling installation activities and resulting increased accumulation of local underwater broadband noise levels (Benhemma-Le Gall *et al*., 2023). It is worth noting that current assessments focus almost exclusively (71% of 83 manuscripts explicitly addressing noise effects) on sound pressure, yet the majority of fish and invertebrates primarily detect particle motion and substrate vibration (Popper *et al.*, 2022; Williams *et al.*, 2024). In fact, vibrational footprint of an operating turbine may be affecting the benthos and shellfish in ways that are currently invisible to current standard acoustic monitors (Popper *et al.*, 2022; Williams *et al.*, 2024). Construction underwater noise can also affect birds through trophic levels - moving through the food web and consequently accumulating across different biological levels from fish recruitment to avian reproduction. For example, a study of Little Tern (*Sternula albifrons*) following monopile installation during herring spawning seasons, suggest that construction noise may interfere with fish recruitment and ultimately reproductive success in terns (Popper *et al.*, 2022; Williams *et al.*, 2024). For certain avian species, such as guillemots and bats, vessel traffic and construction noise are noted as secondary but significant stressors during their seasonal offshore movements (Peschko et al., 2024).

Another widely acknowledged (98% of reviewed manuscripts) additive effect from the deployment of multiple turbines is **habitat change.** The deployment of offshore wind infrastructure, specifically hard surfaces and artificial reefs, can result in permanent habitat alterations that may be classified as habitat loss rather than ecological improvement (Lindeboom *et al.,* 2011; Roach *et al.*, 2018). While these foundations are a suitable habitat for several benthic macrofauna species, with species composition and abundance changing over time, they can influence fish distribution, spawning, and catch rates (Lindeboom *et al.,* 2011). These temporal cumulative biomass effects could eventually alter ecosystems, and predator-prey dynamics (Lindeboom *et al.,* 2011; Roach *et al.*, 2018). Furthermore, there is significant concern that offshore wind projects facilitate the regional expansion of non-native species. This occurs through synergistic cumulative effect of increased structural connectivity and intensified maritime traffic during the construction and maintenance stages (Lindeboom *et al.,* 2011). As the turbines provide a new habitat, the ships provide the ride for non-native species which could result in a regional-scale environmental shift (Lindeboom *et al.,* 2011).

Changes in **suspended sediment** during cable laying and turbine foundation construction is also recognised in the literature (49% or 41 out of 83 manuscripts). This can also temporarily impair the hunting efficiency of visual predators and clog the feeding apparatus of filter feeders (Heery *et al.,* 2017; Rezaei *et al.,* 2023). An example of this effect is seen in fish populations, where elevated levels of suspended particulate matter can damage the eyes and gills of individuals (Baig and Ahmed, 2025). This physical impairment, combined with the reduced clarity of the water column, leads to a measurable reduction in predation success for species that rely on visual cues to capture prey (Goddijn-Murphy, 2026a; Schröder *et al.*, 2006).

A2.2. Operation stage

During the operational stage, the **reef effect** is most significant (31% or 26 of 83 manuscripts). This was often (66% of the 26 manuscripts that address the reef effect) reported as a positive or antagonistic cumulative effect (i.e. a positive trade-off of wind turbines). The introduction of turbine foundations and scour protection provides a hard substrate in otherwise sandy or muddy environments (Dannheim *et al.,* 2025; Rezaei *et al.,* 2023). This attracts epifaunal communities (e.g. mussels, anemones), which in turn attract predatory fish and decapods (Nogues *et al.*, 2021; Rezaei *et al.*, 2023; Turrell, 2026). Using food web models, research shows that the reef effect can increase local biomass, including increase abundance of fish. However, it also risks facilitating the spread of non-indigenous species (Dannheim *et al.*, 2025; Nogues *et al.*, 2023). In this regard, 92% of benthic studies (26 manuscripts of the reviewed 28 that mention reef effect) report the colonisation of turbine foundations by hard-substrate species, often at the expense of native soft-bottom communities.

The most reported (52% or 43 out of 83 manuscripts) significant adverse cumulative effect during the operational stage is **bird collision/mortality** (e.g. Croll *et al.*, 2022; Heinänen *et al.*, 2020; Hooker *et al.*, 2025; Rees, 2012). The literature review suggests a heavy reliance on collision risk models to estimate mortality rates (e.g. Brabant *et al.*, 2015; Goodale and Milman, 2020; Odríguez *et al.,* 2012). Nevertheless, avian species vulnerability is highly species-specific; gannets and gulls show higher collision risk, while divers (loons) and scoters exhibit strong habitat displacement, avoiding wind farm footprints entirely; this can significantly affect energy budgets for migratory populations and, ultimately, survival (Goodale and Milman, 2020).

Based on the literature review analysis, altered wave and current around foundations leads to **changes in marine physical processes**, including changes in grain size distribution (7% or 6 out of 83 total manuscripts). Altered hydrography, combined with the introduction of artificial hard substrates, influences food supply for the fauna living below the structures (e.g. Lindeboom *et al.*, 2015; Nguyen and Gourbesville, 2020; Rezaei *et al.*, 2023 Schröder *et al.*, 2006; Sinclair *et al.*, 2018). These changes tend to attract predators, which in turn causes further additive changes to the bottom communities by increasing predatory pressure (Goddijn-Murphy, 2026b; Schröder *et al.*, 2006).

The effects of **electromagnetic fields** have been studied in individual species' swimming patterns (e.g. sharks/rays) and it has been determined that these can alter their hunting and orientation behaviour near subsea cables (e.g. Heery *et al.*, 2017; Wright *et al.*, 2020). However, the cumulative effects of these cables are still understudied.

A2.3. Decommissioning stage

No (cumulative) effects from decommissioning stage were reported through empirical/experimental studies in the literature reviewed. This is likely due, at least partially, to the fact that only a limited number of offshore wind projects have been decommissioned. A few studies (5%) reported possible effects using modelling methods. For example, one study indicates that decommissioning could result in **habitat change/loss, turbidity, and organic enrichment** in the underwater environments (Brignon *et al.*, 2022). Another study in Horns Rev 1, the oldest large-scale wind farm in the North Sea, used a model for assessing 16 decommissioning scenarios ranging from full removal of infrastructure to partial removal strategies in which parts of the foundation, scour protection, or cables are left in place (Landstr and Olsen, 2026). This study focused on investigating **changes in species richness** associated with habitat changes related to decommissioning.

A2.4. Critical pressure-receptor linkages and effects

The sensitivity of an ecological receptor is determined by its life history, sensory capabilities, and mobility (Rees, 2012; Walsh *et al.*, 2025). The literature review reveals that effects on receptors are rarely a simple linear reaction; it often involves complex trade-offs between different pressures, and suggests distinct species-specific responses based on sensitivity and/or tolerance. Acknowledging that certain pressures affect multiple receptors (e.g. noise affects both marine mammals and fish), Table A2 summarises key pressure-receptor linkages and effects discussed in the reviewed literature.

Table A2. Key pressures and key environmental receptor effects, and literature frequency.

Pressure	Receptor	Effect description	References	Frequency
Noise	Marine mammals (e.g. dolphins, porpoises, seals, whales)	Temporary behavioural changes (e.g. reduction in foraging vocalisations or echolocation); long-distance avoidance; permanent auditory injury; rapid energy depletion and potential starvation (lethal threat); chronic disturbance entailing disruption to movements, breeding, feeding and growth.	Benhemma-Le Gall *et al.*, 2021, 2023; Dähne *et al.*, 2013; Dibo *et al.*, 2025; Green *et al.*, 2022; Hague *et al.*, 2022; Heery *et al.*, 2017; King *et al.*, 2015; Lindeboom *et al.*, 2015; Serpetti *et al.*, 2021.	46% (38 of 83), of which, 58% discuss noise effects/impacts from the construction; 52% from operation; and 7% from pre-piling.

Physical presence	Birds (e.g. sea birds, migratory species, bats)	Avoidance (e.g. gannets, divers, loons, guillemots); relocation and reduced forage availability; resulting cumulative loss of body mass due to frequent avoidance manoeuvres, affecting reproductive success, and ultimately long-term survival; collision and mortality risk (e.g. bats, kittiwakes, gannets, gulls) from attraction to wind farms for foraging, perching or roosting.	Bailey *et al.*, 2014; Drewitt and Langston, 2006; Fox *et al.*, 2019; Goodale and Milman, 2020; Masden *et al.*, 2009; Nehls, 2016; Odríguez *et al.*, 2012; Peschko *et al.*, 2024.	85% of bird-focused studies (36 of 43) discuss avoidance, while 36% (30 of 83) discuss collision risk or mortality.
	Fish (e.g. spawns, migratory fish, elasmobranchs)	Physical alteration of the seabed/habitat and associated reef effect (e.g. higher fish densities, greater prey diversity) and changes in foraging habits (e.g. dietary shifts); enhanced spawning connectivity for species with pelagic larvae by linking natural and artificial hard substrates (e.g. cod, flatfish).	Goddijn-Murphy, 2026b; Heery *et al.*, 2017; Molen *et al.*, 2014; Rehren *et al.*, 2025; Reubens *et al.*, 2014; Rezaei *et al.*, 2023; Wright *et al.*, 2020.	67% (56 of 84) of which 59% focus on commercially valuable fish stocks (e.g. Atlantic salmon, Cod, European hake) and 7% on elasmobranchs (e.g. sharks and rays).
Sediment change/ Hard substrate	Benthos	Reef effect and associated physical alteration of the seabed/habitat (e.g. soft-bottom taxa displaced by hard-substrate colonisers such as mussels, anemones).	Ajmi et al., 2025; Krone *et al.* (2013); Nogues *et al.*, 2023; Pezy *et al.*, 2017; Raoux *et al.* (2017).	34% (28 of 83)
Electromagnetic fields	Fish	Elasmobranchs (e.g. sharks, rays) show high sensitivity to electromagnetic fields, potentially altering orientation and hunting efficiency.	Heery *et al.* (2017); Wright *et al.*, (2020).	5% (4 of 84)

A3. Cumulative social risks

The literature review reveals that only 33% (or 36 of 108 manuscripts reviewed) discuss cumulative social effects of offshore wind, summarised in Table A3. Such effects are often the most contentious aspects of SEA/EIA, entailing competing values, subjective data, and high stakes for local communities. In particular, the literature highlights that the fisheries-conservation-offshore wind nexus is the primary area of cumulative social friction. In general terms, the vulnerability of human receptors is tied to spatial access and economic stability.

A3.1. Fisheries

Fisheries, including fishermen and coastal communities, are the most significant (67% or 30 of 45 manuscripts) subject of cumulative social effects from offshore wind. The fishing industry is uniquely vulnerable to the cumulative loss of space as multiple wind farms are proposed within the same traditional fishing grounds (Dibo *et al.*, 2025), resulting in a spatial squeeze that forces fishermen to travel further offshore into less favourable conditions (Szostek *et al.*, 2025; Trifonova *et al.*, 2025) or to "gear transition" (e.g. from trawling to potting inside the farm) (Trifonova *et al.*, 2025). In contrast, 22% of the literature (10 out of 45 manuscripts) argue that if fishing is banned within offshore windfarms, they can act as *de facto* Marine Protected Areas (MPAs), eventually benefiting fisheries through the "spill-over mechanism" of adult fish into adjacent grounds) (Guşatu et al., 2022; Jhan *et al.*, 2022; Muñoz *et al.*, 2018; Nogues *et al.*, 2023; Rehren *et al.*, 2025; Stelzenmüller *et al.,* 2021). The presence of these spill-over stocks enhances the adaptive capacity of fishing communities (e.g. moving to pot fisheries as an alternative when traditional shrimp fishing becomes inefficient - Stelzenmüller *et al.*, 2021). Yet, other authors argue that cumulative displacement from traditional fishing grounds leads to increased competition between fishers in remaining open areas, which can result in social conflicts and safety risks due to fatigue and longer periods at sea (Szostek *et al.*, 2025). For communities dependent on small-scale fisheries, the cumulative effect of multiple developments can threaten the very existence of their cultural identity and economic viability (Warlick *et al.*, 2025). Significant uncertainty remains in overall effects on the fishing industry, with some authors suggesting that cumulative effects on commercial fishing are currently underestimated and lack robust evidence-based assessment tools (e.g. Bergström *et al.*, 2014; Szostek *et al.*, 2025).

A3.2. Tourism

Visual effects/impacts (discussed in 29% or 13 of 45 reviewed manuscripts), are a significant concern as multiple projects' views can overlap, making them visible from a single point or sequentially along a coastline, and creating a cumulative visual/landscape effect for residents and tourists (Depellegrin, 2016; Nie *et al.*, 2024). As turbines get ever larger in size to optimise energy production, their visual footprint expands, potentially reaching thresholds of societal concern across entire marine provinces by, for example, altering perceptions of the tourism value and restorative nature of the seascape (Depellegrin, 2016; Depellegrin *et al.*, 2024; Goddijn-Murphy, 2026a).

A3.3. Wellbeing of coastal community

Effects on coastal communities are discussed in 33% (17 of 45) manuscripts, including offshore wind effects on cultural heritage and maritime identity which can also affect community wellbeing (Stephenson and Hobday, 2024). Only one manuscript out of 45 (i.e. 2%) addresses mental health effects due to stressors such as noise, and aesthetic/visual changes (Goddijn-Murphy, 2026a). Community wellbeing, and project acceptance are often hindered where stakeholders feel marginalised or excluded from decision relevant to sea spaces (De Luca Peña *et al.*, 2024; Dibo *et al.*, 2025; Stelzenmüller *et al.*, 2022). However, offshore wind can also positively contribute to the wellbeing of coastal communities by providing local employment (e.g. in offshore wind farm operation and maintenance) and by attracting synergistic industries, infrastructure investment, and specialized labour clusters (Glasson *et al.*, 2022; Kannen, 2014; Lindeboom *et al.*, 2015).

A3.4. Critical pressure-receptor linkages and effects

The social effects of offshore wind are defined by a complex interaction of conflicting values and opinions across and within sectors and affected coastal communities, as well as subjective data. Table A3 summarises key pressure-receptor linkages and effects discussed in the reviewed literature. It is acknowledged that certain sectoral social pressures have not been captured in this review (e.g. aquaculture and shipping) as the conflicts pertain spatial competition that mainly results in economic effects rather than social ones.

Table A3. Pressure-social receptor effects, and literature frequency.

Pressure	Receptor	Effect description	References	Frequency
Loss of space	Commercial fisheries/Local fishermen	Spatial squeeze, forcing fishermen to travel further offshore into less favourable conditions; gear transition (e.g. from trawling to potting inside the farm) damaged livelihoods (e.g. social conflicts and safety risks due to fatigue and longer periods at sea; cultural identity; economic viability).	Dibo *et al.* (2025); Szostek *et al.*, (2025); Trifonova *et al.*, 2025; Warlick *et al.*, 2025.	67% (30 of 45) of which 100% report concerns over exclusion of traditional fishing grounds.

Habitat change	Commercial fisheries/Local fishermen	Protected areas and associated spillover of adult fish into adjacent grounds creating increased production/catchment areas.	Guşatu *et al.* (2022; Jhan *et al*. (2022); Muñoz *et al.*, (2018); Nogues, *et al.*, 2023; Rehren *et al.*, (2025); Stelzenmüller *et al.*, (2021); Szostek *et al.*, (2025).	28% (10 of 36)
Visual and seascape changes	Tourism	Overlapping turbines visible from a single point or sequentially along a coastline alter the seascape.	Depellegrin, 2016; Depellegrin *et al.*, 2024; Goddijn-Murphy, 2026a; Nie *et al.*, 2024.	29% (13 of 45)
	Coastal communities	Overlapping turbines visible from a single point or sequentially along a coastline alter the seascape, and associated cultural heritage and maritime identity change (particularly for small fishing villages).	De Luca Peña *et al.*, 2024; Dibo *et al.*, 2025; Stelzenmüller *et al.*, 2022.	33% (15 of 45) of which only one addresses mental health effects (from noise, and seascape change).

Annex B. Cumulative effects assessment in environmental assessment practice

All available SEA Environmental Reports (SEA ERs) of offshore wind plans (n=16), and the most recent five EIA Reports (EIARs) associated with offshore wind projects (n=30) for the countries partnering in this project (i.e. Denmark, Estonia, Germany, Ireland, Portugal, Spain, and UK) were reviewed according to pre-established criteria. The systematic review aimed at understanding contemporary practice in the assessment of cumulative effects, particularly with regards to assessment scope, methods and limitations, spatio-temporal boundaries, and specialised input. The complete review table can be provided upon request.

B1. Cumulative effect assessment practice

The findings of the review of the SEA ERs and EIARs is summarised in Table B1.

Table B1. Summary of findings from the review of Strategic Environmental Assessment Environmental Reports (SEA ERs – n=16) and Environmental Impact Assessment Reports (EIARs n=40).

Review criteria	Justification	Key review findings
Focus	To determine the extent of dedicated attention to cumulative effects (e.g. dedicated chapter versus integration within environmental topic chapters).	• 15 of the SEA ERs and 26 of the EIARs (89% of the reports reviewed) incorporate CEA; one SEA ERs and four EIARs do not consider cumulative effects at all. • Where CEA is incorporated, 32 (or 78%) of the reports have dedicated chapters on CEA, of which 14 are SEA ERs and 18 are EIARs; 22% of the reports, particularly EIARs, address them within relevant environmental topic chapters.
Scope	To determine whether there is a correlation between CEA scope and methods (e.g. site-suitability, project assessment).	• Nine of the 15 SEA ERs with CEA (60%) pertain site suitability assessment; three SEA ERs centre on the assessment of multiple projects; one report considers regional development scenarios of MW output; and another report assesses policy measures. • 16 of 26 EIARs with CEA (58%) centre on assessing how other projects (offshore wind, but also mineral and gas extraction sites, pipelines, telecommunication cables, etc.) may lead to cumulative effects in-combination with the proposed project; 11% of the EIARs include within project cumulative effects only, without consideration of other projects and/or plans/programmes as mandated by legislation; in 31%, in-combination

		effects are also considered with other plans/programmes. • EIARs typically encompass the construction, operation, maintenance and decommissioning phases, but 50% of the cases observe that due to the significant time gap, decommissioning should be assessed in due time. • 58% of the EIAR CEAs also include onshore elements such as substation, grid connection and road widening works.
Approach	To determine common CEA frameworks (e.g. qualitative, quantitative).	• All SEA ERs and EIARs with CEA include a discussion on potential cumulative effects for each of the environmental topics that relies on qualitative expert judgement. • No reports fully quantify cumulative effects. • Project level CEAs are nevertheless more quantitative than SEA ERs, 54% referring to monitoring data from other wind farms and/or modelling results (e.g. on noise, collision risk). • Only 12 reports (29%) specify GIS use to determine co-location or proximity between plans/projects, as well as assessment boundaries (i.e. zones of influence), but the findings suggests that GIS is used – even if only as a background tool, in all the EIARs, and in all the SEA ERs except for the CEA on policy measures.
Methods	To establish which are the most used methods and key aspects considered in CEA (e.g. expert judgements, spatial overlays, staged screening pressure-receptor pathways, modelling, etc.).	• CEA methods at SEA and EIA levels vary significantly across countries; only 11 (or 42%) of the EIARs rely on existing guidance (i.e. UK Government, 2015; 2024) to frame the CEA scope and methodology, resulting in more consistent and comparable approaches. • Only one SEA ER applies a research-based method (i.e. Halpern et al., 2008); and four EIARs rely on a consultancy methodology (i.e. Conesa, 2010). • A typical method includes GIS-based spatial sieving of plans/projects, and delimitation of assessment areas; review of existing scientific literature, monitoring reports; modelling of specific effects at project level (e.g. noise, collision risk), and professional input to interpret the spatial analysis, modelling and/or supporting documentation to make an informed qualitative judgment. • Significant variations are observed in modelling approaches with different modelling techniques applied for different pressures and receptors (e.g. noise effects, bird collision risk, shipping collision

		risk, etc.) and no report establishes ways to aggregate model results into an overall cumulative effect index. • The determination of effect significance also varies: some apply expert judgments to provide a broad qualification while others qualitatively characterise it using a set of attributes such as intensity, extent, persistence, reversibility, accumulation and synergy; and the more quantitative assessments contrast model outputs with established, yet varied, legislative thresholds (e.g. for noise). • Expert judgments are, in all cases, based on the interpretation of best available knowledge on pressure-receptor pathways.
Limitations	To understand ongoing CEA challenges (e.g. gaps in data, know-how, etc.).	• 13 reports (32%) do not include a dedicated section or distinct account of CEA shortcomings or limitations, but rather reflections throughout relevant chapters. • 79% of the reviewed reports that include an account of CEA limitations (10 SEA ERs, and 12 EIARs) acknowledge data gaps (e.g. bird and mammal migratory routes, bats, fishing vessels less than 12 metres in length), as well as variability over time, surveys representing only a 'snapshot' in time. • 68% (nine SEA ERs and 10 EIARs) specify knowledge gaps, but with significant variation across the reports, even for the same pressures/receptors (e.g. for birds: lack of knowledge on the extent displaced birds can find sufficient alternative food sources, on breeding/wintering bird species movements, or on bird collision risk). Different limitations are also acknowledged at SEA and EIA levels within the same jurisdiction (e.g. one SEA ER reports on lack of understanding around the impact of noise on mammal migration routes, while an EIAR recognises uncertainties with regards to predicting both exposure and response of mammals to underwater noise). • 36% (five SEA ERs and five EIA ERs) report lack of knowledge on effect intensities within the study area due to an absence of detail on the scale and distribution of future plans and/or projects; while 21% (three SEA ERs and three EIARs) relate this knowledge gap lack of knowledge on development stages (e.g. planning, construction or operation). • Five EIARs (18%) specifically acknowledge the impossibility of undertaking a meaningful CEA of the decommissioning phase due to the technical and

		analytical difficulties of anticipating changes in 25-35 years' time. • 14% (three SEA ERs and one EIARs) acknowledge lack of systematic assessment criteria for certain receptors (e.g. bats) and thresholds (e.g. noise) on what constitutes an acceptable cumulative effect over time and space. • 18% (two SEA ER, and three EIARs) note uncertainties associated with the dynamic nature of the marine environment where conditions may change during the site preparation, construction, operational and decommissioning phases. • 14% (one SEA ER and three EIARs) indicate that lack of centralised public access to marine datasets affects CEAs, particularly at project level.
Spatial scope	To determine whether assessments focus on administrative/site boundaries or if wider effects are considered (e.g. site/plan footprint, buffer zone, onshore, transboundary region).	• 'Zones of influence' are commonly determined, distinctively, for each environmental and social receptor – which go beyond the plan zoning or project site in all the reviewed reports. • The consideration of onshore elements renders a much larger CEA spatial scope in some SEA ERs. • The spatial scope in EIARs is specified in 12 EIARs only and vary significantly across receptors and across assessments (e.g. they span from 300 meters through to 750 meters from the development site to the entire Exclusive Economic Zone for noise sensitive receptors). • Transboundary effects entail the adoption of a fixed or lax buffer area (e.g. specifically 10Km in one EIAR, and the wider marine area, without specified limitations other than country names in 77% of the EIARs).
Temporal scope	To determine the timeframe of the assessment and infer the extent to which long-term effects are duly considered (e.g. plan versus assessment timeframes).	• CEAs at plan level generally span the timeframe of the plan itself, although this is only specified in 50% of the SEA ERs. • At project level, the temporal scope of CEAs is clearly stated in nine EIARs (35%) where this is considered to span the lifetime of the project; while it is not always specified, it typically ranges between 25 and 35 years.
Monitoring	To understand whether any specific measures are put in place to follow-up on	• Only 10% of the reports (i.e. one SEA ER and three EIARs) specifically require monitoring of cumulative effects (e.g. noise levels, migratory birds, and shipping collision risk).

Funded by the European Union

	cumulative effects throughout the lifetime of wind farm plans or projects (e.g. coordinating monitoring from different developments).	• 12% (two SEA ERs, and three EIARs) recommend coordinated monitoring approaches. These recommendations include establishing and managing a central, GIS-based, repository of environmental data for plan area which will be used to inform robust and comprehensive cumulative and in-combination assessments; and coordination among adjacent member states to monitor developments and engage in a dialogue about joint solutions for sea space monitoring.
Specialist input	To establish whether an interdisciplinary approach is adopted for a meaningful assessment (e.g. marine biologist, hydrologist, social scientists).	• 49% of the reports acknowledge professional judgement input by topic specialist; of these, only three EIARs provide a 'statement of authority', listing the names of competent experts involved in their preparation together with details on their qualifications and experience; in another four, the stakeholder groups providing advice on specific issues are also named. • Seven reports (17%) were prepared by a consortium of consultants, and their individual contributions are recognised.

B2. Current practice challenges

A reflection of the review findings (Table 4) renders a number of CEA challenges in contemporary impact assessment practice (presented according to the order of review criteria):

- **Limited CEA focus:** A significant minority of the revised reports (11%) do not consider cumulative effects at all. In addition, where these are considered, relatively often (22% of reports) they are not granted explicit attention in a dedicated CEA section, particularly at the project level. CEAs of floating turbine developments seem to be poor; these projects typically include prototypes or very small scale developments which could be a possible explanation for such observed limitation. The need for a more dedicated focus could be addressed by updating SEA and EIA legislation and/or by revising guidance to include a specific recommendation for the inclusion of a dedicated CEA chapter in environmental reports.
- **Lack of CEA specific guidance**: Of the countries included in this review, only the UK have specific CEA guidance (NERC, 2013; UK Government, 2024), with practitioners in Ireland also following the same due to similarities in planning systems. Interestingly, while CEA guidance is available, UK SEA ERs point to a need for further guidance on meaningful aggregation of risks and on spectrum of CEA certainty. Reference is also made to another guidance in the Spanish EIARs (i.e. Conesa, 2010), but this is not specific to CEA. The overall lack of guidance points to a significant lack of harmonisation in regulatory

frameworks, limiting the effectiveness of CEAs, hampering coordinated assessments and decisions, and ultimately leading to uneven levels of environmental protection across regions. The development of European or sea-basin-level guidance could improve consistency, transparency and comparability of assessment approaches while still allowing flexibility for context-specific ecological and social conditions.

- **Variability of methods**: CEA methods at SEA and EIA levels vary significantly within and across countries. Where guidance is available (see above), the adoption of systematic approaches enables comparability of assessment results; this can also facilitate transboundary consultation. In all cases, most CEAs at plan level (i.e. SEA) remain basic, relying mainly on GIS to identify plans/projects/receptors and on expert judgement to qualitatively assess and determine effect/ impact significance. At the project level (i.e. EIA), assessments typically adopt topic-specific modelling approaches (e.g. noise disturbance on mammals, birds or shipping collision risk). However, even in those cases, cumulative effect significance or risks are also ultimately qualitatively determined by expert judgement. These issues are compounded by the absence of standardised indicators for quantifying cumulative effects, as well as the lack of clearly defined and meaningful benchmarks against which cumulative effects can be evaluated. Adopting rigid methodologies or indicators, or indeed establishing fixed thresholds for acceptable change becomes inherently problematic, as different plans/projects and/or sea-basin require different considerations, and ecological responses are complex and non-linear. As a result, significance determinations often remain subjective, varying across studies and regulatory contexts as observed in this review. This could be addressed, partially at least, by engaging a range of subject-specific experts, with in-depth knowledge of pressure and receptor interactions, to ensure the subjective nature of such determinations is mitigated through professional expertise. A clearer account of such input should be reported in assessments; half of the reviewed reports acknowledge specific professional inputs, but only 7% specify their expertise.
- **Variability of geographical extent**. In all the reviewed assessments, spatial extents are receptor-specific (e.g. cumulative effects manifest over larger geographical areas for migratory birds and mammals than for benthos), resulting in a substantial variation on ‘zones of influence’ (e.g. from fixed around-the-site buffers to entire Economic Exclusion Zones). In some cases, onshore infrastructure and thus assessments are also included, expanding the geographical envelope. The consideration of transboundary effects adds further variation to geographical extents (typically without specified limitations other than references to ‘wider areas’ or country names). While the spatial extent has limited effect on the effectiveness of assessments beyond the fact that the potential geographical coverage of effects may not be effectively captured, a more harmonised regional-scale approach to CEA could improve understanding of wider geographical contexts. This is also important when monitoring existing plans and projects.
- **Lack of overall cumulative effect significance or risk**. The review reveals that none of the assessments systematically aggregates the risk associated with individual developments

for a given receptor, or indeed, the risk of a given development pressure for multiple receptors. Contemporary research advancements could be incorporated to address this lack of determination of overall cumulative significance or risk and improve current practice, such as accounting for the 4D dimensions of coastal and marine environments and spatially aggregating pressures at different depths, or considering factors such as magnitude, hazard, and receptor behaviour (e.g. ability of receptors to evade pressures), to provide sensitivity scores that reflect the unique vulnerabilities of ecosystem components to pressures and then aggregate these.

- **Lack of model validation**. The review points to an increased application of predictive models particularly at EIA level (e.g. for underwater noise, population shifts, bird or shipping collision risk). While these are essential for forecasting long-term shifts, and can improve understanding of trophic interactions and population-level responses, the widely reported data and knowledge gaps in the reviewed reports suggests limited empirical validation. Empirical data collection and model validation are necessary for more meaningful and reliable assessments. This can be addressed through the implementation of effective monitoring measures – a requirement of both the SEA and EIA Directives (EC, 2001; EU, 2014a). Nevertheless, acknowledging that cumulative environmental effects arise, in particular, from complex, non-linear interactions between multiple stressors, and produce either additive, synergistic, or antagonistic effects that vary across receptors and spatial scales, ecological responses are not easily predictable. These challenges constrain the ability to calibrate and validate predictive models, so expert judgement is often required to interpret and complement model results.
- **Enduring uncertainties**. The review highlights critical data and knowledge gaps (79% and 71% of reports respectively) with regards to underrepresented receptors such as bats or benthic communities, but also to incomplete understanding of ecological processes such as migratory routes and extent of displacement. Similarly, there is poor understanding of effect intensities due either to an absence of detail on the scale and distribution of future wind farms or other renewable energy projects (25% of reports specifically accounting CEA limitations observe this gap) or to different projects being at different development stages (21% of reports, with 18% specifically acknowledge the impossibility of undertaking a meaningful CEA of the decommissioning phase due to the technical and analytical difficulties of anticipating changes over such long periods). Uncertainties associated with the dynamic nature of the marine environment (18% of reports), and data accessibility limitations (14%) are also recognised. Ensuring transparency in the reporting of such assessment limitations is key for evidence-based decision-making. Moreover, enhanced information flows (e.g. through transparent and interoperable data systems) would enable the aggregation of multi-project datasets, facilitating the identification of cumulative effect hotspots and ecologically sensitive receiving environments, thus supporting ecosystem-based management decisions.
- **Lack of CEA-specific monitoring**. There is a dearth of monitoring measures that specifically follow up on identified cumulative effects. Only 4 environmental reports (10%)

include such measures, but for specific pressures and receptors only (e.g. noise and marine mammals, or migratory routes and collision risk). Enforcing monitoring would help address some of the critical CEA shortcomings in this review – particularly with regards to data and knowledge gaps. Such monitoring should adopt standardised and relevant spatial and temporal scales to ensure cross-study and cross-country comparability of data, and their seamless integration to facilitate and enhance future CEAs. Moreover, monitoring and research need to pivot toward evaluating the carrying capacity of entire sea basins rather than evaluating wind farms as isolated entities. In all cases, monitoring reports and associated data should be made publicly available to enhance our understanding of cumulative effects and improve the empirical evidence-base over time, ultimately supporting more quantitative CEAs.

Annex C. Expert perceptions on cumulative effects assessment practice and socio-environmental risks of offshore wind

Semi-structured interviews, supported by a short online survey, were undertaken with 20 experts across the SUSTAINOW partnering countries (i.e. Denmark, Estonia, Ireland, Portugal, Spain and the UK). They represent: marine planning authorities (e.g. Ministry of Climate – Estonia; Department of Climate, Energy and the Environment - Ireland); regulators (e.g. The Danish Energy Agency – Denmark; Environmental Board – Estonia; Maritime Area Regulatory Authority – Ireland; Norte Comissão de Coordenação e Desenvolvimento Regional – Portugal); environmental consultancies (e.g. COWI – Denmark; RPS – Ireland; NIRAS – UK); marine research organisations (e.g. Marine Institute – Ireland; MARE Institute – Portugal; Food and Marine Research Centre (AZTI) – Spain); professional renewable energy and sustainability bodies (e.g. Asociación Empresarial Eólica – Spain; Institute of Sustainability and Environmental Professionals – UK); and developers (e.g. JERA – Denmark; RWE – UK). The subsections below present the key findings for each of the interview/survey questions. Additional detail on interview and survey responses can be provided upon request.

C1. Understanding for cumulative effects assessment

The first survey question intended to gather insights into how CEA is understood by experts. The findings reveal that there are different understandings of CEA, with a notable lean towards a pressure-based definition: 47% (or 7 of 15 survey respondents) defined it as the joint assessment of multiple effects arising from various sectoral activities; 27% (4 respondents) considered it to be the combined assessment of multiple sector pressures on the combined vulnerability of receptors; and the remainder focus on effects on multiple receptors (1 respondent) or emphasise that all three angles are possible as CEA is context-specific.

C2. Cumulative effect assessment methods

One of the most significant findings across the interviews was the absence of a universally accepted or systematic CEA methodology. When asked about CEA methods they use (e.g. as practitioners) or have come across (e.g. as regulators), 55% (11 of 20 interviewees) explicitly stated that they do not use a systematic methodology. According to the interviewees, the most common reasons behind such lack of systematic methods are: lack of standardised national guidance (65% or 13 interviewees); inconsistent datasets (55% or 11); scientific uncertainty (75% or 15); varying project scales (45% or 9); and differing regulatory requirements (35% or 7).

CEA approaches are generally project-specific, adaptive, qualitative, expert-led, and heavily dependent on available data. In general, the interview responses suggest CEA methods to entail a combination of GIS mapping (50% or 10 of 20 interviewees), pressure-receptor matrices (35% or 7), expert judgement and/or interpretation (25% or 5), and/or pressure- or receptor-specific modelling (15% or 3). The application of UK Planning Inspectorate guidance was the only systematic EIA approach referred to by Irish and UK interviewees. And the most advanced methodology was described by the Spanish Food and Marine Research Centre (AZTI) which apply GIS-based Bayesian probability models, expert Delphi exercises, and literature-based weighting systems to map different degrees of cumulative risk.

GIS is typically used for CEA screening (i.e. identifying overlapping projects, pressures, and receptors), or distinctively for either mapping the overlap between different projects or identifying sensitive receptors within a project's zone of influence. GIS appear to be particularly relevant at planning and SEA levels - when considering the background expertise and role of those that emphasised its applicability. It can also be used to support modelling at project (or EIA) level (e.g. mapping fisheries conflict or underwater noise zones). Interviewees highlighted that expert judgement is necessary because of uncertainty in ecological thresholds, incomplete datasets, highly dynamic marine systems, and difficulty in quantitatively modelling cumulative interactions. Setting up of expert groups as part of CEA seems common practice, with expertise including: experts in marine biodiversity, benthic ecologists, fisheries experts, marine ecologists, marine engineers, ornithologists, oceanographers, impact assessment experts, GIS specialist, and experts in social sciences especially in landscape or seascape. While only a small number of interviewees highlighted the use of modelling (15%), these methods appear to be particularly relevant at project (EIA) level for underwater noise propagation, bird collision/displacement, marine mammal impacts, sediment dispersion, and marine process interactions. Overall, the interview findings suggest that CEA remains highly variable across organisations, and indeed plans and projects.

The survey findings support the interview findings on the variability of CEA methods used. When asked about what methods they use or are aware of, there was a strong consensus on the knowledge and use of spatial planning tools such as GIS (with 92% or 12 of 13 survey responses) for evaluating the effects of diverse development scenarios on environmental quality and natural resources. However, and interestingly, more advanced CEA approaches seem also widely known and used: 62% or 8 survey respondents indicated they know about or apply methods such as that of Halpern et al. (2008) for spatially mapping pressures and ecosystem components and weighting these overlaps based on the sensitivity of a given component to a given pressure seem to be significantly used. Other methods that stood out in the survey responses include: ecosystem models (54% responses) for a comprehensive mathematical representation of an entire ecosystem (e.g., populations, functional groups), and interactions through real ecological processes (e.g., predator-prey interactions, large and small perturbations); and impact risk ranking (38%) through linkage-chain-frameworks such as Options for Delivering Ecosystem-based Marine Management (ODEMM) or Spatial Cumulative Assessment of Impact Risk for Management (SCAIRM) for tracing sector-pressure-ecosystem component pressure pathways and scoring them through expert judgement and data where available. In contrast, more specialised causal analysis tools such as Bayesian Belief Networks

Funded by
the European Union

(BBNs), Knowledge Graphs, and Food Web Models seem to be least understood/utilised, with fewer than 25% of the respondents referring to these.

C3. Critical challenges in cumulative effects assessment

The analysis of interviewee responses regarding the two main challenges in CEA, suggests that data gaps, incompatible datasets and data access present the most critical challenges hindering CEA effectiveness. These issues are further explored next (in order of frequency):

- **Data Accessibility:** 75% of the interviewees (15 of 20) highlighted data access as a major challenge. This issue steams from poor data sharing systems (40% or 8) often related to commercial sensitivity (30% or 6), one interviewee noting that "persons and institutions that have the data don't want to share the data" and another stating this is particularly problematic for certain datasets (e.g. "[fisheries] it's confidential in some areas, so some of those data are not really greatly accessible"). The absence of centralised repositories was also repeatedly (30% or 3) noted as a data access barrier, highlighting that consultants should "have access to that single source of the true data". Compounding data access barriers noted by interviewees include uncertainty regarding data ownership and data governance (e.g. coordinated sharing mechanisms).
- **Complexity:** 45% (9 of 20) discussed complexity as a major challenge in CEA, with one interviewee identifying complexity as the "number one challenge". This challenge derives from the fact that effects occur across ecosystems, or national borders, and over long timescales or across multiple project phases. Migratory birds were cited as a primary example of transboundary cumulative complexity by 45% of the interviewees who discussed difficulties with inter-jurisdictional migration routes, datasets being incomplete, and uncertain long-term behavioural responses.
- **Ecological data uncertainty**: 35% (7 of 20) discussed ecological uncertainty. Of these, 5 interviewees highlighted unknown ecological thresholds and significance limits, which are compounded by the limited knowledge on pressure-receptor interactions and behavioural responses, jointly highlighted in 5 responses; one interviewee captured this succinctly noting that the "(...) challenge is identifying where noise overlaps and what the thresholds are, especially given our lack of knowledge about pressure interactions and pressure–receptor interactions"). Another 5 pointed to the lack long-term ecological monitoring and baseline data (e.g. "(...) monitoring data is very hard to get hold of"). Uncertainty regarding habitat/ecosystem recovery rates was also raised by two interviewees.
- **Governance**: 35% (7 of 20) indicated governance fragmentation or institutional/regulatory coordination problems as another major challenge in CEA. All 7 responses pointed to inconsistent CEA frameworks, while 30% (or 6) to poor coordination across sectors and jurisdictions affecting CEA standards and data consistency (e.g. "Different jurisdictions emphasize different issues, making it difficult to create a consistent and coherent dataset across borders"). Governance issues expand beyond CEA, with 4 interviewees highlighting

that fragmented institutional and regulatory responsibilities remain, particularly with regards to the insufficient integration of marine planning, fisheries management, offshore wind licensing, and biodiversity conservation.

- **Extent**: 35% (7 of 20) raised assessment scope and extent as distinct challenges, one interviewee noting that for effective CEA "you must define those limits in scope regarding the value components [i.e. receptors] and also the location and what do you consider to be the close (...) environment that should be taken in account.". This consideration also affects data access (e.g. "(...) and in the case of wind farms located near borders, cumulative effect assessment requires information on developments in neighbouring countries; however, such information may be limited").
- **Data incompatibility:** 25% (5 of 20) noted inconsistent/non-comparable datasets, with an interviewee noting that this challenge is commonly driven by the application of differing analytical approaches and leads to "compounding uncertainty". This is particularly the case when modelling: the absence of interoperable or compatible systems or models, highlighted by 4 interviewees, can further amplify data inconsistency.

C5. Key environmental risks of offshore wind

This question aimed to prioritise environmental risks according to expert opinion. Interestingly, this question was interpreted differently by interviewees: some pointed at pressures, focusing on the causes of risk, while others discussed receptors, considering they are exposed to risks. In all cases, the main risks identified, by order of frequency, were:

- **Birds**. Bird-related effects were the most frequently discussed environmental risk (35% or 7 of 20 interview responses). Two key specific risks were identified: 1) displacement (5 interview responses) and 2) collision (4 interview responses). These two key issues are captured clearly by an interviewee: "One of the most significant cumulative environmental risks is the risk of bird collisions and displacement from habitats (...) This is particularly important in situations where multiple wind farms are planned in close proximity or where other developments are located within the same migration corridors or near important feeding areas"). Displacement may entail moving away from foraging/breeding grounds (2 interviewee responses), changes in migratory routes (2 responses) and/or changes in behaviour (1 response).
- **Underwater noise**: 20% (4 of 20) explicitly identified underwater noise as a significant environmental risk of offshore wind farms. Concerns included piling noise, vessel traffic, seismic surveys, marine mammal disturbance, and overlapping acoustic effects. The 4 interviewees highlighted the lack of standard thresholds and long-term datasets (e.g. "at what point if you have, let's say, 2 boats doing let's say seismic surveys on the North Irish Sea and the South Irish Sea. At what level do they interact?... where did those two noise events meet and cause an impact and whether that impact is cumulative?"). One interviewee framed underwater noise as an uncertainty/data gap, while another discussed it alongside birds, marine mammals, and fisheries risks.

- **Hydrodynamics**: Changes in currents and the wake effect as a result of turbine foundations, affecting the water column's hydrodynamics, were raised by 3 interviewees (e.g. "When you take wind energy out of the system, it gives some wake effects, and then you get impacts on the ecosystem, the lower layers of the ecosystem, and then it accumulates upwards"). They all considered this to be an understudied risk, and thus associated with uncertainty.

Additional environmental risks were identified by the interviewees, with the following risks identified by a single response each: **marine mammals** (i.e. "The biggest impacts relate to our understanding of impacts on wide-ranging species like marine mammals"); **habitat loss** (i.e. "what development can do is 'death by a thousand cuts' (...) where your accumulation effects are things like loss of habitat and you're only doing a little bit here, and you're only doing it a little bit there. And when you add all of that up, that's the issue"); **sediment dispersion (**i.e. "sediment is suspended in the water column if you have fine muddy sediments, and how the impact is for the marine habitats around the area and flora and fauna"); and **biogenic reefs** (i.e. "Vulnerable communities in the marine environment, such as biogenic reefs, are also a concern"). One interviewee also pointed to **ecosystem-wide risks** (i.e. "In addition, the lack of knowledge on sea-scale ecosystem effects of offshore wind farms, and how these effects flow through trophic levels").

C5. Key social risks of offshore wind

This question aimed to prioritise social risks according to expert opinion. The main social risk of offshore wind farms pertains fisheries (45% or 9 of 20 interview responses). One interviewee captured the related issues succinctly: "The main social risk associated with offshore wind is fisheries. Fisheries are consistently a major issue because of conflicts over access to fishing grounds, compensation, and the reliability of fisheries data. It is difficult to quantify and compare the information provided, and fisheries are often challenging from a stakeholder management perspective. "Offshore wind developments displace fishing grounds, particularly for trawling activities, because developers do not want trawling near array cables or within offshore wind farms". Three interviewees noted that accurately mapping fishing data and estimating effects on fisheries income is complex; this contributes to the already difficult interactions between the sectors. Taking the issues raised by these and other interviewees, three critical issues pertain the offshore wind and fisheries coexistence conflicts:

- **Loss or access restriction to fishing grounds:** 35% (or 7) interview responses considered loss of fishing grounds as the main social risk. Several interviewees (6) highlighted that loss of access to fishing grounds is a major area of dispute between the sectors, and one observed that a "joined-up approach to planning marine spaces" could help resolve this conflict.
- **Displacement of fishing activity**: 15% (or 3) responses emphasised displacement as the key risk, noting that "Offshore wind developments displace fishing grounds, particularly for trawling activities, because developers do not want trawling near array cables or within

offshore wind farms" and that "the displacement of fishing effort into already pressured areas" can magnify certain ecological risks.
- **Income loss and compensation disputes**: 15% (or 3) responses observed that loss of income is one of the key concerns amongst fishermen. One noted that "A key challenge in assessing socio-economic impacts is the lack of precise data on income effects for individual fishermen", while another argued that such lack of knowledge on economic effects typically leads to "disputes regarding compensation for disrupted fishing activity".

The interviewees also identified **visual impacts** (25% or 5 responses) as a critical social risk, particularly with regards to seascape effects and associated impacts on tourism and recreation (e.g. diving, surfing, tourist boats). One interviewee noting that "A lot of people were worried that it would have a major negative effect on tourism and recreation" and another questioning "Will people not go to these areas because there's wind farms on the horizon?". An interviewee raised **navigation** as a social risk (i.e. "There are also concerns about (...) offshore banks, and how that might affect navigation interests") while another referred to risks for coastal **community identity** (i.e. "they are passionate about going to sea, I know that it's a cultural thing, it's a huge part of their identity, and the community").

C6. Missing or fragmented datasets

This question explored the most significant data gaps and data management recommendations for improving CEAs. 20% (or) interviewees highlighted that baseline data remains poor and/or not accessible (e.g. "There is an issue around data and baseline setting (...) Improving the availability of baseline data would significantly facilitate cumulative impact assessment"), and shifting baselines create significant problems in CEA (e.g. "You've got cumulative over time, which EA doesn't really pick up because the historical change is in your baseline. That's where you get shifting baseline problems"). The specific datasets missing, according to interviewees are (presented in alphabetical order):

- **Bats** are important data gap, raised by 3 interviewees, noting "Offshore bats are another developing area with limited information, including their movements over the sea and where they are going" and "We know very little about bats. they fly offshore at night and that seemingly interact with windfarms, but we know little about these interactions".
- **Birds** were acknowledged to be most studies but 4 interviewees noted that significant gaps remain with regards to displacement from feeding grounds and migratory routes (e.g. "For migratory birds, there is not a huge amount of empirical information, so we are relying heavily on models", "The critical missing data sets are highly dependent on the region and country, but bird displacement effects remain a key issue, particularly for divers and some other species. Migratory seabirds have generally been more extensively assessed because there is greater knowledge available, but displacement effects are still lacking in many places."). One interviewee also noted that "there are a lot of questions over the impacts of underwater noise on diving birds as well."

- **Ecosystem response**: The general lack of knowledge about how the environment responds to human activities was raised by two interviewees, noting that "In general, we lack a lot of data on what the actual impacts from offshore wind are. We speculate a lot, but there have not been that many studies" and that "This applies not only to specific species like the harbour porpoise but across the marine environment." One interviewee also observed that "The problem is compounded by insufficient monitoring and a broader lack of relevant knowledge."
- **Fishing activity** data was raised by two interviewees, indicating that this is "one of the biggest and most important data sets that are needed to inform where offshore wind is affecting fishing activity" and that "Some datasets need improvement, such as spawning data, where better resolution would help."
- **Water column** was highlighted by an interviewee: "Certain areas like water column data will need modelling and more work."
- **Sediment dispersion** was noted by an interviewee: "Sediment dispersion during construction is another area where data are insufficient."
- **Small fishing vessels** were noted as a data gap by an interviewee: "There's no data from vessels under 12 meters. There will be quite a lot of fishing activity of boats of that scale in areas where there's plans for offshore wind. So that is a hugely important issue, and it is being considered nationally."
- **Effect/impact duration and distances** data are missing for many species as raised by 2 interviewees: "the lasting impacts of it (underwater noise), the distances over which it has impacts, and the species that are impacted" and "There are limited measurements of water sounds and sediment impacts during construction to determine whether these impacts are significant and how long they persist."

The interviewees also raised issues in relation to data management: 30% (or 6 of 20) stressed the need for **centralised marine datasets** (e.g. "The datasets are widely scattered between public and private and in different formats. So it's hard to get data" or "The biggest problem is that there's a lot of data on the marine environment held in different places (...) availability is key, it's often there but not accessible"). The need for more effective **monitoring** that addresses existing data gaps and that captures post-construction effects was also raised by 5 interviewees (e.g. "(...) monitoring measures need to be put in place to capture this and address existing knowledge and data gaps, such as issues around community recoverability" or "What is particularly struggling, in my opinion, is biodiversity information, especially data on species distribution and the monitoring of these aspects"). Both baseline data collection and monitoring need to consider both **resolution** and **scalability** according to 2 and one interviewee respectively. One succinctly captured the associated implications: "What is also really relevant here is the scalability of this approach. You may have datasets collected over time for a specific offshore wind energy area or infrastructure, but if the objective is to support a marine spatial plan, then this information would also need to come from multiple sites. To create monitoring that is scalable and relevant for planning purposes, different offshore wind energy sites would need to aggregate their data. This creates a number of challenges related to data transparency, the involvement of different operators, and, in transboundary areas, the cross-border nature of data collection and data assimilation.”

C7. Co-location conflict perceptions

The survey asked participants to select the primary co-location conflict (with aquaculture, fisheries, shipping, tourism, mineral extraction and oil/gas extraction as well as ‘other’ as options). Commercial fisheries stand out as the primary source of conflict in the marine environment, with 80% (12 out of 15) of respondents ranking it as the most significant challenge; mineral extraction was prioritised by a respondent, and no other sectoral conflicts were identified.

C8. Effects on onshore assets

The survey gathered opinions on the main cumulative effects of offshore wind developments on onshore assets. Infrastructure, such as ports, harbours, and vessels, were seen as most affected onshore (80% or 12 of 15 responses). In addition, 40% responses equally highlighted coastal community income (e.g. employment and skillset) and well-being (visual impact). The ‘other’ responses brought a sharper focus to environmental effects: respondents pointed out that onshore affected assets include biodiversity features such as cliffs and beaches when accommodating grid infrastructure, as well as the potential for severe effects on migrating bird populations.

C9. Energy goals vs biodiversity targets

The last survey question aimed to canvas expert opinion on the prioritisation of (renewable) energy goals and biodiversity conservation targets. A clear majority of 67% (10 of 15) favoured the conservation status of affected species (e.g. IUCN Red List), while 33% prioritised the supply and demand elasticity of energy. Notably, none of the respondents selected public opinion/social acceptance as their primary criterion. Despite this lean toward conservation, two respondents selected ‘other’: one elaborated on the desire for the prioritisation of actions that deliver synergistic/multiple benefits simultaneously, while another argued that while energy security is key, installations must strictly enforce biodiversity compensation and conservation actions as much as possible.

Funded by
the European Union

References

Ajmi S., Boutet M., Bennis A.C., Dauvin J.C. (2025). Impacts of offshore wind farms in the English Channel on larval dispersal and connectivity of benthic species using numerical modeling. *Ocean Dynamics*, *75*(3): 22. https://doi.org/10.1007/s10236-025-01665-8

Ansong J.O., Heather R., McElduff L. (2022). Institutional barriers to integrated marine spatial planning on the island of Ireland. *Marine Policy*, 141: 105082. https://doi.org/10.1016/j.marpol.2022.105082

Azzellino A., Lanfredi C., Riefolo L., De Santis V., Contestabile P., Vicinanza D. (2019). Combined exploitation of offshore wind and wave energy in the Italian seas: A spatial planning approach. *Frontiers in Energy Research*, 7:1–15. https://doi.org/10.3389/fenrg.2019.00042

Baig Y., Ahmed S. (2025). A multi-criteria decision framework for optimized offshore wind energy site selection: a case study from the Gulf of Mannar. *Sadhana - Academy Proceedings in Engineering Sciences*, 50(4). https://doi.org/10.1007/s12046-025-02941-5

Bailey H., Brookes K. L., Thompson P. M. (2014). Assessing environmental impacts of offshore wind farms : lessons learned and recommendations for the future. *Aquatic Biosystems*, 10(8): 1–13. https://doi.org/10.1186/2046-9063-10-8

Bailey H., Senior B., Simmons D., Rusin J., Picken G., Thompson P.M. (2010). Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin*, 60(6): 888–897. https://doi.org/10.1016/j.marpolbul.2010.01.003

Benhemma-Le Gall A., Graham I.M., Merchant N.D., Thompson P.M. (2021). Broad-scale responses of Harbor Porpoises to pile-driving and vessel activities during offshore windfarm construction. *Frontiers in Marine Science*, 8: 1–18. https://doi.org/10.3389/fmars.2021.664724

Benhemma-Le Gall A., Thompson P., Merchant N., Graham I. (2023). Vessel noise prior to pile driving at offshore windfarm sites deters harbour porpoises from potential injury zones. *Environmental Impact Assessment Review*, 103: 107271. https://doi.org/10.1016/j.eiar.2023.107271

Bergström L., Kautsky L., Malm T., Rosenberg R., Wahlberg M., Åstrand Capetillo N., Wilhelmsson D. (2014). Effects of offshore wind farms on marine wildlife - a generalized impact assessment. *Environmental Research Letters*, 9(3): 034012. https://doi.org/10.1088/1748-9326/9/3/034012

Berkenhagen J., Döring R., Fock H.O., Kloppmann M.H.F., Pedersen S.A., Schulze T. (2010). Decision bias in marine spatial planning of offshore wind farms: Problems of singular versus cumulative assessments of economic impacts on fisheries. *Marine Policy*, 34(3): 733–736. https://doi.org/10.1016/j.marpol.2009.12.004

Bisinicu E., Abaza V., Boicenco L., Adrian F., Harcota G., Marin O., Oros A., Pantea E., Spinu A., Timofte F., Tiganov G., Vlas O., Lazar L. (2024). Spatial cumulative assessment of impact risk-implementing ecosystem-based management for enhanced sustainability and biodiversity in the Black Sea. *Sustainability*, 16(11): 4449. https://doi.org/10.3390/su16114449

Blakley J.A.E. (2021). Introduction: foundations, issues and contemporary challenges in cumulative impact assessment. In: Blakley J.A.E., Franks D.M., editors. *Handbook of Cumulative Impact Assessment*. Cheltenham, UK: Edward Elgar Publishing Ltd; p. 2–20.

Borja A., Elliott M., Teixeira H., Stelzenmüller V., Katsanevakis S., Coll M., Galparsoro I., Fraschetti S., Papadopoulou N., Lynam C., Berg T., Andersen J., Carstensen J., Leal M., Uyarra M. (2024). Addressing the cumulative impacts of multiple human pressures in marine systems, for the sustainable use of the seas. *Frontiers in Ocean Sustainability*, 1:1308125. https://doi.org/10.3389/focsu.2023.1308125.

Brabant R., Vanermen N., Stienen E. W. M., Degraer S. (2015). Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms. *Hydrobiologia*, 756(1): 63–74. https://doi.org/10.1007/s10750-015-2224-2

Bragagnolo C., Geneletti D., Fischer T.B. (2012). Cumulative effects in SEA of spatial plans – evidence from Italy and England. *Impact Assessment and Project Appraisal*, 30(2):100-110. https://doi.org/10.1080/14615517.2012.677522.

Brignon J., Lejart M., Nexer M., Michel S., Quentric A., Thiebaud L. (2022). A risk-based method to prioritize cumulative impacts assessment on marine biodiversity and research policy for offshore wind farms in France. *Environmental Science & Policy*, 128: 264–276. https://doi.org/10.1016/j.envsci.2021.12.003

Broadbent I.D., Nixon C.L.B. (2019). Refusal of planning consent for the Docking Shoal offshore wind farm: Stakeholder perspectives and lessons learned. *Marine Policy*, 110: 103529. https://doi.org/10.1016/j.marpol.2019.103529

Conesa V. (2010). Conesa Method for the Evaluation of Environmental Impact. Universidad the La Salle. URL: https://www.scribd.com/document/960917529/CONESA-method-for-impact-assessment-pdf#:~:text=The%20document%20outlines%20the%20Conesa,comprehensive%20framework%20for%20environmental%20evaluation

Critchley E. J., Nilsson A., Helberg M., May R. (2025). Life-cycle impact assessment of offshore wind energy development on migrating bird diversity in the North Sea. *Journal of Applied Ecology*, 62(7): 1597–1610. https://doi.org/10.1111/1365-2664.70087

Croll D.A., Ellis A.A., Adams J., Cook A.S.C.P., Garthe S., Goodale M.W., Hall C.S., Hazen E., Keitt B.S., Kelsey E.C., Leirness J.B., Lyons D.E., McKown M.W., Potiek A., Searle K.R., Soudijn F. H., Rockwood R.C., Tershy B.R., Tinker M., Zilliacus K. (2022). Framework for assessing and mitigating the impacts of offshore wind energy development on marine birds. *Biological Conservation*, 276: 109795. https://doi.org/10.1016/j.biocon.2022.109795

Dähne M., Gilles K., Lucke V., Peschko S., Adler K., Krugel J. (2013). Effects of piledriving on harbour porpoises (Phocoena phocoena) at the first offshore wind farm in Germany. *Environmental Research Letters,* 8(2): 025002. https://doi.org/10.1088/1748-9326/8/2/025002

Dannheim J., Kloss P., Vanaverbeke J., Mavraki N., Zupan M., Spielmann V., Degraer S., Birchenough S.N.R., Janas U., Sheehan E., Teschke K., Gill A.B., Hutchison Z., Carey D.A., Rasser M., Buyse J., van der Weide B., Bittner O., Causon P., Coolen J.W.P. (2025). Biodiversity information of benthic species at artificial structures – BISAR. *Scientific Data*, 12(1): 604. https://doi.org/10.1038/s41597-025-04920-1

De Luca Peña L.V., Dewulf J., Staes J., Moulaert I., Vandamme S., Heymans J.J., Taelman S.E. (2024). Assessing the sustainability of Blue Economy activities using an ecosystem and life cycle-based approach: Possibilities, challenges and implications for an informed policy making. *Ocean & Coastal Management*, 257: 107360. https://doi.org/10.1016/j.ocecoaman.2024.107360

Declerck M., Trifonova N., Black J., Hartley J., Scott B.E. (2022). A new strategic framework to structure cumulative impact assessment (CIA). *International Marine Energy Journal*, 5(3): 339-347. https://doi.org/10.36688/imej.5.339-347

Depellegrin D. (2016). Assessing cumulative visual impacts in coastal areas of the Baltic Sea. *Ocean & Coastal Management*, 119: 184–198. https://doi.org/10.1016/j.ocecoaman.2015.10.012

Depellegrin D., Menegon S., Abramic A., Aguado Hernandez S., Larosa F., Salvador S., Marti Llambrich C. (2024). Addressing ocean planning challenges in a highly crowded sea space: a case study for the regional sea of Catalonia (Western Mediterranean). *Open Research Europe*, 4:46. https://doi.org/10.12688/openreseurope.16836.1

Díaz H., Guedes Soares C. (2020). An integrated GIS approach for site selection of floating offshore wind farms in the Atlantic continental European coastline. *Renewable and Sustainable Energy Reviews*, 134: 110328. https://doi.org/10.1016/j.rser.2020.110328

Dibo A.P.A., Siqueira-Gay J., Duarte C.G., Turra A., Sánchez L.E. (2025). Guiding elements for strengthening cumulative impact assessment regulations for offshore wind energy. *Environmental Management*, 75(11): 3025–3043. https://doi.org/10.1007/s00267-025-02282-3

Drewitt A. L., Langston R. H. W. (2006). Assessing the impact of wind farms on birds. *Ibis*, 148: 29-42. https://doi.org/10.1111/j.1474-919X.2006.00516.x

Duinker P.N., Burbidge E.L., Boardley S.R., Greig L.A. (2013). Scientific dimensions of cumulative effects assessment: Toward improvements in guidance for practice. *Environmental Reviews*, 21(1):40-52. https://doi.org/10.1139/er-2012-0035

Durning B., Broderick M. (2019). Development of cumulative impact assessment guidelines for offshore wind farms and evaluation of use in project making. *Impact Assessment and Project Appraisal*, 37(2): 124–138. https://doi.org/10.1080/14615517.2018.1498186

EC (1992). Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.). European Commission. *Official Journal of the European Union*, No L 206/7, 22.7.92.

EC (2001). Directive 2001/42/EC of the European Parliament and of the council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment. European Commission. *Official Journal of the European Union*, L 197, pp. 30-37, 21.7.2001.

EC (2008). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). European Commission. *Official Journal of the European Union*, L 164, pp. 19-40, 25.6.2008.

EU (2014a). Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. European Union. *Official Journal of the European Union*, L 124, pp. 1-18, 25.4.2014.

EU (2014b). Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning. European Union. *Official Journal of the European Union*, L 257, pp. 135-145, 28.8.2014.

EU (2019). The European Green Deal. European Commission. URL: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Ferguson M.C., Williams K.A., Goodale M.W., Adams E.M., Knaga P., Kingdon K., Avery-Gomm S. (2025). A flexible framework for species-based regional cumulative effects assessments to support offshore wind energy planning and management. *Environmental Impact Assessment Review*, 114: 107912. https://doi.org/10.1016/j.eiar.2025.107912

Fox A.D., Petersen I.K. (2019). Offshore wind farms and their effects on birds. *Dansk Ornitologisk Forenings Tidsskrift*, 113(3): 86-101. https://pub.dof.dk/publikationer/144

Gil-García I. C., Ramos-Escudero A., García-Cascales M. S., Dagher H., Molina-García A. (2022). Fuzzy GIS-based MCDM solution for the optimal offshore wind site selection: The Gulf of Maine case. *Renewable Energy*, 183: 130–147. https://doi.org/10.1016/j.renene.2021.10.058

Glasson J., Durning B., Welch K., Olorundami T. (2022). The local socio-economic impacts of offshore wind farms. *Environmental Impact Assessment Review*, 95: 106783. https://doi.org/10.1016/j.eiar.2022.106783

Goddijn-Murphy L. (2026). 10 things to consider before approving another offshore wind farm: A case study for Highland, Scotland. *Ocean and Coastal Management*, 271: 107956. https://doi.org/10.1016/j.ocecoaman.2025.107956

Goodale M.W., Milman A. (2016). Cumulative adverse effects of offshore wind energy development on wildlife. *Journal of Environmental Planning and Management*, 59(1): 1–21. https://doi.org/10.1080/09640568.2014.973483

Goodale M.W., Milman A. (2019). Assessing the cumulative exposure of wildlife to offshore wind energy development. *Journal of Environmental Management*, 235: 77–83. https://doi.org/10.1016/j.jenvman.2019.01.022

Goodale M.W., Milman A. (2020). Assessing cumulative exposure of Northern Gannets to offshore wind farms. *Wildlife Society Bulletin*, 44(2): 252–259. https://doi.org/10.1002/wsb.1087

Green R.E., Gill E., Hein C., Couturier L., Mascarenhas M., May R., Newell D., Rumes B. (2022). International assessment of priority environmental issues for land-based and offshore wind energy development. *Global Sustainability*, 5: e17. https://doi.org/10.1017/sus.2022.14

Gunn J., Noble B.F. (2011). Conceptual and methodological challenges to integrating SEA and cumulative effects assessment. Environmental Impact Assessment Review, 31(2):154-160. https://doi.org/10.1016/j.eiar.2009.12.003

Guşatu L.F., Zuidema C., Faaij A. (2022). A multi-criteria analysis framework for conflict resolution in the case of offshore wind farm sitting: A study of England and the Netherlands offshore space. *Frontiers in Marine Science*, 9: 1–29. https://doi.org/10.3389/fmars.2022.959375

Hague E.L., Sparling C.E., Morris C., Vaughan D., Walker R., Culloch R.M., Lyndon A.R., Fernandes T. F., McWhinnie L. H. (2022). Same Space, Different Standards: A Review of Cumulative Effects Assessment Practice for Marine Mammals. *Frontiers in Marine Science*, 9: 1–18. https://doi.org/10.3389/fmars.2022.822467

Halpern B.S., Walbridge S., Selkoe K.A., Kappel C.V., Micheli F., D'Agrosa C., Bruno J.F., Casey K.S., Ebert C., Fox H.E., Fujita R., Heinemann D., Lenihan H.S., Madin E.M.P., Perry M.T., Selig E.R., Spalding M., Steneck R., Watson R. (2008). A global map of human impact on marine ecosystems. *Science*, 319:5865. https://doi.org/10.1126/science.1149345

Hammar L., Molander S., Palsson J., Schmidtbauer Crona J., Carneiro G., Johansson T., Hume D., Kagesten G., Mattsson D., Tornqvist O., Zillen L., Mattsson M., Bergstrom U., Perry D., Caldow C., Andersen J.H. (2020). Cumulative impact assessment for ecosystem-based marine spatial planning. *Science of the Total Environment*, 734:139024. https://doi.org/10.1016/j.scitotenv.2020.139024

Hansen H. S. (2005). GIS-based multi-criteria analysis of wind farm development. in Hauska, H. and Tveite, H. (eds.) *ScanGIS 2005: Proceedings of the 10th Scandinavian Research*

Conference on Geographical Information Science. Department of Planning and Environment, pp. 75-87. http://www.scangis.org/scangis2005/papers/

Harvey N., Dew R.E.C. (2016). Coastal impact of onshore wind farms in Australia. *Journal of Coastal Research*, 75(1): 992–996. https://doi.org/10.2112/SI75-199.1

Heery E.C., Bishop M.J., Critchley L.P., Bugnot A.B., Airoldi L., Mayer-Pinto M., Sheehan E.V., Coleman R.A., Loke L.H.L., Johnston E.L., Komyakova V., Morris R.L., Strain E.M.A., Naylor L.A., Dafforn K.A. (2017). Identifying the consequences of ocean sprawl for sedimentary habitats. *Journal of Experimental Marine Biology and Ecology*, 492: 31–48. https://doi.org/10.1016/j.jembe.2017.01.020

Heinänen S., Žydelis R., Kleinschmidt B., Dorsch M., Burger C., Morkūnas J., Quillfeldt P., Nehls G. (2020). Satellite telemetry and digital aerial surveys show strong displacement of red-throated divers (Gavia stellata) from offshore wind farms. *Marine Environmental Research*, 160: 104989. https://doi.org/10.1016/j.marenvres.2020.104989

Hooker J., Lintott P., Boughey K., Worledge L., Park K., Collins J. (2025). Impacts of offshore wind farms on migratory bats in British waters. *Global Ecology and Conservation*, 63: e03911. https://doi.org/10.1016/j.gecco.2025.e03911

Huang Y., Girardin R., Oliveros-Ramos R., Travers-Trolet M., Quennevat A., Safi G., Ben Rais Lasram F., Halouani G. (2025). An ecosystem modelling approach to assess potential impacts of offshore wind farms. *ICES Journal of Marine Science*, 82(9). https://doi.org/10.1093/icesjms/fsaf153

IAIA (2017). Cumulative Effects Assessment FasTips. International Association for Impact assessment. URL: https://iaia.org/fastips-cumulative-effects-assessment/

Isaksson N., Scott B.E., Hunt G.L., Benninghaus E., Declerck M., Gormley K., Harris C., Sjöstrand S., Trifonova N.I., Waggitt J.J., Wihsgott J.U., Williams C., Zampollo A., Williamson B.J. (2025). A paradigm for understanding whole ecosystem effects of offshore wind farms in shelf seas. *ICES Journal of Marine Science*, 82(3). https://doi.org/10.1093/icesjms/fsad194

Jhan H.T., Lee H.T., Ting K.H. (2022). The potential compatibility of designating offshore wind farms within wider Marine Protected Areas—Conservation of the Chinese White Dolphin regarding fishers' perception. *Fishes*, 7(4). https://doi.org/10.3390/fishes7040195

Joseph C., Gunton T.I., Hoffele J., Baldwin M. (2023). Improving cumulative effects assessment: Alternative approaches based upon an expert survey and literature review. *Impact Assessment and Project Appraisal*, 41(2):162-174. https://doi-org.ucd.idm.oclc.org/10.1080/14615517.2023.2170093

Kannen A. (2014). Challenges for marine spatial planning in the context of multiple sea uses, policy arenas and actors based on experiences from the German North Sea. *Regional Environmental Change*, 14(6): 2139–2150. https://doi.org/10.1007/s10113-012-0349-7

King S.L., Schick R.S., Donovan C., Booth C.G., Burgman M., Thomas L., Harwood J. (2015). An interim framework for assessing the population consequences of disturbance. *Methods in Ecology and Evolution*, 6(10): 1150–1158. https://doi.org/10.1111/2041-210X.12411

Krabbe N., Argüello G. (2025). Reconciling marine conservation with offshore wind parks. *Ocean Development and International Law*, 56(4): 570–594. https://doi.org/10.1080/00908320.2025.2591683

Krone R., Gutow L., Joschko T.J., Schroder A. (2013). Epifauna dynamics at an offshore foundation-Implications of future wind power farming in the North Sea. *Marine environmental research,* 85: 1–12. https://doi.org/10.1016/j.marenvres.2012.12.004

Li C., Coolen J.W.P., Scherer L., Mogollón J.M., Braeckman U., Vanaverbeke J., Tukker A., Steubing B. (2023). Offshore wind energy and marine biodiversity in the North Sea: Life cycle impact assessment for benthic communities. *Environmental Science & Technology*, 57(16): 6455–6464. https://doi.org/10.1021/acs.est.2c07797

Lindeboom H., Degraer S., Dannheim J., Gill A. B., Wilhelmsson D. (2015). Offshore wind park monitoring programmes, lessons learned and recommendations for the future. *Hydrobiologia*, 756(1): 169–180. https://doi.org/10.1007/s10750-015-2267-4

Masden E.A., Haydon D.T., Fox A.D., Furness R.W., Bullman R., Desholm M. (2009). Barriers to movement: Impacts of wind farms on migrating birds. *ICES Journal of Marine Science*, 66(4): 746–753. https://doi.org/10.1093/icesjms/fsp031

Morejón V., González Del Campo A. (2026). Toward ecosystem-based strategic environmental assessments for marine spatial planning: Enhancing cumulative effects assessments with a four-dimensional marine baseline. *Science of the Total Environment*, 1022: 181611. https://doi.org/10.1016/j.scitotenv.2026.181611

Muñoz M., Reul A., Gil de Sola L., Lauerburg R. A. M., Tello O., Gimpel A., Stelzenmüller V. (2018). A spatial risk approach towards integrated marine spatial planning: A case study on European hake nursery areas in the North Alboran Sea. *Marine Environmental Research*, 142: 190–207. https://doi.org/10.1016/j.marenvres.2018.10.008

NatureScot (2021). Assessing the Cumulative Landscape and Visual Impact of Onshore Wind Energy Developments. Scotland's Nature Agency. URL; https://www.nature.scot/doc/guidance-assessing-cumulative-landscape-and-visual-impact-onshore-wind-energy-developments

NatureScot (2025). Assessing the Cumulative Impacts of Onshore Wind Farms on Birds. Scotland's Nature Agency. URL: https://www.nature.scot/doc/guidance-assessing-cumulative-impacts-onshore-wind-farms-birds

NERC (2013). Cumulative Impact Assessment Guidelines - Guiding Principles for Cumulative Impacts Assessment In Offshore Wind Farms. Natural Environmental Research Council. URL:

https://tethys.pnnl.gov/sites/default/files/publications/Cumulative-Impact-Assessment-Guidelines.pdf

Nguyen K.D., Guillou S., Gourbesville P., Thiebot J. (2020). In Nguyen K.D., Guillou S., Gourbesville P., Thiebot J. (eds.) *Estuaries and Coastal Zones in times of Global Change*. Singapore: Springer Water, pp. 831–843. https://doi:10.1007/978-981-15-2081-5_48

Nie X., Ma H., Chen S., Li K., Yu Z., Wang H., Wei Z. (2024). Offshore wind farms and tourism development relationship to energy distribution justice for the Beibu Gulf, China. *Land*, 13(5): 1-23. https://doi.org/10.3390/land13050678

Noble B., Liu J., Hackett P. (2017). The contribution of project environmental assessment to assessing and managing cumulative effects: Individually and collectively insignificant? *Environmental Management,* 59: 531-545. https://doi.org/10.1007/s00267-016-0799-7

Nogues Q., Baulaz Y., Clavel J., Araignous E., Bourdaud P., Ben Rais Lasram F., Dauvin J., Girardin V., Halouani G., Le Loc'h F., Loew-Turbout F., Raoux A., Niquil N. (2023). The usefulness of food web models in the ecosystem services framework: Quantifying, mapping, and linking services supply. *Ecosystem Services*, 63: 101550. https://doi.org/10.1016/j.ecoser.2023.101550

Nogues Q., Bourdaud P., Araignous E., Halouani G., Ben Rais Lasram F., Dauvin J., Le Loc'h F., Niquil N. (2023). An ecosystem-wide approach for assessing the spatialized cumulative effects of local and global changes on coastal ecosystem functioning. *ICES Journal of Marine Science*, 80(4): 1129–1142. https://doi.org/10.1093/icesjms/fsad043

Nogues Q., Raoux A., Araignous E., Chaalali A., Hattab T., Leroy B., Ben Rais Lasram F., David V., Le Loc'h F., Dauvin J., Niquil N. (2021). Cumulative effects of marine renewable energy and climate change on ecosystem properties: Sensitivity of ecological network analysis. *Ecological Indicators*, 121: 107128. https://doi.org/10.1016/j.ecolind.2020.107128

Noorollahi Y., Yousefi H., Mohammadi M. (2016). Multi-criteria decision support system for wind farm site selection using GIS. *Sustainable Energy Technologies and Assessments*, 13: 38–50. https://doi.org/10.1016/j.seta.2015.11.007

Peschko V., Schwemmer H., Mercker M., Markones N., Borkenhagen K., Garthe S. (2024). Cumulative effects of offshore wind farms on common guillemots (Uria aalge) in the southern North Sea - climate versus biodiversity?, *Biodiversity and Conservation*, 33(3): 949–970. https://doi.org/10.1007/s10531-023-02759-9

Peters J.L., Remmers T., Wheeler A. J., Murphy J., Cummins V. (2020). A systematic review and meta-analysis of GIS use to reveal trends in offshore wind energy research and offer insights on best practices. *Renewable and Sustainable Energy Reviews*, 128: 109916. https://doi.org/10.1016/j.rser.2020.109916

Pezy J. P., Raoux A., Marmin S., Balay P., Niquil N., Dauvin J. C. (2017). Before-after analysis of the trophic network of an experimental dumping site in the eastern part of the Bay of Seine

(English Channel). *Marine Pollution Bulletin*, 118(1–2): 101–111. https://doi.org/10.1016/j.marpolbul.2017.02.042

Piet G., Grundlehner A., Jongbloed R., Tamis J., De Vries P. (2023). SCAIRM: A spatial cumulative assessment of impact risk for management. *Ecological Indicators*, 157: 111157. https://doi.org/10.1016/j.ecolind.2023.111157

Pine M.K., Jeffs A.G., Radford C.A. (2014). The cumulative effect on sound levels from multiple underwater anthropogenic sound sources in shallow coastal waters. *Journal of Applied Ecology*, 51(1): 23–30. https://doi.org/10.1111/1365-2664.12196

Pinkau, A., Schiele, K.S. (2021). Strategic environmental assessment in marine spatial planning of the North Sea and the Baltic Sea – an implementation tool for an ecosystem-based approach? *Marine Policy*, 130:104547. https://doi.org/10.1016/j.marpol.2021.104547

Popper A.N., Hice-Dunton L., Jenkins E., Higgs D.M., Krebs J., Mooney A., Rice A., Roberts L., Thomsen F., Vigness-Raposa K., Zeddies D., Williams K.A. (2022). Offshore wind energy development: Research priorities for sound and vibration effects on fishes and aquatic invertebrates. *The Journal of the Acoustical Society of America*, 151(1): 205–215. https://doi.org/10.1121/10.0009237

Raoux A., Tecchio S., Pezy J.P., Lassalle G., Degraer S., Wilhelmsson D., Cachera M., Ernande B., Le Guen C., Haraldsson M., Grangeré K., Le Loc'h F., Dauvin J.C., Niquil N. (2017). Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning? *Ecological Indicators*, 72: 33–46. https://doi.org/10.1016/j.ecolind.2016.07.037

Rees E.C. (2012). Impacts of wind farms on swans and geese: a review. *Wildfowl*, 62: 37–72. Retrieved from https://tidsskrift.dk/Wildfowl/article/view/153571

Rehren J., Kruse M., Probst W.N., Gordó-Vilaseca C., Lemmen C., Krishna S., Stelzenmüller V. (2025). Future cumulative effects on demersal fish in a transforming North Sea pressure landscape. *Journal of Environmental Management*, 392: 126727. https://doi.org/10.1016/j.jenvman.2025.126727

Reubens J.T., De Rijcke M., Degraer S., Vincx M. (2014). Diel variation in feeding and movement patterns of juvenile Atlantic cod at offshore wind farms. *Journal of Sea Research*, 85: 214–221. https://doi.org/10.1016/j.seares.2013.05.005

Rezaei F., Contestabile P., Vicinanza D., Azzellino A. (2023). Towards understanding environmental and cumulative impacts of floating wind farms: Lessons learned from the fixed-bottom offshore wind farms. *Ocean & Coastal Management*, 243: 106772. https://doi.org/10.1016/j.ocecoaman.2023.106772

Roach M., Cohen M., Forster R., Revill A.S., Johnson M. (2018). The effects of temporary exclusion of activity due to wind farm construction on a lobster (Homarus gammarus) fishery suggests a potential management approach. *ICES Journal of Marine Science*, 75(4): 1416–1426. https://doi.org/10.1093/icesjms/fsy006

Rodríguez M., Muñoz A.R., Arroyo G.M. (2012). Assessment of offshore wind farm effects on birds and needs to plan their future development in Spain. *Ardeola*, 59(2): 217–236. https://doi.org/10.13157/arla.59.2.2012.217

Sahoo S.K., Pamucar D., Goswami S.S. (2025). A review of multi-criteria decision-making (MCDM) applications to solve energy management problems from 2010-2025: Current state and future research. *Spectrum of Decision Making and Applications*, 2(1): 219–241. https://doi.org/10.31181/sdmap21202525

Sarnocińska J., Teilmann J., Balle J.D., van Beest F.M., Delefosse M., Tougaard J. (2020). Harbor Porpoise (Phocoena phocoena) reaction to a 3D seismic airgun survey in the North Sea. *Frontiers in Marine Science*, 6: 1–10. https://doi.org/10.3389/fmars.2019.00824

Schröder A., Orejas C., Joschko T. (2006). Benthos in the vicinity of piles: FINO 1 (North Sea). In: Köller J., Köppel J., Peters W. (eds) *Offshore Wind Energy*. Springer, Berlin, Heidelberg . https://doi.org/10.1007/978-3-540-34677-7_12

Serpetti N., Benjamins S., Brain S., Collu M., Harvey B.J., Heymans J.J., Hughes A.D., Risch D., Rosinski S., Waggitt J.J., Wilson B. (2021). Modeling small scale impacts of multi-purpose platforms: An ecosystem approach. *Frontiers in Marine Science*, 8: 694013. https://doi.org/10.3389/fmars.2021.694013

Siddagangaiah S., Chen C.F., Hu W.C., Pieretti N. (2022). Impact of pile-driving and offshore windfarm operational noise on fish chorusing. *Remote Sensing in Ecology and Conservation*, 8(1): 119–134. https://doi.org/10.1002/rse2.231

Sinclair K., Copping A.E., May R., Bennet F., Warnas M., Perron M., Elmqvist Å., DeGeorge E. (2018). Resolving environmental effects of wind energy. *WIREs Energy and Environment*, 7(4): 1–10. https://doi.org/10.1002/wene.291

Stelzenmüller V., Cormier R., Gee K., Shucksmith R., Gubbins M., Yates K.L., Morf A., Nic Aonghusa C., Mikkelsen E., Tweddle J.F., Peccu E., Kannen A., Clarke S.A. (2021). Evaluation of marine spatial planning requires fit for purpose monitoring strategies. *Journal of Environmental Management*, 278 (P2): 111545. https://doi.org/10.1016/j.jenvman.2020.111545

Stelzenmüller V., Gimpel A., Haslob H., Letschert J., Berkenhagen J., Brüning S. (2021). Sustainable co-location solutions for offshore wind farms and fisheries need to account for socio-ecological trade-offs. *Science of the Total Environment*, 776: 145918. https://doi.org/10.1016/j.scitotenv.2021.145918

Stelzenmüller V., Letschert J., Gimpel A., Kraan C., Probst W.N., Degraer S., Döring R. (2022). From plate to plug: The impact of offshore renewables on European fisheries and the role of marine spatial planning. *Renewable and Sustainable Energy Reviews*, 158: 112108. https://doi.org/10.1016/j.rser.2022.112108

Stephenson R.L., Hobday A.J. (2024). Blueprint for blue economy implementation. *Marine Policy*, 163: 106129. https://doi.org/10.1016/j.marpol.2024.106129

Szostek C.L., Watson S.C.L., Trifonova N., Beaumont N.J., Scott B.E. (2025). Spatial conflict in offshore wind farms: Challenges and solutions for the commercial fishing industry. *Energy Policy*, 200: 114555. https://doi.org/10.1016/j.enpol.2025.114555

Trifonova N., Scott B.E., Watson S.C.L., Szostek C., Declerck M., Beaumont N. (2025). Fishing, offshore wind energy, climate change and marine spatial planning: Is it possible to plan for a best use of space? *Ecological Solutions and Evidence*, 6(2): 1–8. https://doi.org/10.1002/2688-8319.70039

Turrell W.R. (2026). How strategic ecosystem monitoring and assessments are relevant to the management of a marine industry: Offshore wind electricity generation. *Marine Policy*, 183: 106890. https://doi.org/10.1016/j.marpol.2025.106890

UK Government (2015). Advice Note 17 Cumulative Effects Assessment relevant to Nationally Significant Infrastructure Projects. Planning Inspectorate, UK Government. Withdrawn and superseded by UK Government (2024). URL: https://www.thenbs.com/PublicationIndex/documents/details?Pub=PINS&DocId=327615

UK Government (2024). National Significant Infrastructure Projects – Advice on Cumulative Effects Assessment. Planning Inspectorate, UK Government. URL: https://www.gov.uk/guidance/nationally-significant-infrastructure-projects-advice-on-cumulative-effects-assessment

UN (2015). Paris Agreement. United Nations. URL: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

van der Molen J., Smith H., Lepper P., Limpenny S., Rees J. (2014). Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem. *Continental Shelf Research*, 85: 60-72. https://doi.org/10.1016/j.csr.2014.05.018

Vasileiou M., Loukogeorgaki E., Vagiona D.G. (2017). GIS-based multi-criteria decision analysis for site selection of hybrid offshore wind and wave energy systems in Greece. *Renewable and Sustainable Energy Reviews*, 73: 745–757. https://doi.org/10.1016/j.rser.2017.01.161

Walsh C., Hüppop O., Karwinkel T., Liedvogel M., Lindecke O., McLaren J. D., Schmaljohann H., Siebenhüner B. (2025). Marine artificial light at night: Implications and potential hazards for offshore songbird and bat movements in the Greater North Sea. *Conservation Science and Practice*, 7(3): 1–10. https://doi.org/10.1111/csp2.70008

Warlick A.J., Liu O.R., Layton J., Harvey C.J., Samhouri J.F., Hazen E.L., Andrews K.S. (2025). A framework to evaluate dynamic social and ecological interactions between offshore wind energy development and commercial fisheries in a changing climate: A US West Coast perspective. *PLOS Climate*, 4(5): e0000526. https://doi.org/10.1371/journal.pclm.0000526

Welcker J., Nehls G. (2016). Displacement of seabirds by an offshore wind farm in the North Sea. *Marine Ecology Progress Series*, 554: 173–182. https://doi.org/10.3354/meps11812

Williams K.A., Popper A.N., Hice-Dunton L., Higgs D.M., Jenkins E., Krebs J.M., Mooney T.A., Rice A.N., Roberts L., Thomsen F., Vigness-Raposa K.J., Zeddies D.G. (2024). Sound-related effects of offshore wind energy on fishes and aquatic invertebrates: Research recommendations. In A. N. Popper, J. A. Sisneros, A. D. Hawkins, F. Thomsen (Eds.), *The Effects of Noise on Aquatic Life* (pp. 1617–1634). Springer International Publishing. https://doi.org/10.1007/978-3-031-50256-9_164

Willsteed E.A., Jude S., Gill A.B., Birchenough S.N.R. (2018). Obligations and aspirations: A critical evaluation of offshore wind farm cumulative impact assessments. *Renewable and Sustainable Energy Reviews*, 82: 2332–2345. https://doi.org/10.1016/j.rser.2017.08.079

Wright A.J., Araújo-Wang C., Wang J.Y., Ross P.S., Tougaard J., Winkler R., Márquez M.C., Robertson F.C., Williams K.F., Reeves R.R. (2020). How 'blue' Is 'green' energy? *Trends in Ecology & Evolution*, 35(3): 235–244. https://doi.org/10.1016/j.tree.2019.11.002

SUSTAINOW

sustainow.eu

Funded by
the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.