Cumulative Effect Assessments (CEAs) - Review of methods

Environmental mapping and screening of areas for offshore wind in Denmark

Danish Energy Agency

Date: 15. January 2026

Preface

This report contributes to the project "*Environmental mapping and screening of areas for offshore wind in Denmark*" initiated in 2022 by the Danish Energy Agency. The project aims to support the long-term planning of offshore wind farms by providing a comprehensive overview of the combined offshore wind potential in Denmark. It is funded under the Finance Act 2022 through the program "Investeringer i et fortsat grønnere Danmark" (Investing in the continuing greening of Denmark). The project is carried out by NIRAS, Aarhus University (Department of Ecoscience), and DTU Wind.

The overall project consists of four tasks defined by the Danish Energy Agency (https://ens.dk/energikilder/planlaegning-af-fremtidens-havvindmoelleparker):

1. Sensitivity mapping of nature, environmental, wind and hydrodynamic conditions.
2. Technical fine-screening of areas for offshore wind based on the sensitivity mapping and relevant technical parameters.
3. Assessment of potential cumulative effects from large-scale offshore wind development in Denmark and neighbouring countries.
4. Assessment of barriers and potentials in relation to coexistence.

This report addresses task no. 3 concerning cumulative effects of offshore wind development and presents a review of methodologies and best practice when it comes to performing cumulative effect assessments (CEAs).

By compiling and evaluating current methodologies for cumulative effect assessments, this report aims to contribute to a more informed and structured approach to future CEA efforts concerning offshore wind development. While challenges remain in establishing universally accepted best practices as well as tools and frameworks which cover all relevant aspects, this work provides a foundation for continued development and dialogue and will help navigating the complexities of large-scale offshore wind development and its environmental implications.

Table of contents

List of abbreviations

Abbreviations	Description
BSII CAT	Baltic Sea Impact Index Cumulative Impact Assessment Toolbox
CEA	Cumulative Effects Assessment (corresponds to CIA)
CEAF	Common Environmental Assessment Framework
CHASE	Chemical Status Assessment Tool
CIA	Cumulative Impact Assessment (corresponds to CEA)
CI-Index	Cumulative Impact Index
CIM	Cumulative Impact Mapping
DAPSIR	Drivers-Activities-Pressures-State-Impacts-Responses
EBM	Ecosystem-based Management
EIA	Environmental Impact Assessment
EU	European Union
GES	Good Environmental Status
HELCOM	Helsinki Commission (Baltic Marine Environment Protection Commission)
HOLAS	HELCOM Holistic Assessment
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
KEC	Framework for Assessing Ecological and Cumulative Effects
MARCIS	Marine Spatial Planning and Cumulative Impacts on Seabirds
MCDA	Multicriteria Decision Analysis
MSP	Marine Spatial Plan
MSP Challenge	Maritime Spatial Planning Challenge (simulation platform)
MSPD	Maritime Spatial Planning Directive
MSFD	Marine Strategy Framework Directive
MYTILUS	Marine cumulative impact assessment tool developed in BONUS BASMATI and NorthSEE projects
NSII	The North Sea Impact Index
NSPI	The North Sea Pressure Index
OSPAR	Oslo-Paris Convention (for the Protection of the Marine Environment of the North-East Atlantic)
OWF	Offshore Wind Farm
SCAIRM	Spatial Cumulative Assessment of Impact Risk for Management
SEA	Strategic Environmental Assessment
Symphony	Swedish ecosystem-based marine spatial planning tool
Tools4MSP	Tools for Maritime Spatial Planning
WFD	Water Framework Directive
ZOI	Zone of Influence

Summary

The Danish Energy Agency commissioned this report to support long-term planning for offshore wind development in Denmark. It focuses on cumulative effect assessments (CEAs), which are a legal requirement under EU Directive 2014/52/EU. CEAs aim to evaluate the combined environmental impacts of multiple human activities, such as offshore wind farms, shipping, and fisheries, on marine ecosystems.

The report is part of the offshore wind screening project in Denmark which has been conducted during the period 2022-2025 on behalf of the Danish Energy Agency. The project includes four main tasks: mapping environmental sensitivity for offshore wind, technical screening of wind farm areas in Danish water, assessing cumulative effects, and evaluating coexistence opportunities for offshore wind. This document addresses the third task and provides a comprehensive review of CEA methodologies, including tools, frameworks and known best practices. In this context, the term framework refers to a structured foundation or system that provides guidelines, rules, or reusable components to help organize and solve complex problems, in this context performing CEAs. A tool may be defined as an instrument, device, or resource designed to help perform a specific task more effectively. In some cases where a CEA-method may be considered as both a framework and a tool, the term method is used.

The report begins by outlining the regulatory context, including key EU directives. These vary in their treatment of cumulative impacts, with some offering specific thresholds and others relying on qualitative assessments. The report proceeds to identify numerous challenges in conducting CEAs, including data gaps, lack of baseline data, outdated modelling assumptions, and limited integration of climate change. It also highlights the difficulty of capturing non-linear ecological responses, cascading effects, and spatial-temporal variability. Communication of complex assessments to stakeholders and integration into policy frameworks are additional hurdles.

To address these challenges, the report reviews over 20 methods that are used or can be used to conduct CEAs. These include conceptual frameworks like DAPSIR and KEC, spatial mapping tools such as The Halpern method, Symphony, and BSII CAT, and conservation planning tools like Zonation and Marxan. It also covers scenario-based tools like InVEST and SCAIRM, and simulation platforms like MSP Challenge. Each method has been examined for its applicability to offshore wind development, geographic relevance, and methodological strengths and limitations.

The report also presents a comparative analysis of CEA practices across countries. In Denmark, there is a general focus on ensuring that assessments are carried out in accordance with relevant EU directives and the use of maritime spatial planning tools. The Netherlands employs the KEC framework, and the UK is working towards standardised approaches through the ongoing PrePARED initiative.

Recent developments in CEA include the incorporation of temporal dynamics (including climate change predictions), risk-based modelling, and multi-use marine spatial planning. The report emphasises the need for a multi-tool approach, combining spatial and modelling tools to achieve robust assessments. It also advocates for stakeholder engagement, transparent data practices, and the development of national standards for zone of influence and timeframes.

In conclusion, the report acknowledges the complexity of marine ecosystems and the limitations of existing CEA methods. It recommends building consensus around common approaches and continuously improving them as new knowledge emerges. It calls for interdisciplinary collaboration, integration of climate change, and open-access data to enhance the dependability and utility of CEAs in offshore wind planning.

Sammenfatning

Denne rapport er udarbejdet på vegne af Energistyrelsen for at understøtte den langsigtede planlægning af havvindsudbygning i Danmark. Rapporten fokuserer på vurdering af kumulative effekter (cumulative effect assessment, CEA), som er et lovkrav i henhold til EU-direktiv 2014/52/EU. Formålet med CEA er at vurdere de samlede miljøpåvirkninger fra flere menneskelige aktiviteter, såsom havvindmølleparker, skibsfart og fiskeri, på havets økosystemer.

Rapporten indgår som en del af screeningsprojektet for havvind i Danmark, som er gennemført i perioden 2022-2025 på vegne af Energistyrelsen. Projektet er struktureret omkring fire hovedopgaver: følsomhedskortlægning for havvind, teknisk screening af havvindområder, vurdering af kumulative effekter samt kortlægning af sameksistensmuligheder for havvind. Dette dokument omhandler den tredje opgave og giver en omfattende gennemgang af CEA-metodologier, herunder værktøjer, rammer og kendte bedste praksis. I denne sammenhæng henviser udtrykket ramme til et struktureret fundament eller system, der giver retningslinjer, regler eller genanvendelige komponenter, der hjælper med at organisere og løse komplekse problemer, i denne sammenhæng udførelse af CEA'er. Et værktøj kan defineres som ethvert instrument, enhed eller ressource, der er designet til at hjælpe med at udføre en bestemt opgave mere effektivt. I nogle tilfælde, hvor en CEA-metode kan bruges som både en ramme og et værktøj, anvendes udtrykket metode.

Rapporten indleder med at skitsere den lovgivningsmæssige kontekst, herunder centrale EU-direktiver. Disse varierer i deres tilgang til kumulative påvirkninger, hvor nogle opererer med specifikke tærskelværdier, mens andre baserer sig på kvalitative vurderinger. Rapporten identificerer endvidere en række udfordringer ved udarbejdelse af CEA, herunder datamangler, mangel på baseline-data, forældede antagelser i de anvendte modeller og begrænset integration af klimaforandringer. Derudover fremhæves vanskeligheder ved at indfange ikke-lineære økologiske reaktioner, kaskadeeffekter og rumligt-temporale variationer. Kommunikation af komplekse vurderinger til interessenter og integrationen af resultaterne i politiske rammer udgør yderligere barrierer.

For at imødegå disse udfordringer gennemgår rapporten over 20 metoder, der anvendes eller kan anvendes til at gennemføre CEA'er. Disse omfatter konceptuelle rammer som DAPSIR og KEC, rumlige kortlægningsværktøjer såsom Halpern-metoden, Symphony og BSII CAT, samt planlægningsværktøjer til naturbeskyttelse som Zonation og Marxan. Rapporten behandler også scenariebaserede værktøjer som InVEST og SCAIRM samt simuleringsplatforme som MSP Challenge. Hvert værktøj er blevet gennemgået i forhold til dets anvendelighed for havvindudbygning, geografiske relevans og metodiske styrker og begrænsninger.

Rapporten præsenterer desuden en komparativ analyse af CEA-praksis på tværs af lande. I Danmark er der generelt fokus på, at vurderingerne skal foretages i overensstemmelse med relevante EU-direktiver samt anvendelsen af værktøjer til havplanlægning. I Holland benytter KEC-rammen, og Storbritannien arbejder hen imod standardiserede tilgange gennem den igangværende PrePARED-indsats.

Nye udviklinger inden for CEA omfatter integration af tidslige dynamikker (herunder klimaforudsigelser), risikobaseret modellering og input fra en samlet maritim fysisk planlægning. Rapporten understreger behovet for en fler-værktøjstilgang, hvor rumlige og modelleringsbaserede værktøj kombineres for at opnå robuste vurderinger. Der anbefales desuden tidlig inddragelse af interessenter, gennemsigtige datapolitikker og udvikling af nationale standarder for påvirkningszoner og tidsrammer.

Afslutningsvis anerkender rapporten kompleksiteten i havets økosystemer og begrænsningerne ved eksisterende CEA metoder. Det anbefales at opbygge konsensus omkring fælles tilgange og løbende forbedre dem i takt med ny viden. Rapporten opfordrer til tværfagligt samarbejde, integration af klimaforandringer og anvendelse af open-access data for at styrke pålideligheden og anvendeligheden af CEA i planlægningen af havvind.

1. Introduction

1.1 Background

The transition to renewable energy is accelerating in response to climate change impacts, climate adaptation costs, and growing energy demands worldwide. Offshore wind plays a pivotal role in meeting EU targets for reducing greenhouse gas emissions by 2030 and achieving climate neutrality by 2050 (European Commission, 2025a). However, offshore wind development introduces new pressures on marine environments, in addition to the pressures that already exists. Pressures from the development of an offshore wind farm (OWF) include risks to biodiversity through habitat loss, species displacement, and collision hazards (Bennun, et al., 2021). The sensitivity of marine ecosystems to these pressures remains poorly understood for most topics (Stokholm, et al., 2025). Some receptor groups, such as seabirds and cetaceans, are more studied than others (Thomassen, et al., 2025), yet substantial gaps remain in understanding the scale and significance of actual impacts (Sinclair, 2025).

For OWF projects in Denmark, impact assessments of numerous topics are required, reflecting both intrinsic environmental values and socio-economic interests. Impacts assessments of environmental values include biological and ecosystem components, such as benthic flora and fauna, fish, marine mammals, birds, and bats, as well as water quality, seabed topography and sediment, hydrography, coastal morphology, and climate. Assessments of some environmental values are more directly linked to the human experience, such as landscape, recreative areas and activities, and cultural heritage (e.g. cultural environments, marine archaeology). Impact assessments of socio-economic interests include for instance infrastructure (e.g. air traffic, safety of navigation at sea, radars), fisheries and other industries, natural resources, and defence/military considerations.

Impacts from offshore wind are rarely isolated, and focusing solely on direct effects can lead to misleading conclusions and undermine the validity of impact assessments (Willsteed, et al., 2018; Nelson & Shirley, 2022). Thus, so called cumulative effect assessment (CEA) is now a central part of environmental assessment. With the implementation of EU Directive 2011/92/EU, and revision 2014/52/EU, it is stated directly in the text that the environmental impact assessment (EIA) must include an assessment of the cumulative effects of the project. This also applies for strategic environmental assessment (SEA) through the EU Directive 2001/42/EC. Thereby, it became a legal requirement to include CEA, reflecting the need for a more integrated understanding of environmental pressures.

The objective of conducting a CEA is to adopt a broader perspective by integrating multiple activities, the pressures they exert, and their cumulative effects on key ecosystem components like marine habitats and species (Willsteed, et al., 2024). Effects from offshore wind development are often associated with negative impacts on the ecosystem components. However, positive environmental and social impacts can also occur, for instance in projects which implement multiple use of areas (Tamis, et al., 2024).

Cumulative effect assessments (CEAs) can be defined as a specialized form of environmental impact assessment (EIA) that evaluate the combined effects of multiple projects (or human activities) and natural processes on ecosystems (Jones, 2016). Combined environmental effects may occur when the impact of a single project (or human activity) is added to those from past, ongoing, and reasonably foreseeable future activities (European Commission, 2020). Projects/activities may include existing activities with ongoing effects, government-led plans or programs, approved or proposed projects, and projects under construction.

1.2 Purpose, scope, and structure of the report

The Danish Energy Agency (Energistyrelsen) has requested more insight into the practice of performing cumulative effect assessments (CEAs) in the context of planning for future large-scale offshore wind development in Denmark.

The purpose of this report has been to explain current CEA practices in a clear and accessible way and to review existing approaches that can support future efforts to establish a consistent CEA-method for offshore wind development in Denmark and neighbouring countries.

The report outlines the regulatory context and describes initiatives in the development of CEAs. The report presents a review of known international best practices, which mainly includes specific methods, including frameworks and tools, used to perform CEAs. In this context, the term framework refers to a structured foundation or system that provides guidelines, rules, or reusable components to help organize and solve complex problems, in this context performing CEAs. A tool may be defined as an instrument, device, or resource designed to help perform a specific task more effectively. In some cases where a CEA-method may be considered as both a framework and a tool, the term method is used.

The focus of this report has been on the assessment of environmental aspects; however, socio-economic factors are also mentioned to some extent.

Lastly, a comparative analysis of the different approaches is presented to help assess which approaches might be more suited for future offshore wind CEAs in Denmark and neighbouring countries. The conclusion gives a final view on the current situation and provides recommendations for future CEA efforts.

1.3 CEAs of offshore wind development

Cumulative effect assessments (CEAs) are required as part of the environmental assessment procedures for offshore wind farm projects, as previously mentioned. However, past and current CEAs have mostly relied heavily on expert judgment. The approach often lacks consistency due to differing baselines, conceptual frameworks, and assumptions, making comparisons between assessments difficult (Blakley & Russell, 2022; Caine, 2019; Hague, et al., 2022). Terminological inconsistencies, such as "Cumulative Effects Assessment (CEA)" versus "Cumulative Impacts Assessment (CIA)", further complicate the field (Foley, et al., 2017). In this report, the term CEA is used consistently, aligning with EU environmental legislation, although referenced sources may use alternative terminology.

There is currently no universally accepted definition of the CEA process (Willsteed, et al., 2024), and methodologies vary significantly in terms of scale, ecosystem components, and how pressures are combined. Data scarcity is also a major barrier, affecting both the accuracy and reliability of the assessments. Missing or incomplete data can lead to underestimations of impact, with potentially profound consequences, for instance in the case of marine ecosystems (Hague, et al., 2022). In short, there is an extensive list of identified challenges when conducting CEAs, which are summarised in Table 1.

As Denmark and its neighbouring countries with access to wind-rich seas work to support the EU's plans for expanding offshore wind under the Green Deal and REPowerEU strategies (European Commission, 2025b; European Commission, 2025c), the need for strong and reliable CEA practices has become increasingly urgent. CEAs are essential for understanding long-term, large-scale impacts on the environment, especially when impacts stem from various sources and interact with other stressors. Without CEAs, there is a major risk of overlapping pressures on marine ecosystems, conflicts with for instance fisheries and conservation goals, and undermining long-term sustainability. For example, species with limited adaptive capacity are especially vulnerable to overlapping pressures. Inaccurate assessments can result in permits being granted for projects that cause irreversible harm (Caine, 2019). Therefore, cumulative impacts must be a central consideration in offshore wind planning and development, and efforts to improve this practice is necessary.

To support sustainable marine management, CEAs must provide decision-makers with reliable knowledge that prevents overlooked impacts and irreversible consequences (Hague, et al., 2022; Caine, 2019). This underscores the need for standardized, transparent, and comparable CEA methods. Some of the most recent initiatives to close the identified gaps and improve environmental impact assessments is presented in section 3 in this report.

Table 1 Detailed overview of gaps and challenges in CEA derived and modified from JPI Oceans' "A Common Handbook Cumulative effects assessment in the marine environment" (JPI Oceans, 2024).

Challenges	Explanation
Data gaps and inconsistencies	Limited availability and quality of data on various pressures and ecological components can hinder accurate assessments. Poor or absent knowledge on some pressures may increase uncertainty on the assessment. Varying data density and quality between geographical areas may also lead to skewed results.
Population-level response	There is also a lack of high-resolution data and population-level impact assessments especially for commercial fish species, and protected species like harbour porpoises (Thomassen, et al., 2025). Newly published reports also stress the need for better integration of fisheries data and cross-sectoral datasets to improve model accuracy (Eklipse Expert Working Group, 2025; ICES, 2025). Calculating sensitivity values alone cannot be directly linked to changes in population status, as population outcomes also depend on the life history traits of the species in question and the extent to which individuals can utilize alternative areas when they are displaced from a wind farm site (Stokholm, et al., 2025). The need for better process-based population modelling, to account for variations in life history traits and dynamics of the receptor group populations, such as animal energetics and movements, is necessary.
Outdated modelling data	Significant variations in the design and layout of both current and future offshore wind farms, which in turn affect their environmental impacts. The studies currently used to assess the consequences of individual wind farms are limited, as they are based on projects with smaller turbines and smaller overall footprints compared to those planned. As a result, future wind farms may affect much larger areas of the marine environment than those for which data presently exists. This highlights the need for caution when evaluating the potential impacts of future wind farms based solely on how animals have responded to existing installations in the past (Stokholm, et al., 2025).
Tools to detect the spatial and temporal variability	Marine systems exhibit considerable spatial and temporal variability, making it challenging to capture the full range of ecological responses and pressures. The analysis should be conducted at an appropriate spatial and temporal resolution, according to the resolution of the pressures and responses.
Accounting for different project development phases	Cumulative impacts are especially pronounced when "different phases of offshore wind development, happening simultaneously in an area, each have different pressures and impacts on the environment over different periods of time." (Nordic Energy Research, 2022).
Interactions and synergies	Within CEA approaches, the assumption of additivity is widely accepted and currently considered the best available method. This means the impact risks from different impact chains are combined, without considering whether they might interact in ways that make the overall effect stronger or weaker (Tamis, et al., 2024). Most of the outcomes are poorly known, and ecological studies and more data are needed to assess them.

Challenges	Explanation
Lack of baseline data	Incomplete or missing baseline data for certain pressures and ecological components make it difficult to establish reference conditions for assessing changes. Data describing pristine (untouched) environmental conditions are needed to assess the response to the alteration.
Sensitivity weights and expert judgment	Reliance on sensitivity weights derived from expert judgement introduces subjectivity and uncertainty, especially when the understanding of ecosystem responses is incomplete.
Non-linear ecological responses	The assumption of linear ecological responses to pressure may not hold true, as ecosystems often exhibit non-linear responses that may include thresholds and irreversible changes.
Spatial and temporal scales mismatch	Mismatches in the scales of pressure data and ecological response data can lead to inaccurate assessments, particularly when pressures and ecological features operate at different scales.
Cascading effects	Cumulative effects assessments may struggle to capture cascading effects through trophic levels and ecosystem components, resulting in an underestimation of overall impacts.
Model complexity and uncertainty	Complex ecological models used in cumulative effects assessments introduce uncertainties, and the sensitivity of results to model parameters may be challenging to quantify.
Ecosystem connectivity	Many marine ecosystems are interconnected, and pressures in one area may have far-reaching effects in distant areas, making it challenging to attribute impacts to specific sources.
In-combination effects	One of the key challenges when assessing how sensitive marine species are to the development of offshore wind is that animals react to multiple pressures at the same time, and that the impact of these pressures are not necessarily constant in time and space (Stokholm, et al., 2025). The sensitivity assessments of the distinct species groups only implicitly consider the cumulative impacts of the various factors that affect animals by individual wind farms as well as cumulative pressures of multiple wind farms over large spatial scales. For instance, piling of monopiles may cause underwater noise but also particle dispersions, which may influence fish in various degrees. The impact radius may vary from species to species.
Climate change interactions	The influence of climate change on marine systems introduces additional complexity, with changing ocean temperatures, acidification, and other climate related factors interacting with existing pressures. Climate change is often mentioned as an indirect impact but is not systematically integrated into the CEAs (Kuempel, et al., 2025; Declerck, et al., 2022a). The assessments may therefore lack spatio-temporal appropriate baselines linking ecosystem components (e.g. physical indicators) to population dynamics which leads to uncertain predictions at populations levels (Declerck, et al., 2022a).
Incorporation of socio-economic data	Socio-economic interests, including for instance fisheries, natural resources, and marine tourism, are just as important when conducting CEAs. Fisheries for instance are interlinked with the environment, both relying on nature to provide the wanted resources, as well as exerting additional pressure. Socio-economic interest therefore must be valuated from two angles, as is normal practice in EIAs.
Management and policy integration	Integration of CEAs into marine management and policy frameworks is often challenging due to the need for interdisciplinary collaboration and coordination among various stakeholders.
Public engagement and communication	Communicating complex CEAs to the public and decision-makers can be challenging, requiring effective strategies to convey uncertainties and potential impacts.

2. Regulatory and policy contexts

The assessment of cumulative impacts in Denmark and Europe in general is based on guidance documents, legislation, declarations, or directives related to the specific subjects being handled. Examples include EU directives (e.g. the SEA and EIA Directives, Marine Strategy Framework Directive, Habitat Directive and Maritime Spatial Planning Directive) and their implementation in national legislation. Some of these contain specific threshold values to compare data against for impact assessment, while others do not. When no specific threshold values are provided, the assessments become more qualitative and subjective. Few legislative frameworks provide definitions of cumulative impacts or clear guidance in terms of methods that can be applied when conducting a CEA. When the regulatory framework is uncertain, it becomes difficult to know whether the assessments are conducted properly (Masden, et al., 2010).

2.1 The EU Strategic Environmental Assessment (SEA) Directive and the EU Environmental Impact Assessment (EIA) Directive

The EU SEA and EIA Directives (Directive 2001/42/EC and Directive 2014/52/EU) concerning environmental assessment of plans and programs (SEA) and environmental assessment of individual projects (EIA), respectively, are implemented in the Danish Act on Environmental Assessment of Plans and Programs (*miljøvurderingsloven*, LBK nr 4 af 03/01/2023). Content requirements for the EIA report are specified in the Act's Appendix 7, 5e, where the following is stated regarding assessments of cumulative impacts: "*the cumulation of the project's effects with other existing and/or approved projects, taking into account any existing environmental issues related to areas of particular environmental significance that may be expected to be affected, or the use of natural resources*" (The Danish Ministry of Environment and Gender Equality, 2023a).

The Danish Ministry of Environment and Gender Equality have published guidelines for the assessment of projects and for plans and programs (The Danish Ministry of Environment and Gender Equality, 2023b). The guidelines are legal guides and are based on the legislative history, Danish board and court practice, the EU directives that the law implements, the practice of the EU Court of Justice, and the EU Commission's guidance on the directives.

In the guidelines directed at specific projects, it is stated that the purpose of the environmental assessment rules is to evaluate the significant impacts of the project on the environment, considering the environmental carrying capacity of the area. This means that identical projects may be subject to environmental assessment in some contexts and not in others. One of the factors that is influential is the extent of the project's impact on the environment, which concerns both intensity and geographical extent, seen in relation to other activities and the vulnerability of the area. Therefore, a project should not only be assessed in isolation in relation to tolerance limits and guideline values. The project must be assessed in cumulation with the impact on the environment from already existing or approved projects. This means that a project, which in isolation would not have a significant impact on the environment, may still be subject to environmental assessment. The guidelines refer to the practice of the EU Court of Justice, according to which the cumulative assessment cannot be limited to projects of the same type and must include both direct and indirect effects.

The guidelines are, as mentioned, legislative guides, which presents relevant examples of Danish and EU board and court decisions, but the guidelines do not present specific methodologies or approaches to conducting a CEA. Both Danish and EU EIA guidelines refer to the EU Commission's guidelines for the assessment of indirect and cumulative impacts as well as impact interactions (in-combination effects) (European Commission, 1999). The EU Commission guidelines do not recommend a single method for assessing cumulative impacts but suggest various approaches which the practitioner can adapt and combine to suit the project in question, e.g. expert opinions, spatial analysis, network analysis, and modelling. The guidelines further provide information on the boundary setting for cumulative assessments on both a spatial and temporal scale. The former should consider the distance of which an impact can travel and any interaction networks as well as the nature of the impact and potential natural boundaries. The latter should consider activities in the past, present and future such as historical use of the area, local or national planning horizons for future development as well as the lifespan of the project.

2.2 The EU Habitats Directive and the EU Birds Directive

The overall aim of the EU Habitats Directive (Council Directive 92/43/EEC) is to ensure that a wide range of species and habitat types are maintained, or restored, to a favourable conservation status within the EU. The EU Birds Directive (Directive 2009/147/EC) aims to protect all naturally occurring wild bird species present in the EU and their most important habitats.

The two directives are implemented in Danish legislation, e.g. through the Executive Order on the designation and administration of international nature conservation areas and the protection of certain species ("Habitats Executive Order", *Habitatbekendtgørelsen*, BEK nr 1098 af 21/08/2023) as well as the Executive Order on the conservation of certain animal and plant species and the care of injured game (*Artsfredningsbekendtgørelsen*, BEK nr 521 af 25/03/2021). Furthermore, the directives are implemented in the Executive Order on the administration of international nature conservation areas and the protection of certain species regarding offshore projects on the establishment, etc., of electricity production facilities and electricity supply networks (*VE-offshorehabitatbekendtgørelsen*, BEK nr 588 af 26/05/2025).

Cumulative effects are addressed in the Habitats Directive and its implementation in Danish legislation by stating that any plan or project, either individually or in combination with other plans or projects, must be subject to appropriate assessment, if they are likely to have a significant effect on the Natura 2000 site. Cumulative effects in relation to Natura 2000 areas are elaborated further at a general level in the guidelines to a previous version of the Danish Habitat Executive Order (The Danish Environmental Protection Agency, 2020).

Certain guidance on CEA can be found in the EU Commission notice on the assessment of plans and projects in relation to Natura 2000 sites (European Commission, 2021). The notice provides a stepwise process for carrying out a CEA (mentioned as CumIA) in relation to protected habitats and species but does not contain specific suggestions for methods and tools to be used for the assessment. Instead, the notice refers to the methodological approaches mentioned in the EU Commission's guidelines (European Commission, 1999) (see section 2.1).

In the annex to the EU Commission notice, further guidance can be found through examples from Member States (European Commission, 2021). For instance, the annex contains an example from Germany of setting thresholds for habitat loss to determine significant adverse effects on habitat types, including the cumulative effects. The standards used in the given example are now broadly accepted and recommended, regarded by administrative courts, and used in appropriate assessments.

2.3 The EU Marine Strategy Framework Directive (MSFD)

The EU Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC) aims to protect, preserve, and restore marine ecosystems, preventing their deterioration. The directive requires Member States to develop national marine strategies to achieve or maintain good environmental status (GES) in the marine environment. This directive also contributes to the ambition of the European Green Deal, namely the EU's Biodiversity Strategy for 2030 and the Zero Pollution action plan (European Commission, 2025d). The MSFD builds on existing EU legislation such as the Water Framework Directive (Directive 2000/60/EC) as well as the Habitats and Birds Directives among many others.

The MSFD is implemented over six-year cycles. National marine strategies must comprise regular assessments of the marine environment, setting objectives and targets, establishing monitoring programs and putting in place measures to improve the state of marine waters. In Danish legislation, the MSFD is implemented through the Marine Strategy Act (*Havstrategiloven*, LBK nr 123 af 01/02/2024). The Danish marine strategy is divided into three parts: 1) Basis analysis, environmental targets, and socioeconomic analysis; 2) monitoring program and; 3) plan for measures. The MSFD requires the use of an ecosystem-based approach, which by its nature has cumulative effects in focus (The Danish Ministry of Food, Agriculture and Fisheries, 2019).

The basis analysis of the second (current) Danish Marine Strategy contains a cumulative assessment across the MSFD's 11 descriptors (The Danish Ministry of Food, Agriculture and Fisheries, 2019). The assessment is conducted only additively and does not contain synergistic or antagonistic effects. The method uses software based on Halpern, et al., (2008), which requires four different types of input, including maps of the spatial distribution of stressors, maps of the distribution of ecosystem components, information of effect distances as well as the sensitivities of the ecosystem components (Stock, 2016). It is stated in the basis analysis that the methodology for the cumulative assessment should undertake continued development. More information on the methodology developed by Halpern, et al., (2008) can be found in section 4.2.5.

2.4 The EU Maritime Spatial Planning Directive (MSPD)

The EU Maritime Spatial Planning Directive (MSPD) (Directive 2014/89/EU) requires the coastal Member States to produce maritime spatial plans for the marine waters under their jurisdiction. The aim of the MSPD is to ensure that marine spatial planning can be used as a cross-cutting policy tool enabling public authorities and stakeholders to apply a coordinated, integrated, and transboundary approach. Similarly to the MSFD, the MSPD applies an ecosystem-based approach with the intent to promote the sustainable development of the maritime and coastal economies and the sustainable use of marine and coastal resources.

The MSPD is implemented in the Danish Act on Maritime Spatial Planning (*Lov om maritim fysisk planlægning*, LBK nr 400 af 06/04/2020). The Danish Maritime Spatial Plan (MSP) aims to support sustainable growth while balancing the needs of different stakeholders and protecting marine ecosystems (Danish Maritime Authority, 2024). The MSP designates specific zones for e.g. renewable energy, including offshore wind farms, to ensure efficient use of marine space and minimize conflicts with other activities.

Cumulative effects are not addressed directly in the directive nor the Danish act, but the ecosystem-based approach, which must be implemented in the marine spatial planning, is described further in the Danish Maritime Spatial Plan Statement (Danish Maritime Authority, 2023). In the statement, it is stated that the ecosystem-based approach should be understood as the management of human activities in a way that ensures the collective pressure from such activities is kept within levels compatible with achieving good environmental status. Hence, cumulative effects assessments are integrated in the ecosystem-based approach implemented in marine spatial planning. The Danish Maritime Spatial Plan is closely linked to the Danish Marine Strategy (see section 2.3) and has been developed in accordance with the strategy's environmental objectives and plan for measures (Danish Maritime Authority, 2023).

The above is supported by a report from the European Commission on the progress of the implementation of the MSFD. It is stated in the report, that future maritime spatial plans will have to cater for cumulative impacts of anthropogenic pressures by applying an ecosystem-based approach, and complying with all relevant environmental legislation, for example the EU SEA Directive, the Bird and Habitats Directives as well as the WFD and MSFD (which are covered in sections 2.1 to 2.3) (European Commission, 2022).

Several CEA methods have been applied in relation to maritime spatial planning in Europe and other parts of the world, see for instance Willsteed, et al., (2024), and the review descriptions in section 4.

3. Initiatives to close the gaps of CEAs

Many international organizations, including the European Union (EU), the United Nations Environment Programme (UNEP), the World Health Organization (WHO), and the International Union for Conservation of Nature (IUCN), recognize the importance of considering cumulative effects in environmental assessments (JPI Oceans, 2024). Some of the most recent initiatives funded by the EU and/or cross-border cooperations between the Nordic countries, many which include Denmark, have focused on cumulative effect assessment of offshore wind development.

As mentioned previously the current CEA practice may be perceived as fragmented and non-uniform, and this lack of standardization has led to inconsistent practices and results. It is stressed by many that the marine environment cannot be sustainably managed as long as assessments do not meet the same standard (Hague, et al., 2022; Caine, 2019; Willsteed, et al., 2018). This has prompted calls for harmonized approaches, such as those explored in the Joint Nature Conservation Committee's (JNCC) 2024 review of CEA methodologies. Emerging data-driven tools and frameworks aim to improve comparability and transparency across assessments.

The sections below present some (non-exhaustive list) of the initiatives and projects which in many ways define the road ahead for the development of CEAs for offshore wind development in Europe.

3.1 EU initiatives

The European Union (EU) has increasingly recognized the need for improved CEAs in the marine environment and in the context of offshore wind development, due to concerns regarding for example marine biodiversity, fisheries, and ecosystem health. Below are some of the projects supporting the CEA-progress accounted for.

HORIZON Europe

Horizon Europe is the European Union's flagship funding programme for research and innovation. It promotes collaboration and enhances the impact of scientific and technological advancements by supporting the development and implementation of EU policies. The programme also addresses global challenges, including climate change (European Commission, 2025e). Relevant projects funded by Horizon Europe are described below.

<u>BLUE CONNECT (2024-2028)</u>
The BLUE CONNECT project aims to enhance marine ecosystem resilience and promote sustainable stewardship of Europe's coastal and offshore habitats through collaboration and involvement with government agencies, local MPA managers and stakeholder groups (BLUE CONNECT, 2023).

<u>ONE-BLUE (2024–2027)</u>
The Spanish National Research Council (CSIC) coordinates the ONE-BLUE project. It focuses on combined impacts of emerging marine pollutants, microplastics, and climate change (CSIC, 2024). In 2024, the project started fieldwork activities to collect environmental data in the Arctic Ocean, Irish Sea, and Mediterranean Sea (Finnova Foundation, 2024).

<u>ACTNOW project (2023–2027)</u>
The ACTNOW (Advancing understanding of cumulative impacts on European marine biodiversity, ecosystem functions and services for human wellbeing) project, coordinated from the Netherlands, aims to advance the state-of-the-art in understanding and forecasting the cumulative impacts of climate change and interacting drivers on marine systems (European Commission, 2022; ACTNOW, 2023).

EKLIPSE Initiative (2025)
Under the Horizon Europe project BioAgora, the EU Directorate-General for Environment (DG ENV) tasked the EKLIPSE platform with evaluating the impacts (including cumulative) of the expansion of offshore wind energy production on the achievement of the good ecological status (GES) of the marine environment. The focus is on developing better methods for integrating scientific knowledge into policy, and ensuring policymakers have access to robust, interdisciplinary evidence. The EKLIPSE initiative is also meant to support the implementation of the Marine Strategy Framework Directive (MSFD) through improved CEA.

GES4SEAS (2022-2026)
The Horizon Europe funded project GES4SEAS has developed a comprehensive toolbox to support the achievement and management of Good Environmental Status (GES) in European seas (GES4SEAS, 2024; Borja, et al., 2024). One of the tools developed is the SCAIRM-tool (see section 4.2.16).

UNITED project (2020-2023)
The UNITED project, referring to *"Multi-Use offshore platforms demoNstrators for boostIng cost-effecTive and Eco-friendly proDuction in sustainable marine activities"*, has also been part of the Horizon research project co-funded by the EU. The UNITED project addresses challenges within five key pillars. One of these pillars is the environmental pillar, where there is a focus on assessing environmental impacts and interactions between impacts from multi-use of the oceans (UNITED, 2023). This study applies the Spatial Cumulative Assessment of Impact Risk for Management (SCAIRM) method (see section 4.2.16) to evaluate how combining activities like renewable energy, aquaculture, nature restoration, and tourism can reduce cumulative ecological impacts compared to single-use configurations (Tamis, et al., 2024).

Other EU funded projects

ICES Working Group on Cumulative Effects Assessment Approaches in Management (WGCEAM)
The International Council for the Exploration of the Sea (ICES), commissioned by the EU, and their working group on Cumulative Effects Assessment Approaches in Management (WGCEAM), delivered a comprehensive assessment report of the economic, social, ecological, and cumulative effects and impacts of offshore wind farms (OWFs) and floating wind farms (FLOWs) in the Baltic Sea, Celtic Sea, and North Sea (ICES, 2025).

SIMAtlatic (2019–2021)
SIMAtlantic (Supporting Implementation of Maritime Spatial Planning in the Atlantic) was an EU-funded project under the European Maritime and Fisheries Fund (EMFF). Its main goal was to support the establishment and implementation of Maritime Spatial Plans (MSP) in five European Atlantic countries: France, Ireland, Portugal, Spain, and the United Kingdom (including Northern Ireland) (Casimiro, et al., 2021; SIMAtlantc, 2021).

NorthSEE project (2016-2021)
The NorthSEE project (A North Sea Perspective on Shipping, Energy and Environmental Aspects in Maritime Spatial Planning) aims to achieve greater coherence in maritime spatial planning (processes) and in maritime spatial plans (capturing synergies and preventing incompatibility) (NorthSEE, 2019; Lukic, et al., 2020). The NorthSEE project also aim to creating better conditions for sustainable development of the area in the fields of shipping, energy, and environmental protection. The NorthSEE project has utilised tools like Symphony (see section 4.2.8) and MYTILUS (se section 4.2.9).

3.2 Other initiatives

In addition to the EU initiatives described in section 3.1, there are several other cross country/institution collaboration initiatives and projects that have or still are contributing to the development of MSP- and/or CEA-practices, some of which are accounted for in short below.

CLEAN (2022-2026)

The CLEAN project, an institutional collaboration lead by the Arctic University of Norway, focuses on understanding the cumulative impacts and risks posed by multiple stressors on High North ecosystems. It examines how climate change, pollutants transported over short and long distances, invasive species, and human activities—such as harvesting and aquaculture—interact to influence ecosystems and the services they provide. The project also explores management challenges and strategies for mitigating these combined effects (CLEAN, 2025). CLEAN aims to deepen knowledge of the complex causal relationships behind cumulative impacts by studying direct and indirect effects, as well as synergies among stressors. This will be achieved through experimental research, statistical analysis of field data, and process-based modelling (CLEAN, 2025).

PrePARED (2022-2025)

The PrePARED (Predators and Prey Around Renewable Energy Developments) project is an initiative focused on improving environmental assessments for offshore wind development in the UK, particularly regarding cumulative effects assessment (Sinclair, 2025). Key objectives of the PrePARED projects have been to identify inconsistencies in current CEA practices across UK jurisdictions, and to develop a UK-wide standardised guidance for CEA.

HELCOM Initial Holistic Assessment (HOLAS I, II & III) (2003-2023)

The Helsinki Commission (HELCOM) initiated the first assessment (HOLAS) of the ecosystem health of the Baltic Sea (HELCOM, 2010), which evolved to HOLAS II & III providing a baseline for the development of the Baltic Sea Impact Index Cumulative impacts Assessment Toolbox (BSII CAT) (se section 4.2.6), developed in EU co-funded Pan Baltic Scope project (HELCOM, 2017; HELCOM, 2023).

SEANSE (2018-2020)

The Strategic Environmental Assessment on North Sea Energy (SEANSE) project was initiated to develop a coherent approach to Strategic Environmental Assessments (SEAs) for offshore renewable energy development across North Sea countries. SEANSE compiled a comparative overview of offshore wind planning criteria across North Sea countries and provides a structured and collaborative framework for strategic environmental assessment in the context of offshore renewable energy. SEANSE compiled planning criteria for offshore wind farms across North Sea countries, including siting conflicts with shipping, fisheries, and protected areas (SEANSE project partners, 2018). A key output of SEANSE project was the Common Environmental Assessment Framework (CEAF). The project was co-funded by the European Maritime and Fisheries Fund and involved planning authorities from the Netherlands, Germany, France, Scotland, and Denmark (SEANSE project partners, 2018).

SYMBIOSE (2015)

The Danish SYMBIOSE project aimed to compile a national catalogue of pressures and ecosystem-component data layers (Mohn, et al., 2015). SYMBIOSE ecosystem components covers plankton communities, fish, birds, and mammals. The methodology is based on the methodology adopted by the HARMONY project for the eastern North Sea but applied nationwide in SYMBIOSE. The result is a catalogue of spatial maps and data sheets with a detailed description of data sources and methods for selected data layers. The maps developed provide a state-of-the-art data collection for a future mapping of cumulative pressures and impacts in Danish marine waters (Mohn, et al., 2015).

HARMONY (2010-2012)
The HARMONY project has developed and made available a toolbox supporting national MSFD implementation with special focus on issues of a transnational relevance and importance. It builds on cooperation among member states sharing the Greater North Sea sub-region, Denmark, Germany, Norway and Sweden, through active involvement in several OSPAR[1] groups (Sørensen, et al., 2012; Korpinen, et al., 2012). A key HARMONY deliverable was the North Sea Pressure Index (NSPI) and the North Sea Impact Index (NSII). HARMONY provided the first transnational approach to cumulative impact mapping in the North Sea, supporting: ecosystem-based management, cross-border cooperation under MSFD and OSPAR frameworks, and better-informed marine spatial planning and conservation strategies. The project was coordinated by Department of Bioscience, Aarhus University, Denmark and funded by the Danish Ministry of Environment (Sørensen, et al., 2012).

BONUS BASMATI (2017-2020)
The BONUS BASMATI project (Baltic Sea Maritime Spatial Planning for Sustainable Ecosystem Services) aims to develop integrated and innovative solutions for Maritime Spatial Planning (MSP) from a local to a Baltic Sea Region scale (BONUS BASMATI, 2000). The outcomes of the project include concepts for sustainability impact assessments of plan proposals related to marine and coastal ecosystem services and marine protected areas as well as a concept for data management and stakeholder engagement. Som tools related to the project are 'Baltic Explorer – tools for collaboration', "SPACEA – a GIS toolbox to facilitate easy spatial and environmental suitability analysis', 'ESA4MSP – an ecosystem service assessment tool', 'SEANERGY – a tool for analysing conflicts and synergies between different marine uses' (Arki, et al., 2020).

Contributions of NIVA Denmark Water Research
NIVA Denmark Water Research has played a significant role in advancing methodological frameworks and data infrastructure for cumulative impact assessment in marine spatial planning (MSP). NIVA Denmark co-authored the Symphony tool (se section 4.2.8) and contributed to the Baltic Sea Impact Index (BSII) (se section 4.2.6), both used for spatial cumulative impact mapping. NIVA supports the implementation of the Marine Strategy Framework Directive (MSFD) and Maritime Spatial Planning Directive (MSPD) (se section 2.3 and 2.4) by advising on how to assess and manage collective pressures.

A 2016 literature study by NIVA Denmark laid the groundwork by cataloguing available spatial data layers on human pressures and ecosystem components in Swedish marine waters, identifying key gaps and opportunities for integrated assessment approaches (Andersen & Kallenbach, 2016). The objective of the study was to provide an interim list of ecologically relevant pressures and ecosystem components to be included in the SYMPHONY project. Building on this foundation, NIVA Denmark has contributed to the development of GIS-based tools, sensitivity matrices, and scenario modelling frameworks that support ecosystem-based planning. NIVA Denmark has contributed to tools that are designed for strategic-level CEA, suitable for use in marine spatial planning (MSP), environmental impact assessments (EIAs), offshore wind siting, and habitat protection strategies.

[1] OSPAR refers to the Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic.

4. Review of existing CEA methods

This section presents a review of existing best practices and methods, including tools and frameworks, for performing cumulative effect assessments. The first part presents an approach to collecting and sorting out which information has been considered most relevant in the context of CEAs for offshore wind development in Denmark. The second part present the various methods, each by giving a general introduction, a brief description of the main aspects of the method, the applicability, examples of use, and a summary. Third, we present a summary table.

Several established methods for cumulative effect assessments are currently in use, each with its own strengths and limitations. These are designed to provide essential information for ecosystem-based management and vary widely in their assumptions, regional scales, activities, and ecosystem components. Some methods are not initially designed for CEA-purposes or for use in the marine environment but may be adapted and/or used in combination with other methods. Their concepts and approaches can be and have been used to account for cumulative pressures, impacts risk, priority rankings, and in some cases the effects of multi-use (MU) marine configurations (se section 4.2.16). In addition, it is often necessary to combine several types of practices to conduct a CEA, including evaluating individual or multiple pressures and stressors, integrating data, applying models, and facilitating effective communication (Table 2).

Several of the CEA-methods are inspired by the widely cited method developed by Halpern et al., (2008) (see section 4.2.5). These methods are all adjusted and tailored to varying degrees to fit their respective conceptual scope and purpose. There has been, and continues to be, substantial ongoing work in the field of CEA, as evidenced by the wide range of available methods. The diversity of these approaches reflects the complexity and evolving nature of cumulative impact analysis. However, not all methods have been included in this report. This may be due to their limited relevance within the specific context of this report, or because certain methods exhibit significant overlap in functionality, making it unnecessary to include each one individually. By excluding some methods, the intention has not in any circumstance been to undermine their quality or utilisation.

Table 2 Types of methods needed to conduct a Cumulative Effects Assessment. Modified after (JPI Oceans, 2024).

Methods	Description
Analysis of single and multiple pressures and stressors	Laboratory assessment and/or field assessment of multiple stress effects. Literature review. Metanalysis and other statistical tools. Tools to relate drivers to pressures.
Data integration	Integration of data from multiple sources including physical, chemical, and biological parameters, and social-economic data into a database or a Geographical Information System (GIS). This can be challenging, especially if data are collected at different spatial and temporal scales.
Modelling	Modelling tools are essential for predicting the cumulative effects of different pressures, stressors, and their potential interactions. They can help identify areas of high vulnerability and guide management decisions. Tools can be conceptual, as the DAPSI(W)R(M) (to frame the system and its functionalities) or numerical (biogeochemical, oil spill, high trophic level) to quantitatively represent the system. Numerical models may be based on statistical methods, machine learning, or deterministic models.
Communication	Communicating the results of cumulative effects assessments to stakeholders, policymakers, and the public is essential for raising awareness and promoting effective management. Visualization tools and other communication strategies can help to convey complex scientific information in an accessible and engaging way.

4.1 Approach to collecting information on existing CEA-tools

To find high-quality and up to date information about CEA methods, tools and frameworks, the approach in this report has been to extract relevant information from a combination of authoritative guidance documents, regulatory frameworks, practical guides, research papers and reviews, case studies and collaborative projects between countries and institutions. Online search has also been assisted using artificial intelligence (AI) tools such as Copilot and ChatGPT, which are still considered as recent innovations which are constantly evolving, and where utilisation requires human supervision[2].

These are the steps followed, not necessarily in this order:

1. Define the concept of a CEA and describe the typical CEA process (international best practices) and main recognised challenges.
2. Search for sector-specific and/or regional guidelines.
3. Use academic and multidisciplinary perspectives:
   - Academic journals and multidisciplinary reviews provide critical perspectives on evolving methods, integration of social and environmental factors, and emerging best practices;
   - Central references are:
     i. The JPI Oceans (2024) handbook "*A common handbook: Cumulative effects assessment in the marine environment*";
     ii. JNCC report 768 by Willsteed et al., (2024) "*Cumulative Effects Assessments to support marine plan development*".
4. Examine existing published reviews to identify the latest advancements in marine CEA, including:
   - Research paper by Simeoni et al., (2023) covering marine CEA approaches from 2000 to March 2022 (30 papers);
   - Research paper by Blakley & Russell (2022), covering CEA methods from 2008 to 2018 (11 papers related to marine CEA);
   - Research paper by Morejón et al., (2025) reviewing the data from the above-mentioned references and additional papers to identify CEA-methods suitable for strategic impact assessments (SEA) for marine projects;
   - Research paper by Dibo, et al., (2025) "*Guiding Elements for Strengthening Cumulative Impact Assessment Regulations for Offshore Wind Energy*".
5. Review of authoritative handbooks and frameworks.
6. Review of practical guides, and case studies:
   - Practical Guides: step-by-step guides that include methodologies, tools, and real-world case studies;
   - Examples and Case Studies: Reviewing documented case studies for insights into how different sectors and regions apply CEA frameworks.

When applying AI-assistant tools like Copilot and ChatGPT some guiding principles have been necessary:

- Defining the scope and needs:
  - What kind of receptors and impacts assessed;
  - Which sectors/projects;
  - Geographic or regulatory context.
- Used Copilot and ChatGPT:
  - to search the internet for information;

[2] Artificial intelligence (AI) has been used to increase efficiency. AI tools are still considered to be recent innovations which are constantly evolving, and the practice of integrating AI into the work process also require ongoing development. Reliable application of AI depends on the critical thinking and sound judgment of the individuals conducting the research. Just as human errors can occur, this can also happen when using AI.

- for summaries and comparisons;
- to stay updated as CEA methods evolve.

4.2 CEA-methods

A cumulative effects assessment can be conducted using various methodologies (Table 2). A general practice may look like the workflow shown in Figure 4.1. Existing methods apply slightly different approaches due to for instance different geographical context, initial objectives, and expected data input, and some of these methods, including tools and frameworks, are presented in the next sections. In this context, the term framework refers to a structured foundation or system that provides guidelines, rules, or reusable components to help organize and solve complex problems, when performing CEAs. A tool may be defined as an instrument, device, or resource designed to help perform a specific task more effectively. In some cases where a CEA-method may be considered as both a framework and a tool, the term method is used.

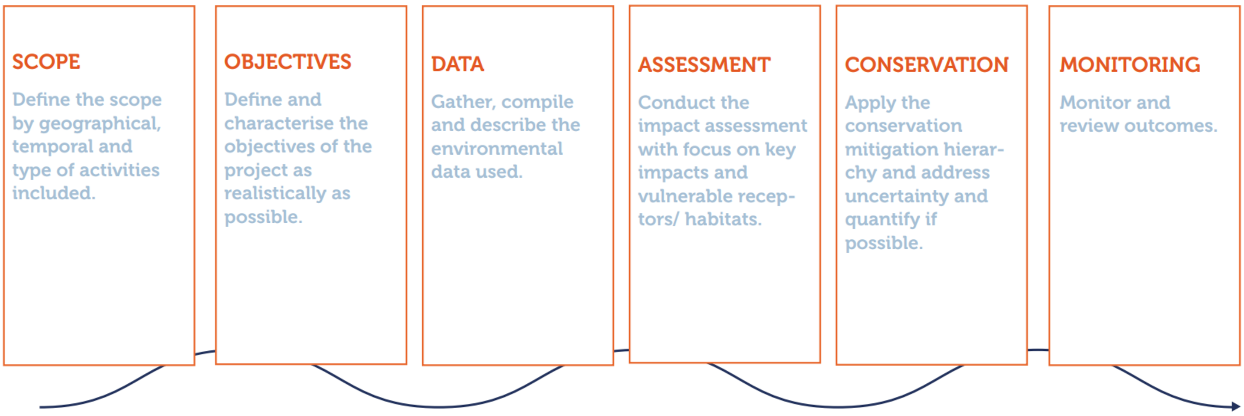

Figure 4.1 The general workflow of a Cumulative Effects Assessment (JPI Oceans, 2024).

4.2.1 DAPSIR

General introduction

The DAPSIR (Drivers-Activities-Pressures-State-Impacts-Responses) framework is an evolution of the traditional DPSIR (Drivers-Pressures-State-Impact-Response) model developed by OSPAR[3] (OECD, 1993), designed to better capture the complexity of human-environment interactions (Atkins, et al., 2011; Elliott, et al., 2017).

Method

The DAPSIR framework provides a structured approach to assess how socio-economic drivers lead to human activities, which in turn exert pressures on ecosystems, affecting their state and generating impacts on ecosystem services and human welfare (see Figure 4.2). Responses are then formulated to mitigate or adapt to these impacts.

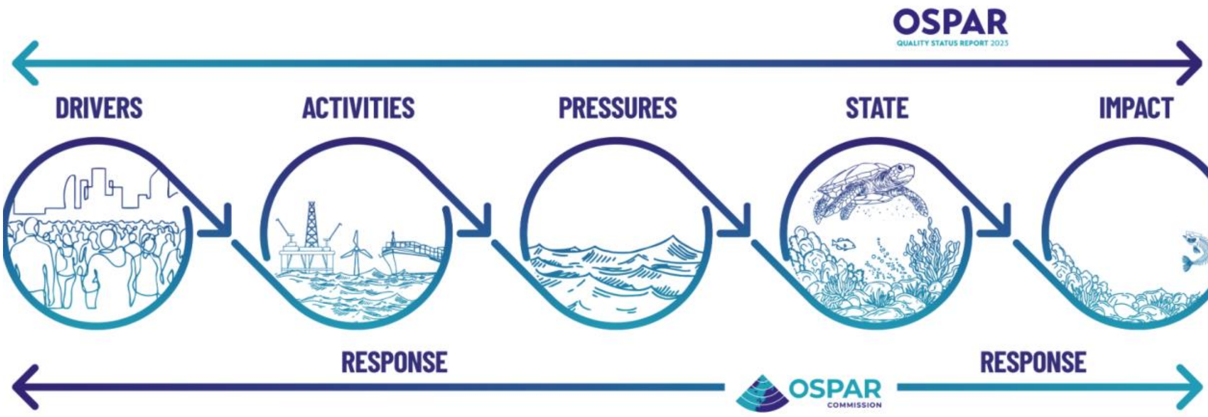

Figure 4.2: The DAPSIR framework that underpins assessments conducted under the QSR 2023 (OSPAR, 2023a).

Applicability and limitations

The DAPSIR framework is particularly valuable for structuring thematic assessments and guiding policy responses in complex marine environments. It is flexible and scalable, applicable to various sectors and regions. Supports ecosystem-based management and natural capital accounting. The framework is however dependent on data quality and model assumptions, especially for pressure-state-impact linkages.

Examples of use

DAPSIR was used by OSPAR in the Quality Status Report 2023 to quantify pressures and assessing their cumulative effects in the Northeast Atlantic (OSPAR, 2023a). For instance, it was used to identify key pressures and impacts from offshore wind, fisheries, and shipping (OSPAR, 2023b). Research by Bekhuis (2021) also applied DAPSIR to explore future socio-economic and environmental scenarios in the Northeast Atlantic, highlighting uncertainties and opportunities for sustainable development.

Summary

The DAPSIR framework is a well-ordered system for understanding and managing cumulative effects in marine environments. It provides a clear structure for linking human activities to environmental change and supports integrated responses.

[3] The OSPAR Convention is a binding international agreement that governs environmental cooperation among 15 European countries, including Denmark, and the European Union (OSPAR, 2025). It was adopted in 1992, merging and updating the earlier Oslo (1972) and Paris (1974) Conventions, and entered into force in 1998. The OSPAR Convention establishes a legal framework for preventing and eliminating pollution from land-based sources, offshore activities, and dumping at sea, while also promoting the protection of biodiversity and ecosystems. Through its annexes, OSPAR sets out specific obligations for the Contracting Parties, including monitoring, reporting, and implementing measures to reduce hazardous substances, eutrophication, and radioactive discharges.

4.2.2 KEC

General introduction

The Framework for Assessing Ecological and Cumulative Effects (KEC) is used to calculate the possible effects of existing and future offshore wind farms on the populations of protected species and their habitats. The KEC is continuously refined and supplemented with the latest insights, with an updated version released approximately every two years. In addition to the most recent insights from new research, each updated version also includes calculations of the cumulative effects of a new wind farm scenario. Assumptions that were made earlier are continually refined by new insights. The most recent version of the KEC, KEC 5.0, dates from April 2025 (Rijkswaterstaat, 2025), and includes updated models for birds, bats, and marine mammals, and uses scenario data for Dutch and international offshore wind farms.

Method

The KEC can be divided into three building blocks and a separate threshold component: 1) Conceptual Framework; 2) Knowledge base update, the KEC instruments; 3) Calculations, the KEC calculations, and; 4) ecological thresholds (Rijkswaterstaat, 2025). The drafting and adoption of the ecological thresholds is stated as an important last step but not a part of the actual KEC methodology. The thresholds are subject for governmental decision. The description and assessment of the cumulative effects of plans and projects in the KEC is a step-by-step procedure based on the DPSIR method (see section 4.2.1) (Rijkswaterstaat, 2025).

Applicability and limitations

The Framework for Assessing Ecological and Cumulative Effects (KEC) is developed for governments and agencies that make decisions regarding offshore wind energy. The framework supports identification and assessment of cumulative impacts related to development of offshore wind. The framework provides information on recent methods and knowledge as well as information on uncertainties and lack of knowledge within the field (Rijkswaterstaat, 2025). The framework has a limited focus on known significant, adverse impacts related to protected species and the effects on population levels of these species (Rijkswaterstaat, 2025). Thereby the calculations from the framework can be used as an input in a larger CEA. The calculations in the framework are based on mechanistic models providing quantitative calculations on the impacts. When calculating for cumulative impacts, assumptions regarding future windfarms are based on a precautionary principle meaning that worst-case assumptions are included in the calculations (Rijkswaterstaat, 2025). It is important to be aware that some of the calculations presented in the framework represents more than what is legally required, while other calculations included in the framework represent less than the legally required minimum (Rijkswaterstaat, 2025).

Examples of use

The KEC has been used in the Netherlands, as part of the Offshore Wind Energy Ecological Programme, also called the Wozep programme (Rijkswaterstaat, 2023). The Wozep research results are then used to improve these KEC calculations.

Summary

KEC is a Rijkswaterstaat framework for assessing ecological and cumulative impacts of offshore wind farms on protected species. Updated every two years, the latest version (KEC 5.0, April 2025) uses mechanistic models and precautionary assumptions to calculate cumulative effects. It supports government decision-making, focuses on significant population-level impacts, and applies the DPSIR approach (see section 4.2.1). KEC is used in the Netherlands within the Wozep programme to refine its models.

4.2.3 CEAF

General introduction

The Common Environmental Assessment Framework (CEAF) was a key output of the SEANSE project. For the assessment of cumulative effects, a set of coherent methods and approaches was compiled and further developed within the CEAF (SEANSE project partners, 2018). The CEAF was designed to be flexible and applicable across national contexts, initially North Sea countries, facilitating cross-border cooperation and harmonisation of environmental assessments (van Oostveen, et al., 2018). The aim was for CEAF to provide a common framework and language to discuss the potential impacts of wind farm development plans (Rijkswaterstaat, 2018).

Method

The CEAF uses an adaptive management approach and considers potential future scenarios of offshore wind development and their ecological consequences. It incorporates species distribution data, construction timelines, and turbine specifications to estimate impacts (Figure 4.3). CEAF was tested on three offshore wind scenarios in the southern North Sea, assessing cumulative collision mortality and displacement for four seabird species (e.g., black-legged kittiwake, red-throated diver) (Leemans, et al., 2019). A separate study modelled the cumulative effects of underwater noise from wind farm piling on harbour porpoise populations, using acoustic propagation and population response models (de Jong, et al., 2019).

Applicability and limitations

CEAF is considered a prototype method tested during SEANSE (2018–2019) and still intended for refinement. The CEAF method provide a structured and transferable approach to cumulative impact assessment in MSP. However, the method is case study-based, meaning its outputs depend heavily on the quality and scope of input models and data. It does not produce standardized metrics of ecological vulnerability or population-level effects, which limits its use for quantitative impact thresholds.

Examples of use

CEAF was used to assess cumulative seabird impacts from offshore wind scenarios in the southern North Sea areas of Belgium, Germany, and the Netherlands (Leemans, et al., 2019), and assess transboundary cumulative impacts of large-scale offshore wind development in German and Duch waters (SEANSE project partners, 2018). A regional case study in East Scotland evaluated cumulative effects of wind farm development on marine mammals (de Jong, et al., 2019).

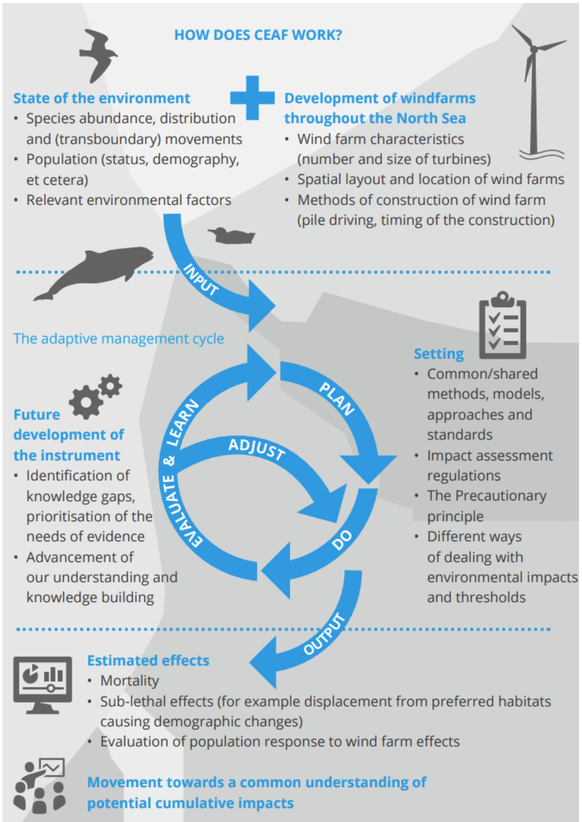

Figure 4.3: Conceptual presentation of the Common Environmental Assessment Framework (CEAF) (Rijkswaterstaat, 2018).

Summary

The CEAF methodology may support ecosystem-based MSP and facilitates cross-border harmonisation of cumulative impact assessments. While it lacks standardized metrics for ecological vulnerability and relies on case-specific modelling, it is a valuable method for identifying data needs, impact pathways, and planning trade-offs in offshore wind development.

4.2.4 Bayesian network-based CEA framework

General introduction

The Bayesian network-based CEA framework proposed by Furlan, et al., (2020) was developed to address the complexity of evaluating cumulative impacts from offshore renewable energy developments in the UK, particularly under the influence of climate change. This framework integrates ecosystem-based management principles with probabilistic modelling through Bayesian networks, which are capable of representing nonlinear relationships, feedback loops, and uncertainty inherent in marine ecosystems and climate-driven processes (Furlan, et al., 2020).

Method

The core of the framework is the Habitat Risk Assessment Dynamic Bayesian Network (HRA-DBN). This model combines physical and biological indicators, trophic interactions, and anthropogenic pressures such as offshore wind farms. Dynamic Bayesian networks are used to model temporal changes in ecosystem states and evaluate risk under different scenarios. Data inputs include empirical observations, simulation outputs, and expert knowledge, making the approach flexible in situations where data availability is limited. The outputs of the model include risk scores for habitats and species, as well as spatially explicit maps that can be integrated into GIS platforms for marine spatial planning. These outputs are particularly useful for strategic environmental assessments and licensing processes, as they provide decision-makers with a clear representation of cumulative impacts under various development and climate scenarios.

Applicability and limitations

Although designed for UK offshore renewable energy projects, the framework can be adapted to other regions facing similar challenges. It supports strategic planning by identifying biodiversity hotspots and keystone species and facilitates compliance with regulatory requirements under SEA and EIA directives. The probabilistic nature of Bayesian networks makes the framework suitable for addressing data scarcity, as it can incorporate expert judgment alongside empirical data. This is critical for marine environments where monitoring programs are often limited in scope and duration (Furlan, et al., 2020).

The framework needs large, high-quality datasets for reliable predictions, which are often scarce in marine environments. Building and calibrating Bayesian networks is resource-intensive, requiring specialized expertise and computational power. When empirical data are lacking, reliance on assumptions and expert judgment can introduce bias. Although adaptable, applying the framework to new regions or ecosystems often requires significant customization, including developing new network structures and parameters.

Examples of use

The framework has been applied in UK North Sea case studies to predict species redistribution under climate change, such as fish shifting about 70 km per decade. It has also assessed cumulative effects of multiple offshore wind farms on seabirds, marine mammals, and fish, supporting the design of compensatory measures and ecosystem-scale mitigation strategies. While tools like iPCoD, DEPONS, and SeaBord are commonly used in licensing, the Bayesian network approach enhances these by incorporating multi-stressor interactions and climate variability (Furlan, et al., 2020).

Summary

The Bayesian network-based CEA framework offers a robust and holistic approach to CEAs for OWF developments. Its strengths lie in its ability to integrate climate change considerations, handle uncertainty, and provide spatially explicit outputs for decision-making. Looking ahead, the framework has the potential to evolve into a shared online platform for regulators, developers, and stakeholders, supporting ecosystem-based management and adaptive planning in the context of offshore renewables.

4.2.5 The Halpern method – Cumulative impact mapping

General introduction

The Halpern method for cumulative impact mapping first developed by Halpern, et al., (2008), and later updated (Halpern, et al., 2015b; Halpern, et al., 2025), is a spatially explicit method for visualizing the combined effects of multiple human activities on marine ecosystems at a large scale. It overlays anthropogenic activities with environmental features to identify areas of high cumulative pressure. While the method is effective for identifying spatial hotspots of human influence, it simplifies the complexity of ecological responses by focusing on presence and intensity rather than specific pressure types or ecological consequences. The Halpern method is widely used in marine spatial planning, environmental assessments, and ecosystem-based management. It supports decision-making by highlighting areas where conservation efforts or regulatory measures may be most needed. Several other tools and frameworks build upon this approach by Halpern, et al., (2008), such as Symphony, Tool4MSP, BSII CAT, and MYTILUS, which are all accounted for in the next sections.

Method

The approach of the Halpern method follows four main steps:

1. Compile Data: Human stressors (e.g., fishing, shipping, pollution, climate change), and marine ecosystems (e.g., coral reefs, seagrass beds, pelagic zones). Represent all data on a common grid.
2. Normalize Stressor Intensity: Scale each stressor layer to a 0–1 range based on its maximum observed intensity.
3. Assign Sensitivity Scores: For each ecosystem–stressor pair, assign a vulnerability score (0 = no impact, 1 = high impact) using expert judgment and literature.
4. Calculate Cumulative Impact for each 1 km^2 grid cell as follows:

$$I_C = \sum_{i=1}^{n} \sum_{j=1}^{m} D_i \times E_j \times \mu_{i,j}$$

D_i = log-transformed and normalized intensity of stressor i

E_j = presence or absence of ecosystem j

$\mu_{i,j}$ = impact weight for the anthropogenic driver i and ecosystem j

The results of the Halpern method are heat maps showing relative cumulative impact values (e.g. Figure 4.4).

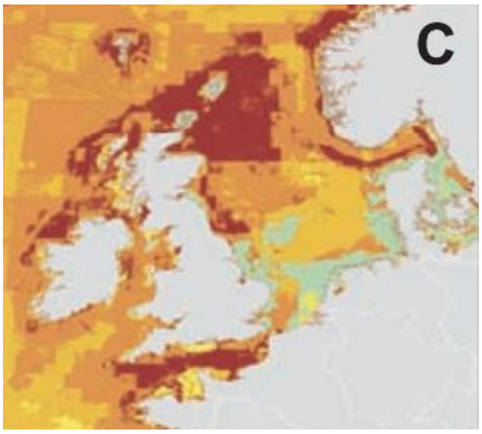

Figure 4.4: Example of heat map output from Halpern, et al., (2008), showing the highly impacted areas (dark red) in the Norh sea.

Applicability and limitations

The Halpern method may be used as a powerful visualization tool, valuable for preliminary assessments and stakeholder engagement. However, the model assumes that stressors combine additively, ignoring synergistic or antagonistic interactions between pressures. Studies show that ecological responses to multiple stressors are often nonlinear, which can lead to under- or overestimation of impacts (Halpern & Fujita, 2013). It has been commented that fishing impacts were assumed to occur only at catch locations, ignoring the broader ecological footprint (e.g., gear damage, bycatch). This spatial mismatch can misrepresent actual ecosystem impacts (Heath, 2008). Vulnerability scores for ecosystem-stressor combinations are mainly based on expert judgment, not dynamic ecological data. They do not account for context-specific resilience or recovery rates. It does not account for pressure magnitude in a dynamic or temporal context (e.g., seasonal variations, long-term trends) (Halpern & Fujita, 2013). Original 2008 model of the cumulative impact mapping was a snapshot, not accounting for changes over time. Later updates (Halpern, et al., 2015b) addressed this by adding trend analysis.

Examples of use

Halpern et al. (2008) applied cumulative impact mapping to assess cumulative human impacts across the world's oceans, identifying regions with high anthropogenic pressure such as the North Sea, South China Sea, and parts of the Mediterranean. CUM has been used to account for human pressures and their potential impact on the Baltic Sea ecosystem (Korpinen, et al., 2012), and used in regional marine spatial planning efforts, such as in British Columbia, the Baltic Sea, and the U.S. West Coast, to inform zoning and conservation priorities. Recent adaptations of the Halpern method incorporate climate-related stressors (e.g., ocean acidification, sea temperature rise) to assess future risks (Halpern, et al., 2015b).

Summary

The Halpern method is used for visualizing cumulative pressures on marine ecosystems. It provides a clear spatial overview of where human activities overlap with sensitive habitats, aiding in prioritization and planning. Several other tools and frameworks build upon the approach by Halpern, et al. (2008), such as Symphony, Tool4MSP, BSII CAT, and MYTILUS, which are all accounted for in the next sections.

4.2.6 BSII CAT

General introduction

The Baltic Sea Impact Index Cumulative Impact Assessment Toolbox (BSII CAT) was developed in EU co-funded Pan Baltic Scope project by HELCOM (Baltic Marine Environment Protection Commission) to support cumulative impact assessments in the Baltic Sea region (HELCOM, 2017; Bergström, et al., 2019). It is part of a suite of spatial tools designed to quantify the combined effects of multiple human pressures on marine ecosystems. The toolbox builds on the methodology introduced by Halpern et al., (2008) and has been applied in HELCOM's holistic assessments (HOLAS II and III) (HELCOM, 2017).

Method

The BSII CAT includes several integrated tools (HELCOM, 2017; Bergström, et al., 2019):

- BSII Tool: Calculates cumulative impacts using spatial data layers on pressures and ecosystem components, combined with a sensitivity score matrix. Outputs include:
  - BSII grid layer
  - BSII statistics matrix showing contributions of each pressure-ecosystem combination
- BSPI Tool: Calculates cumulative pressure intensity without considering ecosystem components, but weights pressures based on average sensitivity scores.
- For both BSII and BSPI the assessments are based on assessment of grid cells of 1 square kilometres, where BSII is the sum of all impacts on the ecosystem components in each grid cell, and BSPI is the sum of pressure intensities in each grid cell.
- Ecological Value Tool (EV Tool): Identifies areas of high ecological value using ecosystem component data and ecological value matrices.
- Ecosystem Service Tool (ES Tool): Assesses areas with high potential for ecosystem service provision using ecosystem component data and service matrices.
- BSII Batch Tool: Performs batch calculations (calculations on a group of data points at once rather than individually) of BSII for ecological value or ecosystem service areas.
- Sensitivity Score Matrix Tool: Generates customized sensitivity matrices by combining existing BSII matrices with ecological value or ecosystem service coefficients.

Applicability and limitations

The BSII CAT is suitable for regional cumulative impact assessments, marine spatial planning (MSP), identifying ecologically valuable or vulnerable areas, and scenario analysis for ecosystem services and pressures. The BSII CAT tools support ecosystem-based management and transboundary cooperation in the Baltic Sea region. However, the BSII CAT does not provide temporal modelling as it focuses on spatial patterns without time-series analysis. It also mainly provides static sensitivity scores, as it is based on expert judgment and may not reflect dynamic ecological responses. BSII CAT is also tailored to the Baltic Sea region, and adaptation to other regions may require significant data and calibration.

Examples of use

Used in HELCOM HOLAS II and III assessments to evaluate cumulative impacts across the Baltic Sea. Applied in Pan Baltic Scope to support MSP and identify priority areas for conservation and ecosystem service provision (Bergström, et al., 2019). Integrated into HELCOM's online map viewer and GitHub repository for open access (GitHub, 2025).

Summary

BSII CAT provides a comprehensive and regionally tailored assembly of tools for assessing cumulative impacts in the Baltic Sea. Its modular design and integration with ecological value and ecosystem service assessments make it a powerful tool for MSP and environmental planning. Future enhancements could include dynamic modelling and broader applicability beyond the Baltic region.

4.2.7 Tools4MSP

General introduction

The Tools4MSP CEA module is a geospatial tool developed to support ecosystem-based maritime spatial planning (MSP) (Menegon, et al., 2018). The Institute of Marine Sciences of the Italian National Research Council (CNR-ISMAR) developed the tool. It builds on the global CEA methodology introduced by Halpern et al., (2008) and adapted for regional applications such as the Adriatic Sea. The tool enables planners to identify and monitor cumulative pressures from human activities on marine ecosystems, including transboundary impacts.

Method

The Tools4MSP method investigates the source of the environmental pressure and the connected pathways and interactions. The method gives the pressures a weight and evaluates the vulnerability and consequences connected to the different pressures.

The Tools4MSP CEA depends on the following inputs:

- Area of analysis
- Grid cell resolution
- Layers of human activities (intensity of human uses)
- Environmental components
- Pressure weights
- Distance of pressure spread
- Sensitivities of environmental components
- Ecological models on the components respond to pressures

Applicability and limitations

Tools4MSP CEA is suitable for: transboundary planning; Identifying high-impact areas and pressure hotspots; supporting strategic planning and scenario analysis (e.g., future development vs. conservation); and informing transboundary management strategies, ecosystem-based management. The tool directly supports key MSP steps, such as defining current conditions, data gathering and baseline assessment; identifying constraints and future conditions; and evaluating alternative management actions. However, Tools4MSP use expert-based inputs (e.g., sensitivity scores, pressure weights) which may vary by region and require stakeholder validation. The tools also rely on static assumptions in pressure propagation unless enhanced with external models (e.g., hydrodynamic data), and it does not include temporal dynamics unless integrated with time-series datasets.

Examples of use

Tools4MSP was originally developed within the ADRIPLAN Project (2013–2015), which focused on maritime spatial planning in the Adriatic-Ionian region, including cumulative impact assessments for activities such as maritime transport, fisheries, and aquaculture. It was later enhanced under the Italian Flagship Project RIT-MARE and integrated into the Tools4MSP Geoplatform, a collaborative, web-based system for MSP analysis built on GeoNode. Tools4MSP is a Python-based Free and Open-Source Software (FOSS), available as a stand-alone library and as a GeoNode plugin, supporting advanced geospatial and statistical analysis. Typical outputs include geospatial maps of Marine Use Conflict (MUC) scores and cumulative effects assessment results for the selected area (Menegon, et al., 2018).

Summary

Tools4MSP is a geospatial tool for maritime spatial planning that assesses cumulative impacts of human activities on marine ecosystems. It builds on Halpern et al.'s (2008) global methodology and adapts it for regional contexts like the Adriatic Sea. Outputs include maps that support strategic planning, scenario analysis, and transboundary management. Its integration into MSP workflows and support for scenario analysis make it a valuable tool for ecosystem-based planning. However, its reliance on expert-derived parameters and lack of temporal modelling highlight areas for future enhancement (Menegon, et al., 2018).

4.2.8 Symphony

General introduction

Symphony is a scenario-based CEA tool and an ecosystem-based marine spatial planning tool, developed to assess the pressures of human activities on nature/ecological values in the Swedish Seas (Hammar, et al., 2020), based on generic CEA principles of Halpern et al. (2008). Symphony is developed by the Swedish Agency for Marine and Water Management (SwAM, 2020). The tool uses distribution maps of ecosystem components and spatial information on the intensity of environmental pressures, combining these into a sensitivity matrix of each component to the various pressures. The cumulative impact for areas is calculated by adding up the individual pressures from all ecosystem components. The results can be presented as heat maps (Hammar, et al., 2020). New utilisations of the Symphony tool have included future climate change effect of temperature, salinity, and ice cover which have been implemented as human pressure layers (Wåhlström, et al., 2022; Järnberg, et al., 2023).

Method

Symphony calculates cumulative impacts using a grid-based approach, dividing Sweden's territorial waters and Exclusive Economic Zone (EEZ) into cells. The method involves five key steps:

1. *Mapping ecosystem components and human-induced environmental pressures.*
2. *Developing an expert-based sensitivity matrix to assess ecosystem reactions to these pressures.*
3. *Calculating baseline cumulative impacts using GIS-based maps following Halpern et al.,* (2008).
4. *Analysing alternative MSP scenarios.*
5. *Generating visual MSP results with heat maps and sector analysis.*

Applicability and limitations

Symphony is specifically designed for cumulative impact assessment in marine environments. It is particularly useful during the initial stages of MSP, allowing planners to identify areas of concern and evaluate the ecological consequences of different spatial scenarios. Its strength lies in its ecosystem-based approach, spatial resolution, and ability to integrate multiple pressures. However, it relies heavily on expert judgment for sensitivity scoring and does not directly model population-level ecological effects or long-term ecological dynamics. The Symphony tool is also limited by restricted data inclusivity (e.g. historical or seasonal data cannot be included in the tool) and limited ecological connectivity (e.g. species interactions via food webs are absent). Thus, Symphony is not an appropriate tool to account for in-combination effects.

Limitations

Results provided by Symphony are based on the best available data, but this often includes several uncertainties. While some nature values have been mapped in detail in some areas, other areas are modelled based on extrapolated data (from data nearby) consisting of few observations. The accuracy of the available data will increase if more areas are being mapped, which will increase the reliability of the modelled results.

Examples of use

Symphony was used in the development of Sweden's national maritime spatial plans to assess cumulative impacts and support ecosystem-based planning (Hammar, et al., 2020). Symphony was applied to identify areas of ecological concern in the Baltic Sea and guide offshore wind development while minimizing environmental conflicts (Hammar, et al., 2020). Symphony has later been used in several international collaborations, including NorthSEE, Baltic LINes, and ClimeMarine. Symphony has also been included in international collaborations with countries in the Western Indian Ocean through SwAM's Program for Development Cooperation *(*SwAM Ocean 2019–2022) (Willsteed, et al., 2024).

Summary

Symphony is a robust and purpose-built tool for cumulative impact assessment in marine spatial planning. It enables planners to visualize and quantify the combined effects of multiple human activities on marine ecosystems, supporting informed decision-making and sustainable ocean use. While it does not model ecological thresholds or long-term population dynamics, its integration of spatial data, expert knowledge, and scenario analysis makes it a valuable component of ecosystem-based MSP frameworks. There are examples of the use of Symphony internationally, including Sweden. NIVA Denmark has contributed to the development of the tool with data from Swedish waters, and there is potential for it to also be used in Denmark.

4.2.9 MYTILUS

General introduction

MYTILUS is an open-source tool developed in capacity-building MSP projects for active learning environments and aims to better assess the cumulative impact of human pressures on marine ecosystems and improve stakeholder engagement (Hansen, 2019). The tool is inspired by the method developed by Halpern, et al., (2008). It was created and developed as part of the Interreg NSR NorthSEE and BONUS BASMATI projects, respectively, with development led by Henning Sten Hansen at Aalborg University (Hansen, 2019). The tool is designed to support ecosystem-based maritime spatial planning (MSP) by enabling scenario-based analysis of various maritime activities and their ecological consequences (Bonnevie, et al., 2022).

Method

The method is inspired by the method developed by Halpern, et al., (2008), and includes three types of data categories; spatial pressures from human activities, spatial ecosystem components, and expert-derived sensitivity scores that evaluate each pressures' effect on each ecosystem component. As for the method developed by Halpern, et al., (2008), an impact is calculated for each grid cell using a mathematical formula. The mathematical formula is adopted from Halpern, et al., (2008) (see section 4.3.1) (Bonnevie, et al., 2022). With the MYTILUS tool it is possible to develop different scenarios and for example compare a baseline scenario with an adapted scenario, for visual comparison (Bonnevie, et al., 2022). An important priority when developing the design of MYTILUS was to provide an intuitive, easy-to-learn interface with focus on strong use of maps and visuals and to improve the usability found in other well-known CEA tools.

Applicability and limitations

MYTILUS is particularly useful for: assessing cumulative impacts of multiple maritime activities; supporting MSP processes through scenario comparison; engaging stakeholders in planning discussions with fast, visual feedback. However, as the tool use expert-based sensitivity values this may introduce subjectivity. The model does not account for time-based changes or pressure frequency, and it focuses on presence/absence rather than dynamic ecological processes and cause-effect relationships between different components (Bonnevie, et al., 2022)

Examples of use

Used in BONUS BASMATI and NorthSEE projects to assess cumulative impacts in the Baltic and North Sea regions (Hansen, 2020). Applied in stakeholder workshops to demonstrate the effects of different spatial planning proposals (VASAB Workshop Report, 2021).

Summary

MYTILUS offers a flexible and accessible, and open-source, platform for cumulative impact assessment in marine environments. Its scenario-based design and rapid calculation capabilities make it ideal for participatory MSP processes. However, its reliance on static sensitivity values and lack of temporal modelling suggest areas for future development.

4.2.10 Marine Cumulative Effects Assessment (CEA)

General introduction

The Marine Cumulative Effects Assessment (CEA) tool, developed by Lonsdale et al., (2020) is a dedicated CEA approach. The tool considers the three-dimensional (3D) nature of the marine environment, and the spatial and temporal effects-footprints likely to occur during the lifetime of a development (Lonsdale, et al., 2020). The tool is increasingly relevant as offshore wind and other marine developments expand, requiring robust methods to evaluate cumulative environmental impacts (Lonsdale, et al., 2020).

Method

The Marine CEA tool models both the spatial and temporal impacts of maritime activities. It integrates spatio-temporal data on human activities with data on the sensitivity of marine receptors to various pressures. A key feature is its consideration of the three-dimensional nature of marine environments, including the duration and operational phases of developments. This enables quantification of impacts over time and space, supporting more realistic and comprehensive assessments. Integrated within a GIS platform, this tool provides an effective visual representation (Lonsdale, et al., 2020).

Applicability and limitations

The Marine CEA tool is notable for its ability to account for the three-dimensional structure of marine space and the duration of developments. The visual representations make the tool useful in decision making processes (Lonsdale, et al., 2020). However, its effectiveness is often limited by the availability and quality of input data, particularly for long-term and large-scale effects. For assessing the temporal trends and effects, there is a need for improving the temporal data (Lonsdale, et al., 2020).

Examples of use

The Marine CEA tool was developed and applied in the UK. However, the approach is also meant to be used worldwide to assess the cumulative impacts of offshore wind developments and other marine activities (Lonsdale, et al., 2020).

Summary

The Marine CEA tool provides a comprehensive, marine-specific approach to cumulative effects assessment. Its strengths include the integration of the three-dimensional nature of marine environments,, and its applicability to a wide range of marine activities. However, it remains data-dependent.

4.2.11 North Sea Pressure Index (NSPI) and North Sea Impact Index (NSII)

General introduction

The North Sea Pressure Index (NSPI) and North Sea Impact Index (NSII) were developed as part of the HARMONY project (2010–2012), a transnational collaboration involving Denmark, Germany, Norway, and Sweden, coordinated by Aarhus University (Sørensen, et al., 2012; Andersen, et al., 2013). These indices were designed to provide harmonized, spatially explicit assessments of cumulative human pressures and their potential impacts on marine ecosystems in the Greater North Sea sub-region. The development of NSPI and NSII was motivated by the need for standardized tools to support the implementation of the EU Marine Strategy Framework Directive (MSFD) and to facilitate cross-border marine spatial planning (MSP) and ecosystem-based management. The methodology is inspired by the approach of Halpern et al., (2008).

Method

Both NSPI and NSII use a grid-based GIS framework to integrate spatial data on human activities and ecosystem components:

- NSPI (Pressure Index): The NSPI quantifies the intensity and spatial distribution of anthropogenic pressures in the North Sea. It aggregates data on multiple human activities (e.g., shipping, fisheries, offshore wind, pollution) into a single pressure score for each grid cell. The index is calculated by normalizing and summing the intensity of each pressure type, allowing for comparison across regions and activities. The NSPI corresponds in concept to the Baltic Sea Pressure Index (BSPI) presented by for instance (Korpinen, et al., 2012).

- NSII (Impact Index): The NSII builds on the NSPI by incorporating the sensitivity of ecosystem components to each pressure. For each grid cell, the NSII multiplies the pressure intensity (from NSPI) by expert-derived sensitivity scores for relevant ecosystem components (e.g., benthic habitats, fish, birds, mammals). The resulting impact scores provide an estimate of the cumulative risk or potential effect of human activities on marine ecosystems.

Both indices rely on harmonized data layers, standardized sensitivity matrices, and transparent documentation of assumptions and uncertainties. The methodology is inspired by the approach of Halpern et al., (2008).

Applicability and limitations

The NSPI and NSII are designed for strategic-level cumulative effects assessment, supporting ecosystem-based management, marine spatial planning, and conservation strategies in the North Sea. Their main strengths are:

- Transnational harmonization of data and methods
- Compatibility with MSFD and OSPAR frameworks
- Ability to visualize and compare cumulative pressures and impacts across regions

However, both indices have limitations:

- Heavy reliance on expert judgment for sensitivity scoring using NSII
- Static approach that does not account for temporal dynamics or synergistic/antagonistic interactions between pressures
- Results depend on the quality and consistency of input data, which can vary between countries

Examples of use

The NSPI and NSII were used to produce the first transnational cumulative impact maps for the North Sea, informing marine spatial planning and conservation at both national and regional levels (Andersen, et al., 2013).

The indices have contributed to the harmonization of cumulative effects assessment practices under the MSFD and OSPAR frameworks.

Summary

The North Sea Pressure Index (NSPI) and North Sea Impact Index (NSII) provide harmonized, spatially explicit tools for assessing cumulative human pressures and their potential impacts on marine ecosystems in the North Sea. Their emphasis on cross-border cooperation and standardized methodologies has set a precedent for future transnational assessments. While limitations remain regarding dynamic modelling and ecological interactions, NSPI and NSII remain valuable resources for strategic planning, MSP, and implementation of the MSFD in the North Sea region.

4.2.12 Zonation

General introduction

Zonation is a set of spatial conservation planning methods and analyses implemented in one package, developed by the Finnish Environment Institute to inform conservation planning decisions (Moilanen, et al., 2005; Moilanen, et al., 2009; Minin, et al., 2014). The tool uses spatial data on biodiversity features (i.e., species distribution, habitat, ecosystem services), costs and threats to provide outputs of priority rank maps and performance curves. Zonation is designed to produce balanced priority rankings, distributing conservation targets across multiple features rather than focusing on a single set target.

Method

Zonation operates by integrating biodiversity data, threats, and costs to generate spatially explicit priority maps and performance curves. The algorithm iteratively removes the least valuable spatial units, ensuring that the most important areas for biodiversity and ecosystem services are retained until the end of the process. This approach allows for the identification of areas that contribute most to overall conservation value, even when trade-offs are necessary (Minin, et al., 2014).

Applicability and limitations

The Zonation software is not a specifically designed CEA tool (Moilanen, et al., 2009). It has however been used to model conservation actions and development conflicts with ecological features. Its strength lies in spatial prioritisation and the ability to visualise trade-offs between conservation and development objectives. However, it does not directly quantify cumulative pressures or population-level impacts, which limits its use for detailed CIA. Modern applications leverage big data and digital platforms, enabling Zonation to process large, multi-layered datasets (e.g., species, habitats, human activities) for more robust and transparent decision-making. This is particularly relevant for offshore wind planning, where multiple pressures and stakeholders must be considered.

Examples of use

Zonation has been applied to balance conservation and development priorities, including the siting of offshore wind farms, by identifying areas of high biodiversity value and potential conflict in the Baltic Sea. Recent scenario analyses have used Zonation and similar spatial models to inform MSP and support ecosystem-based management in heavily used marine coastal regions, for instance in the North Sea (Edelvang, et al., 2017).

Summary

Zonation is effective for spatial conservation planning and for supporting ecosystem-based marine spatial planning, especially where multiple objectives and stakeholders are involved. However, its limitations include a lack of direct assessment of cumulative pressures and population-level effects, making it best used in combination with other CEA tools for comprehensive impact assessment.

4.2.13 CUMELEO

General introduction

The CUMELEO is a methodological model designed for quantitative cumulative impact assessments in the marine environment, specifically for offshore wind development, and applied regionally to the Wadden Sea and Dutch North Sea coastal zone (de Vries, et al., 2011; de Vries, et al., 2011). It provides a structured approach to quantify how multiple human activities affect marine species and habitats at a population level. Originally designed to support policy and environmental planning, CUMELEO integrates spatial data and ecological sensitivity to evaluate the consequences of pressures such as shipping, fisheries, and coastal infrastructure (de Vries, et al., 2011).

Method

Activity-to-Pressure Mapping: Links human activities (e.g., shipping, fishing, dredging) to specific pressures (e.g., noise, abrasion, pollution), see Figure 4.5.

Pressure-to-Impact Assessment: Evaluates how pressures affect ecosystem components based on intensity and sensitivity.

Stepwise approach:

1. Scoping – Define spatial and temporal boundaries.
2. Identification – Select ecosystem components, pressures, and activities.
3. Assessment – Quantify intensity of activities, pressure propagation, and ecosystem sensitivity.

Calculation: Combines pressure intensity and sensitivity scores to estimate cumulative impact at population or ecosystem level.

Applicability and limitations

CUMELEO is particularly useful for assessing population-level impacts of human activities; supporting marine spatial planning and environmental permitting and evaluating trade-offs between development and conservation (de Vries, et al., 2011).

Examples of use

CUMELEO is applied to assess cumulative impacts of shipping, fisheries, and coastal infrastructure in the Wadden Sea and Dutch North Sea (de Vries, et al., 2011). CUMELEO has also been adapted for the Northeast Atlantic (van der Wal & Tamis, 2014).

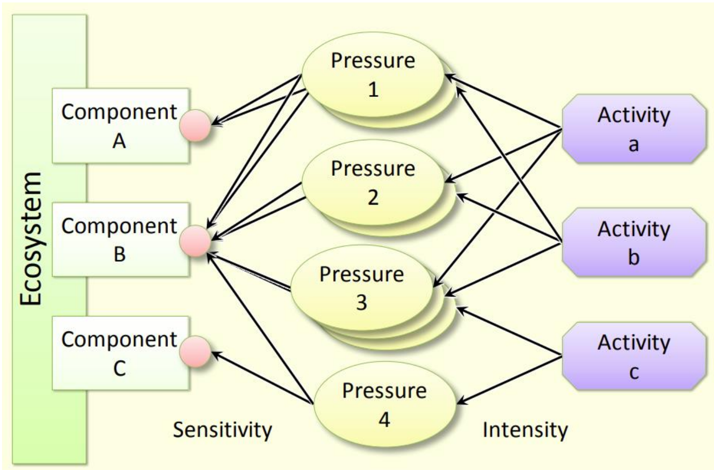

Figure 4.5: A generic outline of CUMULEO CEA-model in which relationships between activities, pressures and ecosystem components/ indicators need to be elucidated (Karman & Jongbloed, 2008; van der Wal & Tamis, 2014).

Summary

CUMELEO provides valuable insights into population-level effects of cumulative pressures in marine environments. Its spatial modelling capabilities and scenario-based approach make it a useful model for planning and for performing impact assessments. However, it requires enhancement to address temporal variability, ecosystem-wide interactions, and dynamic sensitivity.

4.2.14 Marxan

General introduction

Marxan is a spatial conservation planning tool developed to support the design of cost-effective protected area networks (Ball, et al., 2009; Studwell, et al., 2021). It uses a target-based approach, identifying sets of planning units that meet conservation goals while minimizing costs and spatial fragmentation. The tool was not originally designed for CEAs, but it can be adapted to identify risk zones and support marine spatial planning. Like Zonation, Marxan informs conservation planning decisions, but differs in its target-based methodology. It returns a selection of areas that meet predefined conservation targets at the lowest possible cost.

Method

Marxan operates by using simulated annealing and iterative improvement algorithms to select spatial units that collectively meet conservation targets. It incorporates spatial data on biodiversity features, costs, and constraints to generate outputs such as selection frequency maps and heatmaps. These outputs highlight areas most frequently selected across multiple runs, indicating their importance in achieving conservation goals.

Applicability and limitations

Marxan is not a dedicated CEA tool. However, it can be adapted to inform CEA by using exposure to risk or ecological vulnerability as cost inputs. Its strength lies in spatial prioritisation and scenario analysis, making it useful for identifying trade-offs between conservation and development objectives. It does not directly quantify cumulative pressures or population-level impacts, which limits its use for detailed CEA.

Examples of use

Marxan was applied in the BaltSeaPlan and BALTSPACE projects to identify suitable offshore wind sites in the Pomeranian Bight / Arkona Basin, balancing wind availability, construction costs, and ecological constraints development (Göke, et al., 2018). Marxan was featured in the BaltSeaPlan Report 29 and the European MSP Platform as a tool for balancing energy targets with ecological and economic constraints, demonstrating its potential for cumulative impact-informed planning (European MSP Platform, 2018). Marxan has also been used in combination with the InVEST Habitat Risk Assessment (see section 4.2.14) model to prioritize seabird foraging habitats in the Greater Farallones and Cordell Bank National Marine Sanctuaries in California, USA, incorporating maritime activity risks as cost layers (Studwell, et al., 2021).

Summary

Marxan is an effective tool for spatial conservation planning and marine spatial prioritization, especially in contexts where specific conservation targets must be met efficiently. While it does not directly quantify cumulative pressures, it can be adapted to support risk-informed planning by using exposure or consequence layers as cost inputs. This makes it a valuable component in multi-tool CEAs, particularly for offshore wind development and ecosystem-based MSP.

4.2.15 InVEST

General introduction

The Integrated Valuation of Ecosystem Services and Tradeoffs toolbox (InVEST) is designed for scenario-based, ecosystem service-focused planning (Guerry, et al., 2012). InVEST is a suite of open-source spatial modelling tools developed by the Natural Capital Project, a collaboration between Stanford University, WWF, The Nature Conservancy, and the University of Minnesota (Tallis, et al., 2013; Sharp, et al., 2018). InVEST is designed to quantify and map ecosystem services and assess how changes in land or sea use affect the delivery of these services. It enables decision-makers to quantify the importance of natural capital, to assess the trade-offs associated with alternative choices, and to integrate conservation and human development. The tool is continuingly under development (Natural Capital Project, 2025).

Method

InVEST models are spatially explicit and use GIS data to simulate ecosystem service flows and impacts in maps. InVEST is used to explore how changes in ecosystem services lead to changes in benefits that flow to people, calculated in either biophysical terms or economic terms (Natural Capital Project, 2025). New versions of InVEST are open-source versions.

A part of the InVEST toolbox is the Habitat Risk Assessment (HRA), which evaluates:

- Exposure: The intensity and spatial overlap of human activities (e.g., shipping, fishing, offshore wind).
- Consequence: The vulnerability and response of specific habitats to those pressures.
- Risk: A combined score indicating the potential degradation of ecosystem services.

The HRA model can be applied under current and future scenarios, helping planners visualize areas of high ecological risk and prioritize mitigation strategies (Tallis, et al., 2013; Arkema, et al., 2014).

Applicability and limitations

InVEST is applicable to strategic-level CEA, especially where ecosystem service trade-offs are central to planning. Models can be adapted to local, regional, or global scales, and outputs are visual and interpretable, supporting stakeholder engagement. However, the models lack population-level ecological modelling, and as many other CEA tools they require expert input for parameterization and sensitivity scoring and depend on high-quality spatial data.

Examples of use

InVEST has been used to assess seabird habitat risk from maritime activities in the Greater Farallones and Cordell Bank National Marine Sanctuaries along the California coast (Studwell, et al., 2021). Applied to evaluate coral reef vulnerability under tourism and fishing pressures in Belize (Arkema, et al., 2014), and supported offshore wind planning by identifying ecological trade-offs in the Baltic Sea. InVEST has also be applied by governments, NGOs, and researchers in over 50 countries for marine and coastal planning (Tallis, et al., 2013).

Summary

InVEST is a powerful tool for ecosystem service-based cumulative impact assessment, offering spatially explicit insights into how human activities affect marine and coastal habitats. Its modular design and scenario capabilities make it ideal for multi-objective planning, especially in contexts involving offshore energy, habitat protection, and climate resilience. While it does not model ecological thresholds or population dynamics, it complements other CEA tools by focusing on ecosystem service risk and valuation.

4.2.16 SCAIRM

General introduction

The Spatial Cumulative Assessment of Impact Risk for Management (SCAIRM) method is a novel approach developed to assess cumulative ecological risks from multiple offshore activities. It was designed to support ecosystem-based marine spatial planning (MSP) and strategic environmental assessments, particularly in the context of multi-use (MU) marine configurations such as offshore wind combined with aquaculture, nature restoration, or tourism (Piet, et al., 2023; Tamis, et al., 2024). SCAIRM was developed as part of the Horizon Europe funded GES4SEAS project (GES4SEAS, 2024), and applied within the UNITED project which piloted multi-use platforms across European seas.

Method

SCAIRM investigates impact chains by linking causes from stressors to impacts through the three main elements: activities, pressures, and ecosystem components. The SCAIRM tool includes 42.333 impact chains in the North Sea (Tamis, et al., 2024; Piet, et al., 2023).

SCAIRM evaluates Impact Risk by combining:

- Exposure: The chance of spatial and temporal overlap between pressures (e.g. noise, habitat loss) and ecosystem components (e.g. fish, birds, marine mammals).
- Effect Potential: The pressure intensity and the ecosystem's resistance and recovery capacity.

The result of SCAIRM is an aggregation of the identified risk impacts representing the cumulative pressures. Thereby, the total Impact Risk can be calculated for each ecosystem component (Tamis, et al., 2024). Thus, SCAIRM can be used to help identify which pressures and activities pose the greatest risk to specific species or habitats. The method is scenario-based and allows comparison between single-use (SU) and multi-use (MU) configurations across installation, operation, and decommissioning phases.

Applicability and limitation

Key findings for the applicability of SCAIRM is summarised below (Piet, et al., 2023; Tamis, et al., 2024):

- Multi-use scenarios consistently showed lower or equal ecological impact risk compared to single use.
- The method supports ecosystem-based marine spatial planning (MSP) and aligns with EU directives like the MSFD and EIA directive.
- It enables scenario testing for different configurations and phases (installation, operation, decommissioning), helping planners communicate results, optimise spatial design, and reduce cumulative impacts.
- The method combines both qualitative and quantitative approaches and is flexible and scalable making the method suitable for both data-rich and data-poor contexts. Further, the method can be adapted to different sea basins and ecological conditions.

Using SCAIRM to evaluate multiple use only highlights negative impacts on the ecosystem components. However, positive environmental and social impacts can also occur from multiple use of areas (Tamis, et al., 2024).

Examples of use

SCAIRM has been applied in several real-world pilot studies under the UNITED project. Five pilots across the Baltic Sea, North Sea, and Mediterranean Sea tested multi-use configurations combining offshore wind, aquaculture (macroalgae, shellfish, finfish), nature restoration (e.g. flat oyster beds), solar energy, and tourism (e.g. diving, day trips) (Tamis, et al., 2024).

Summary

SCAIRM is a robust, spatially explicit, risk-based CEA tool tailored for marine environments. It is especially valuable for strategic planning in offshore wind development, offering a way to quantify and mitigate cumulative ecological impacts through scenario testing and multi-use optimisation. Its strengths include compatibility with EU policy frameworks, flexibility across ecological contexts, and support for integrated planning and decision-making.

4.3 Complementary tools

In addition to the CEA methods presented in the previous sections, there are other methods being developed that may be relevant for the CEA-advances in the context of offshore wind in Denmark and neighbouring countries, although these may deviate when it comes to the conceptual scope and therefore it seemed appropriate to segregate them. These deviations in conceptual scope include: a tool meant for the terrestrial environment; a tool tailored for geographic marine areas in principle not relevant for Denmark; a tool designed for the accounting for cumulative effects on the ecological and chemical state of water bodies; and an innovative approach to encourage development of new modelling- and visual tools useful for policy makers.

4.3.1 MARCIS

General introduction

MARCIS (Marine Spatial Planning and Cumulative Impacts on Seabirds) is a collaborative research project funded by the Research Council of Norway (2021–2025) and will be launched in 2025 (NINA, 2025). Its primary aim has been to develop a decision-support tool for assessing the cumulative impact of human marine industries on seabirds and migrating land birds in marine ecosystems.

Method

The tool combines spatial mapping, sensitivity analysis, and cumulative impact modelling. The approach is ambitious, involving high-resolution spatial data (10×10 km^2 grids), monthly temporal resolution, and integration of multiple stressors. MARCIS builds on the established cumulative impact assessment model by Halpern, et al. (2008), alongside agent-based and population-level modelling. The inclusion of radar tracking and machine learning for species identification in case studies (e.g., Hywind Tampen) demonstrates innovation. However, the success of this method depends heavily on data availability and quality, as well as the robustness of assumptions in sensitivity scoring. Data from the survey programs SEAPOP and SEATRACK provides datasets for MARCIS (NINA, 2025).

Applicability and limitations

MARCIS is intended for marine spatial planning, risk assessment, and policy support. If implemented effectively, the tool could provide significant value to regulators, industry stakeholders, and conservation bodies. Its ability to visualize cumulative impacts and test scenarios is a strong feature. However, practical uptake will depend on usability, transparency of the underlying models, and stakeholder trust in the outputs.

Examples of use

MARCIS has not yet been fully implemented as a standard tool, but there has been early application in a case study: the project developed an early demo version of the MARCIS app in 2023, using the Trollvind offshore wind farm area as a test case (NINA, 2023). The tool is still in development and co-design phase, with strong emphasis on collaboration between science, industry, and management. The current version allows scenario testing and visualization of cumulative impacts, but it is not yet widely deployed in regulatory or planning processes.

Summary

MARCIS is a forward-looking project that combines advanced ecological modelling, spatial data integration, and stakeholder engagement. By delivering a web-based decision-support tool, MARCIS will enable transparent, science-based planning and contribute to sustainable offshore wind development in the North Sea.

4.3.2 CHASE

General introduction

The Chemical Status Assessment Tool (CHASE*)* was developed, under the EU co-financed HELCOM BalticBOOST project, to provide an integrated assessment of chemical status in marine environments (Andersen, et al., 2016). It was originally named the HELCOM Chemical Status Assessment Tool (Andersen, et al., 2022). It combines data on hazardous substances in water, sediments, and biota, as well as bio-effect indicators, into a single evaluation tool (Andersen, et al., 2016).

Method

CHASE is an integrative multi-metric tool which give a combined assessment using numerous indicators and allow a coherent inclusion of different substances, matrices, species, and analytical methods. There are four categories in the tool: water, sediment, biota, and biological effects, by which indicators are grouped (Andersen, et al., 2022). The CHASE tool employs a simple scheme, whereby each indicator is assessed against a threshold value. First, each of the four elements are assessed individually, and the final status of the assessment unit (e.g. spatial unit) is afterwards defined as the lowest status of these four elements. The final status can be categorized as: bad, poor, moderate, good, or high. If the status is either high or good, the area is described as a "Non-problem Area", while a status in the three remaining categories will result in the categorisation "Problem Area" (Andersen, et al., 2016; Andersen, et al., 2022).

Applicability and limitations

The CHASE tool can in combination with temporal trend assessments of individual substances be advantageous for use in remedial action plans and, in particular, for the science-based evaluation of the status and for determining which specific substances are responsible for a status as potentially affected (Andersen, et al., 2016). Further CHASE can be used to meet increasing environmental legislative and political demands for ongoing monitoring and assessment of the environmental status of marine waters including the chemical status (Andersen, et al., 2022). The assessments build upon threshold values, and therefore the results depend on the quality of these threshold values. It is recommended that the threshold values should be further developed to improve the assessments (Andersen, et al., 2016).

Examples of use

The CHASE tool was originally developed for the assessment of 'chemical status' in the Baltic Sea as part of an HELCOM initiative (HELCOM, 2010) and has subsequently been applied in the Greater North Sea and the Baltic Sea using data provided by the bordering countries: Denmark, Germany, Norway, Sweden, The Netherlands, United Kingdom, Belgium and France (Andersen, et al., 2016). Newer research has applied the tool to the Mediterranean Sea, the NorthEast Atlantic Ocean, and the Black Sea (Andersen, et al., 2022).

Summary

The CHASE tool is designed for chemical status assessment in aquatic environments and uses monitoring data to classify areas based on contamination levels. Although it is not a CEA tool it is a valuable tool which can be applied to account for the chemical pressure accumulation in marine areas. CHASE supports integration with broader environmental monitoring programs, such as HELCOM.

4.3.3 CI-Index

General introduction

The Cumulative Impact Index (CI-Index) was developed to assess and map cumulative impacts on marine ecosystems by considering interactive effects of anthropogenic pressures and climate change. Unlike traditional additive approaches, CI-Index integrates Multi-Criteria Decision Analysis (MCDA) with spatial modelling to capture complex relationships between multiple stressors, ecosystem vulnerability, and exposure patterns (Furlan, et al., 2019).

Method

The CI-Index approach includes:

- Identification of pressures and climate drivers (e.g., trawling, maritime traffic, temperature rise).
- Mapping of ecosystem components (e.g., seagrass beds, coral habitats).
- Weighting pressures and vulnerabilities using MCDA techniques.
- Scenario analysis for reference and future conditions (e.g., climate change projections).
- Spatial modelling to calculate cumulative impact scores across grid cells.
- This method goes beyond additive models by considering interactions among pressures and their combined effect under different climate scenarios.

Applicability and limitations

CI-Index is suitable for Marine Spatial Planning (MSP) and climate adaptation strategies; identifying hotspots of cumulative impact for conservation prioritization; and supporting integrated management under EU directives (MSFD, MSP Directive). The CI-Index was specifically designed for the Adriatic Sea. Applying it to other regions would require re-tuning parameters, recalibrating interactions, and re-mapping relevant data layers, making broad application non-trivial.

Examples of use

The CI-Index has been applied in the Adriatic Sea to assess cumulative impacts from 17 human activities and climate drivers on five key marine ecosystems during 2000–2015 and future scenarios (Furlan, et al., 2019). Results showed higher cumulative impacts in the North Adriatic, with projected increases under climate change scenarios.

Summary

The CI-Index (Cumulative Impact Index), developed by Furlan et al., (2019), is a spatial tool designed to assess cumulative impacts on marine ecosystems by combining human pressures and climate change drivers. Unlike traditional additive models, it uses Multi-Criteria Decision Analysis (MCDA) to weight pressures and ecosystem vulnerabilities, allowing for more nuanced evaluations. The method integrates spatial data on human activities, environmental components, and climate projections to identify impact hotspots and support marine spatial planning and climate adaptation strategies.

4.3.4 MSP Challenge

General introduction

MSP Challenge is an interactive simulation platform and serious game designed to support ecosystem-based maritime spatial planning (MSP). It integrates Ecopath with Ecosim (EwE) food-web modelling to simulate ecological consequences of spatial planning decisions in real time (Steenbeek et al., 2020). The platform combines advanced game technology with scientific models to help planners, stakeholders, and policymakers understand complex interactions between human activities and marine ecosystems (Steenbeek, et al., 2020).

Method

The MSP Challenge approach combines three key components:

- EwE ecosystem models tailored to specific sea basins (e.g., North Sea, Baltic Sea).
- Simulation game mechanics that mimic real-world MSP processes, including role-play and scenario development.
- Planning Support System (PSS) linking spatial decisions (e.g., wind farms, shipping routes, MPAs) to ecological outcomes through dynamic simulations.

Participants engage in interactive sessions where they design spatial plans, negotiate with other stakeholders, and observe ecological feedback via indicators and heat maps. The platform uses real geospatial data (e.g., EMODnet, Copernicus) and integrates models for shipping, energy production, and ecology, providing a realistic and immersive planning environment (Steenbeek, et al., 2020; Santos, et al., 2020).

Applicability and limitations

This integrated method is particularly useful for:

- Transboundary MSP, where coordination across jurisdictions is essential.
- Stakeholder engagement, fostering dialogue and shared understanding.
- Capacity building, helping planners understand ecological trade-offs.
- Policy testing, allowing exploration of alternative management scenarios.

It supports ecosystem-based management by making ecological consequences visible and tangible during planning. However, the platform requires high-quality spatial and ecological data to function effectively. Adapting MSP Challenge to a new region involves significant effort in collecting, validating, and integrating datasets. MSP Challenge is designed as a serious game to foster stakeholder engagement and collaborative learning. While this is a strength for participatory processes, it means the tool is not intended for detailed quantitative impact assessments or regulatory compliance.

Examples of use

North Sea and Baltic Sea editions have been used in transboundary MSP workshops involving multiple countries. Simulations explored effects of spatial zoning on fish stocks, shipping, and energy infrastructure. Stakeholder sessions have demonstrated how game-based learning improves negotiation and understanding of ecological trade-offs (Abspoel et al., 2019; Santos et al., 2020). These examples demonstrate how the tool can facilitate learning, negotiation, and more informed decision-making (Abspoel, et al., 2019; Santos, et al., 2020).

Summary

MSP Challenge is a next-generation planning support tool that combines serious gaming with ecosystem modelling to make MSP processes interactive, evidence-based, and collaborative. By linking spatial decisions to ecological outcomes, it helps planners and stakeholders navigate complex marine governance challenges in a dynamic and engaging way (Steenbeek, et al., 2020).

4.3.5 Human Footprint Index

General introduction

The Global Human Footprint Index is a spatial dataset that quantifies the relative human influence on the terrestrial environment (Sanderson, et al., 2002). Developed by the Wildlife Conservation Society (WCS) and the Center for International Earth Science Information Network (CIESIN) at Columbia University, the Index provides a global perspective on anthropogenic impacts, supporting wildlife conservation planning, natural resource management, and research on human-environment interactions (Columbia University, 2024).

Method

The Human Footprint Index is calculated using a composite of nine global data layers, including human population pressure (population density), land use, and infrastructure (built-up areas, nighttime lights, land use/land cover), and human access (coastlines, roads, railroads, navigable rivers). Each 1-kilometer grid cell is assigned a value representing the degree of human influence, normalized by biome and realm. A value of zero indicates the least influenced (most wild) areas, while 100 represents the most influenced (least wild) (Columbia University, 2024).

Applicability and limitations

Although originally designed for terrestrial environments, the Human Footprint Index is increasingly recognized as a valuable tool for broad-scale human pressure mapping. It is classified as a cumulative impact assessment (CIA) tool by recent literature (Willsteed, et al., 2024), but its direct application to marine and coastal environments remains limited. Adaptations are being explored to incorporate marine-specific pressures and to assess habitat quality in coastal regions (Willsteed, et al., 2023)

Examples of use

The Index has been used globally to identify high-impact zones, inform conservation priorities, and support policy decisions. Potential exists for its adaptation to coastal and marine environments, where it could help identify areas of cumulative human pressure and inform marine spatial planning (Columbia University, 2024).

Summary

The Global Human Footprint Index is a robust tool for mapping and understanding human pressures at broad spatial scales. While not marine-specific, it provides a valuable foundation for cumulative effects assessment and is increasingly being considered for adaptation to coastal and marine contexts. Its effectiveness depends on the integration of relevant data layers and ongoing methodological development.

4.4 Summary

Table 3 summarize some of the main attributes about each method described in the previous sections, to reflect on their utility in the context of CEA development for offshore wind in Denmark. The summary is based on the information reviewed, and it cannot be ruled out that some of the methods have been or are currently being used in additional contexts not accounted for here.

Table 3 Summary of reviewed CEA-methods and their current application, both in planning and geographical context.

CEA method	Approach	Collaboration project / institution	Developed for CEA	Marine spatial planning	Applied to offshore wind	North Sea region	Baltic Sea region	Northeast Atlantic / Mediterranean	Global / other	Reference
DAPSIR	Linkage between Drivers-Activities-Pressures-State-Impact-Response.	OSPAR, Quality Status Report 2023	x		x			x		(Elliott, et al., 2017)
KEC	1) Conceptual Framework; 2) Knowledge base update, the KEC instruments; 3) Calculations, the KEC calculations, and 4) ecological thresholds	Wozep programme	x		x	x				(Rijkswaterstaat, 2023)
CEAF	Scoping, Defining stressors, Stressor-receptor pathways; Spatial/temporal scale; Assessment of cumulative effects/Evaluation.	SEANSE	x	x	x	x				(SEANSE project partners, 2018)
Bayesian network CEA	Integrates ecosystem-based management principles with probabilistic modelling through Bayesian networks.	Bayesian network	x	x	x	x				(Furlan, et al., 2020)
The Halpern method	Spatially explicit method for visualizing the combined effects of multiple human activities on marine ecosystems at a large scale. The method laid the foundation for subsequent CEA-development (see below).	-	x	x	x	x	x	x	x	(Halpern, et al., 2008)
BSII CAT	Part of a suite of spatial tools designed to quantify the combined effects of multiple human pressures on marine ecosystems. E.g. the BSII and BSPI tools, the Ecological Value and Ecological Service tools.	HELCOM HOLAS II and III	x	x			x			(Bergström, et al., 2019) Builds on Halpern et al. (2008)
Tools4MSP	Geospatial analysis and identifying the source of the environmental pressure and the connected pathways and interactions.	ADRIPLAN and RITMARE	x	x				x		(Menegon, et al., 2018). Builds on Halpern et al. (2008)

CEA method	Approach	Collaboration project / institution	Developed for CEA	Marine spatial planning	Applied to offshore wind	North Sea region	Baltic Sea region	Northeast Atlantic / Mediterranean	Global / other	Reference
Symphony	Sensitivity matrix, sensitive ecosystem components to pressure; spatial information.	Sweden's national maritime spatial plans	x	x	x	x	x			(Hammar, et al., 2020) Builds on Halpern et al. (2008)
MYTILUS	Quantifies cumulative human impacts on marine ecosystems by integrating spatial data on pressures and ecosystem components with expert-derived sensitivity scores.	NorthSEE and BONUS BASMATI	x	x	x	x	x			(Bonnevie, et al., 2022) Builds on Halpern et al. (2008)
CI-Index	Integrates Multi-Criteria Decision Analysis (MCDA) with spatial modelling to capture complex relationships be-tween multiple stressors, ecosystem vulnerability, and exposure patterns.	Bayesian network	x	x				x		(Furlan, et al., 2019)
Marine CEA	Pressure matrix of maritime activities, including three-dimension of marine environment.	Horizon Europe project CERES.	x	x	x	x		x		(Lonsdale, et al., 2020)
NSPI & NSII	Strategic-level cumulative effects assessment. NSPI quantifies the intensity and spatial distribution of anthropogenic pressures. NSII builds on the NSPI by incorporating the sensitivity of ecosystem components to each pressure.	HARMONY	x	x	x	x		x		(Sørensen, et al., 2012)
Zonation	Spatial prioritization tool. Integrating biodiversity data, threats, and costs to generate spatially explicit priority maps and performance curves.	The Finnish Environment Institute			x	x	x			(Moilanen, et al., 2005) (Moilanen, et al., 2009)
CUMULEO	Activity-to-Pressure Mapping; Pressure-to-Impact Assessment: Stepwise approach (1. Scoping, 2. Identification, 3. Assessment); Calculation of population indices (reproduction, survival).	Wadden Sea and Dutch North Sea	x	x	x	x				(de Vries, et al., 2011)
Marxan	Spatial prioritization tool. Incorporates spatial data on biodiversity features, costs, and constraints to generate outputs such as selection frequency maps and heatmaps.	BaltSeaPlan and BALTSPACE			x		x			(Ball, et al., 2009)

CEA method	Approach	Collaboration project / institution	Developed for CEA	Marine spatial planning	Applied to offshore wind	North Sea region	Baltic Sea region	Northeast Atlantic / Mediterranean	Global / other	Reference
InVEST	Spatially explicit and use GIS data to simulate ecosystem service flows and impacts in maps. The InVEST toolbox includes the Habitat Risk Assessment (HRA).	Natural Capital Project		x	x		x	x		(Guerry, et al., 2012; Tallis, et al., 2013)
SCAIRM	Ecosystem-based marine spatial planning (MSP) and strategic environmental assessments (ESA).	EU's Horizon project, UNITED and GES4SEAS		x	x	x	x	x		(Piet, et al., 2023)
MARCIS	Decision-support tool for assessing the cumulative impact of human marine industries on seabirds and migrating land birds in marine ecosystems.	Research Council of Norway	x	x	x	x				(NINA, 2025)
CHASE	Provides an integrated assessment of chemical status in marine environments.	HELCOM				x	x	x		(Andersen, et al., 2016)
MSP Challenge	Interactive simulation platform and serious game designed to support ecosystem-based maritime spatial planning.	MSP Challenge		x	x	x				(Steenbeek, et al., 2020)
Human Footprint Index	Spatial representation of human impact. Habitat quality added to human pressures.	Columbia University	x						x	(Sanderson, et al., 2002)

5. Comparative analysis of approaches

This section provides comparative analyses of the CEA methods presented in section 4, based on their function and geographic application as well as their country-specific application. The section also presents the CEA methods used by the technical reports published as part of the Danish Energy Agency's overall screening project and finally provides a summary of recent developments to CEA methods and potential prospects.

5.1 CEA methods across contexts and geography

The CEA tools and frameworks presented in section 4 have been applied by different jurisdictions and in various contexts and geographies.

Table 4 presents the tools and frameworks used in previous CEAs for offshore wind development according to their function in the CEA process and their geographic or regulatory relevance. Tools may appear in multiple categories where applicable. The categorization is based on the information reviewed, and it cannot be ruled out that some of the methods have been or are currently being used in additional contexts not accounted for here.

Table 4 CEA methods are presented by their function and geographic application or relevance in previous studies.

CEA Stage	CEA offshore wind in the North Sea/Baltic	Other / Adaptable
Scoping & Conceptualization	KEC, CEAF, Marine CEA, Bayesian network-based CEA framework	DAPSIR
Spatial Screening & Mapping, Prioritization & Planning	Halpern method, Symphony, MYTILUS, Marine CEA, NSPI and NSII	Tools4MSP, Human Footprint Index, BSII CAT, Zonation, Marxan, MARCIS
Impact Modelling & Quantification, Impact Risk	CUMELEO, Symphony, MYTILUS, NSPI and NSII	Tools4MSP, SCAIRM, InVEST, CI Index, CHAISE, MARCIS
Policy & Regulatory Integration	KEC, CEAF, Bayesian network-based CEA framework	DAPSIR, Human Footprint Index
Stakeholder engagement	Halpern method, Symphony, MYTILUS	MSP-challenge, InVEST, MARCIS

5.2 CEA implementation across countries

CEA implementation varies widely across jurisdictions as shown in Table 5. These differences reflect varying legal mandates, data availability, and institutional capacities. Harmonisation efforts are, however, underway, particularly through EU and North Sea collaborations as presented in section 3, and in many cases particularly in the context of offshore wind development (van Duren, et al., 2021).

Table 5 CEA implementation in different countries and their key features and considerations.

Country	Key Features	Key considerations
Denmark	Strong alignment with EU MSFD and EIA directives. Likely relevant to apply CEA-methods used in the North Sea and the Baltic Sea regions, as suggested in Table 4. Denmark was involved in the HARMONY-project e.g. presenting the tools: North Sea Pressure Index (NSPI) and North Sea Impact Index (NSII). Denmark has been part of the SEANSE project, providing the CEAF which is meant to facilitate cross-border cooperation and harmonisation of environmental assessments in the North Sea region (van Oostveen, et al., 2018), and aiming to provide a common framework and language to discuss the potential impacts of wind farm development plans (Rijkswaterstaat, 2018; SEANSE project partners, 2018). NIVA Denmark has contributed to the development of the Symphony tool with data from Swedish waters, and there is potential for it to also be used in Denmark.	Limited standardisation across projects; reliability on expert judgement which limits comparability, climate effects often excluded.
Sweden	Symphony has been used in the development of Sweden's national maritime spatial plans to assess cumulative impacts and support ecosystem-based planning (Hammar, et al., 2020). Symphony was applied to identify areas of ecological concern in the Baltic Sea and guide offshore wind development while minimizing environmental conflicts. Sweden was involved in the HARMONY-project e.g. presenting the tools: North Sea Pressure Index (NSPI) and North Sea Impact Index (NSII).	Reliability on expert judgment which limits comparability; restricted data in-clusivity; limited ecological connectivity (Hammar, et al., 2020).
Netherlands	KEC Framework 4.0/5.0 offers strategic-level CEA integration for offshore wind farm zones. The Netherlands was also part of the SEANSE project, providing the CEAF.	The KEC Framework is still evolving; limited transparency on assumptions (Rijkswaterstaat, 2022; Rijkswaterstaat, 2025).
UK	Emerging standardization through the PrePARED project, e.g. recommended standardised zone of influence (ZOI), timeframes, and modelling (Sinclair, 2025). The Bayesian network-based CEA framework was developed to address the complexity of evaluating cumulative impacts from offshore wind in the UK, particularly under the influence of climate change (Furlan, et al., 2020).	CEAs still vary by developer; lack of regulator-led strategic CEAs (Sinclair, 2025).
Germany	Emphasis on spatial planning and ecological thresholds.	Reliability on expert judgment which limits comparability; limited focus on population-level modelling.

Country	Key Features	Key considerations
	Germany was involved in the HARMONY-project e.g. presenting the tools: North Sea Pressure Index (NSPI) and North Sea Impact Index (NSII). Germany was also part of the SEANSE project, providing the CEAF.	
Canada/US	Strategic CEAs led by regulators; strong guidance on cumulative thresholds.	Often disconnected from project-level assessments (Dibo, et al., 2025).

5.3 CEA methods in relation to environmental topic

Cumulative effect assessment (CEA) methodologies usually vary significantly depending on the environmental or social topic or receptor group being assessed. This is due to several factors, such as the character of the impact, the species/species groups' sensitivity, existing data etc.

The Danish Energy Agency's screening project (which this report is part of - see Preface and section 1.2) has resulted in a range of reports assessing the cumulative effects of the potential offshore wind expansion on several environmental topics, including marine mammals, birds, underwater noise, wind, hydrodynamics and waves (The Danish Energy Agency, 2025). The topic-specific tools used in the various reports differ in terms of data requirements, modelling complexity, and regulatory acceptance, hereby presenting a key challenge when it comes to integrating these diverse outputs into a unified CEA framework. A short description of the methods used, and the assumptions made to account for cumulative effects are presented below for six of the environmental topics included in the project with Environmental mapping and screening of areas for offshore wind in Denmark (The Danish Energy Agency, 2025).

Wind (Hahmann, et al., 2025)
Combined effects of offshore wind farms may create regions of reduced wind speed and enhanced turbulence downstream. To assess the cumulative effects on wind from future offshore wind development, a mesoscale model was used to capture atmospheric conditions, particularly the wind. The modelling was conducted for the North Sea, South Baltic Sea and the Kattegat using three scenarios: 1) no wind farms; 2) existing farms as of November 2021; and 3) projected deployment in 2030[4].

Due to the nature of the phenomenon, studies in the literature can validate only certain aspects of the wind farm wake with measurements, but not all. Therefore, the results of the cumulative effect assessment are educated estimates of a possible effect. Furthermore, the wake losses presented in the report only include those associated with reduced wind speed in the mesoscale model parameterisations. Other losses – such as those related to the turbine availability, electrical efficiency, turbine performance, environmental factors, and curtailments – are not included.

Waves and sediment transport (NIRAS, 2025)
To simulate the wave climate under different wind farm configurations, the modelling tool MIKE 21 Spectral-Wave Model (SW) was used, considering factors such as wind, individual wind turbine foundations, seabed topography, and wave interactions. The model was calibrated using buoy-based wave measurements from 2019 to ensure the most accurate representation of wave dynamics and wave propagation.

[4] The studies of cumulative impacts are based on a 2030 scenario for future offshore wind development, which has been created specifically for the project (Environmental mapping and screening of areas for offshore wind in Denmark). Therefore, it does not represent the official position of the Danish Energy Agency regarding the future offshore wind development in Danish waters.

The analysis is based on collected data on significant wave height (i.e. the average height of the upper third of the waves in a given wave state) and peak period (i.e. the time interval between wave crests in the most energy-rich part of the wave spectrum).

Hydrodynamics and biogeochemical conditions (Maar, et al., 2025)
The report describes a model study to assess the spatial impact of current (2021) and future (2030 scenario)[4] offshore wind farms on hydrodynamics and biogeochemical environmental conditions in the North Sea and the inner Danish waters. The study focuses on two key mechanisms: the wake effect, which reduces wind impact at the sea surface and thus increases water stratification, and mixing around turbine foundations, which can break up stratification and promote vertical transport of nutrients.

The study applies a high-resolution hydrodynamic modelling system for the entire North Sea using the open source FlexSem modelling framework. The hydrodynamic model provides values for e.g. salinity, temperature, current velocity, and water mixing. In the study, the hydrodynamic model is coupled to a biochemical model simulating nutrient cycling. Similar modelling is conducted for the inner Danish waters and western Baltic Sea. Further, the high-resolution Weather Research and Forecasting (WRF) model used for the cumulative assessment of the impact on wind (wake effects) were also applied and the drag effect of the monopiles (wind turbine foundations) was also added to the FlexSem model.

Values for a range of ecosystem parameters was considered in the analysis, including stratification index (PEA), surface current speed, bottom stress, surface temperature, surface salinity, light attenuation, surface nutrient concentrations (nitrate and phosphate), surface Chlorophyl a, depth-integrated primary production, depth-integrated zooplankton production, surface zooplankton biomass, bottom oxygen and benthos biomass.

Underwater noise (Griffiths, et al., 2026)
The report on underwater noise addresses underwater noise from offshore wind turbines during the operational phase. The cumulative effect of underwater noise on porpoises during the construction phase of an offshore wind farm is highlighted in the report on cumulative effects on harbour porpoises.

The modelling of underwater noise in the operational phase was carried out using Quonops' modelling tool, which was developed by Quiet Oceans. Three noise scenarios were modelled: 1) Noise from offshore wind turbines, 2) noise from offshore wind turbines and service vessels, and 3) noise from offshore wind turbines, service vessels, and general shipping traffic. These models were created for two offshore wind scenarios: a current (2023) scenario with existing offshore wind farms in Danish waters and a future (2030) scenario with the expected expansion of offshore wind in Danish waters[4]. The modelled noise levels were assessed in relation to threshold values (LOBE, Level of Onset of Biological adverse Effects). These threshold values indicate sound levels at which animal life is adversely affected.

Harbour porpoises (Gallagher, et al., 2026)
The study of the cumulative effects on harbour porpoises as a result of the future large-scale expansion of offshore wind in Danish waters and the North Sea in general, has been carried out based on so-called agent-based modelling. The model used in the study is based on the DEPONS model, which was originally developed to study the impact on harbour porpoises from underwater noise. In this study, the model was developed to investigate how harbour porpoise populations respond to several types of impacts, including:

- Underwater noise from the pile driving of wind turbine foundations
- Underwater noise from shipping traffic
- Changes in food availability in offshore wind farms (increased food availability)

The modelling is based on a future 2030 scenario for offshore wind[4], in which a gradual expansion of offshore wind farms is incorporated according to either the actual year of establishment (for already established farms) or the expected year of establishment. In addition, the modelling has also been carried out for a control scenario that does not include offshore wind farms.

The modelling period covers the period 2020-2031 in order to illustrate the impact of offshore wind farms established in 2030.

Birds (Isojunno, et al., 2026)
The method behind the analysis of the cumulative effect on birds as a result of large-scale offshore wind development is based on a risk assessment, that takes into account the relevant types of impacts from offshore wind farms and the conservation status of the bird species included in the analysis.

The three relevant types of impacts that offshore wind farms can have on birds are habitat changes, displacement and collision with wind turbines. These impacts are included in the model. The method has been used for mapping the sensitivity for offshore wind on birds (Isojunno, et al., 2025), and adapted to the purpose of analysing the cumulative impact on birds. Several improvements have therefore been made to the analysis, including:

- Expert assessments have been obtained for input parameters.
- The risk of impact is calculated over time as more offshore wind farms are established.
- Analyses of the impact in relation to season have been introduced.

The report uses a scenario for offshore wind, which has been modified in the report to assume that 50 turbines will be installed per year, starting in areas with the lowest risk to birds.

5.4 Recent developments in CEA and potential prospects

Recent developments in cumulative effects assessment (CEA) emphasize the need for ecosystem-based approaches and integration into strategic environmental assessments (SEA), especially in marine spatial planning contexts. These advances aim to improve ecological relevance and decision-making utility of the existing and future tools and methods. Recent research advocates for more holistic, risk-based, and ecosystem-integrated methods to improve cumulative effects assessments. By applying structured impact pathway frameworks this may promote more accurate and transparent cumulative impact assessments for government, industry, and researchers. This can for instance include making comparisons between projects easier and clearer (i.e., Figure 5.1), checking if assessments match scientific evidence, creating monitoring plans, finding the right people to consult, and spotting gaps or opportunities in assessments to help with approvals and management (Kuempel, et al., 2025). Recent projects also aim to improve stakeholder involvement in co-creation processes (Borja, et al., 2024).

Recent enhancements to the CEA methods include temporal dynamics, integrated risk-based assessments, and 4D spatial-temporal modelling, which allow for more nuanced understanding of cumulative impacts over time and space (Morejón, et al., 2025). Recent developments, such as risk-based modelling and temporal integration, enhance its utility for strategic planning and adaptive management. However, its effectiveness depends on the availability of high-quality data and interdisciplinary collaboration. Multi-use marine spatial assessments have been adapted in recent studies to evaluate ecological footprint reduction through integrated offshore activities (i.e. coexistence) between marine spatial uses and interests such as offshore wind farms, aquaculture, fisheries, shipping and nature conservation and development (Tamis, et al., 2024).

AI-driven risk screening and AI-driven cumulative impact screening is also being tested in renewable energy siting and transmission planning and will likely be a part of optimizing the CEA-process in the future. This refers to the application of artificial intelligence (AI) and machine learning (ML). Use of AI in Impact Assessment confirms growing adoption for automating data collection, predictive modelling, and stakeholder engagement, and best practices of use of AI are being developed (Bingham, et al., 2025).

At present, no single tool can be applied when conducting CEAs, and the different environmental topics must be assessed with individually adapted tools and methods (Hogdson & Halpern, 2019; Hammar, et al., 2020). The recent review by Morejón, et al., (2025), which proposes a framework for ecosystem-based SEA-CEA, emphasizes that combining tools, especially spatially explicit methods (GIS, Bayesian Networks, multicriteria decision analysis (MCDA)) and risk-based frameworks, represents the current best practice for robust, holistic CEA in marine and coastal planning contexts, which hence could be the future prospect of CEAs.

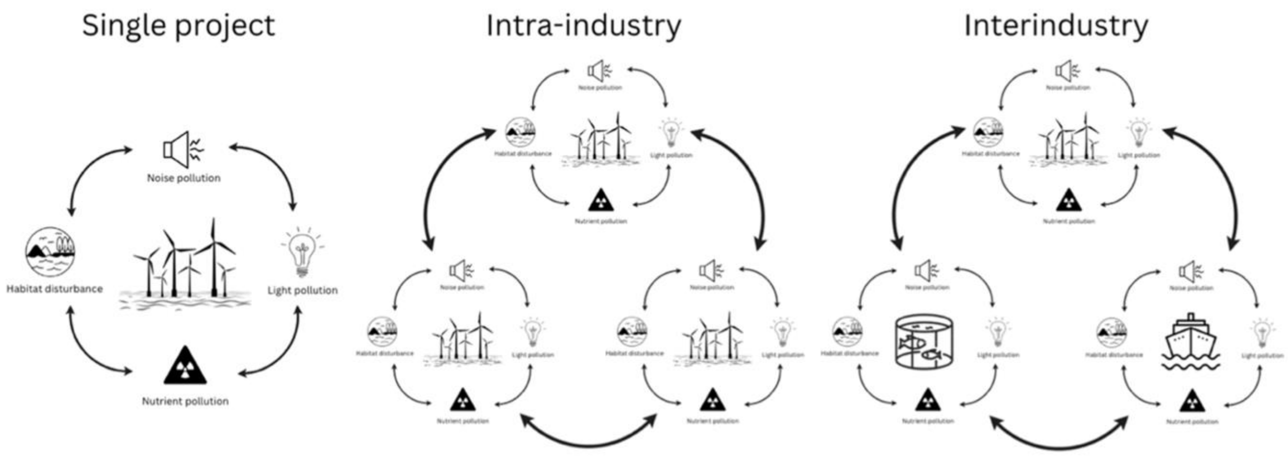

Figure 5.1 Schematic of within project, between project (same industry), and between industry cumulative impacts. Habitat disturbance, noise pollution, light pollution, and nutrient pollution are used as examples of potential impacts from offshore wind farms, offshore aquaculture, and shipping. Source: Kuempel, et al. (2025).

6. Conclusion and recommendations

As shown in this report, CEAs of the marine environment are being developed in many different contexts worldwide. Because of the complexity of marine ecosystems and the interactions between multiple receptors and impacts, it is unlikely that any single method can fully and accurately capture all effects. However, rather than creating entirely new methods, it would be beneficial to agree on common approaches and continue improving them as new knowledge becomes available.

A recent report by the International Council for the Exploration of the Sea (ICES, 2025) confirms that no existing model or assessment tool can fully account for all cumulative pressures from offshore wind farms or provide a complete evaluation of their economic, social, and ecological impacts, such as those on commercial fisheries. Given the significant resources required, ICES recommends that future model development and data collection focus on the economic, social, and ecological effects most relevant to managers and stakeholders.

Another challenge is that, while CEAs aim to be holistic, each application is often limited by geographic boundaries. Individual nations manage their own waters, even under shared legal or policy frameworks such as the EU Maritime Spatial Planning Directive. This suggests that region-specific approaches, already emerging, may always be necessary to some extent.

Despite these challenges, common ground is beginning to emerge, along with recommendations for the way forward (Dibo, et al., 2025; Sinclair, 2025). Below are actions that authorities could consider (some may already be in place, under evaluation, or planned) to advance CEA practices in the context of offshore wind development in Denmark and neighbouring countries:

<u>Apply both established and emerging tools and methods</u>

- Adopt a multi-tool approach, by combining spatial tools such as Symphony with modelling tools for robust assessments.
- Advance temporal 4D modelling and risk-based modelling (e.g., SCAIRM) (Morejón, et al., 2025).

<u>Contribute to innovation and joint efforts</u>

- Support research and innovation to refine tools and methodologies.
- Proceed to participate and contribute to transboundary CEA initiatives in the North Sea and Baltic regions.

<u>Stakeholder Engagement and Regulatory Alignment</u>

- Facilitate early involvement of regulators and cross-border coordination which has been shown to improve consistency and credibility (Rijkswaterstaat, 2022; Dibo, et al., 2025).
- Stakeholder engagement should also be facilitated by transparent data practices, allowing affected parties (e.g., fisheries, NGOs, local communities) to understand and challenge the basis of assessments.

<u>Establish guidelines to ensure comparable and realistic assumptions of impact/influence</u>

- Further development of national or regional standards for Zone of Influence (ZOI) and time frames is recommended, as proposed in the PrePARED report (Sinclair, 2025). The ZOI must be biologically meaningful and receptor-specific (e.g. management units for marine mammals).
- Establish temporal scope and screening criteria (Sinclair, 2025).
- Avoid compounding worst-case scenarios in assessments by for instance setting some guidelines to limit piling days and vessel activity to plausible levels (Sinclair, 2025).

Data consistency

- Set requirements for population-level modelling. This is increasingly required for marine mammals and birds to assess demographic consequences.
- Foster interdisciplinary collaboration to ensure all relevant data types and perspectives are included.
- Consistent integration of climate change into both baseline and future scenarios as recommended by recent research (e.g., Declerck, et al., (2022a) and Kuempel, et al., (2025)).

Data transparency and accessibility

- Data transparency and accessibility are foundational for credible, reproducible, and stakeholder-trusted cumulative effects assessments. Transparent data practices enable 1) Consistent and comparable assessments across projects and jurisdictions, 2) Efficient regulatory review and public scrutiny, and 3) Integration of new scientific knowledge and stakeholder input over time.
- The adoption of common data sets across projects is strongly recommended to enhance the consistency and comparability of CEAs. This may reduce conflicts between user groups, shorten assessment timescales, and minimise the need for conservative assumptions that can skew results. For example, the use of shared geospatial databases and harmonised monitoring protocols.
- Baseline data should be robust, reflecting both historical and projected future states of the marine environment. This is particularly important as the baseline is not static: climate change, regulatory changes (e.g., new marine protected areas), and shifting species distributions all affect the context for assessment.
- Address confidentiality proactively by agreeing on protocols for sensitive data.
- Require that all data used in CEAs be made available for review, ideally through open-access platforms. This includes raw monitoring data, model inputs and outputs, and documentation of assumptions and uncertainties.

7. References

Abspoel, L., Mayer, I., Keijser, X. & Warmelink, H., 2019. Communicating Maritime Spatial Planning: The MSP Challenge approach. Marine Policy. *Marine Policy.*

ACTNOW, 2023. *ACTNOW Vision & Goals.* [Online]
Available at: https://www.actnow-project.eu/goals
[Accessed 6 10 2025].

Andersen, J. H. et al., 2022. Mapping of contamination problem areas in Europe's seas using a multi-metric indicator-based assessment tool. *Marine Pollution.*

Andersen, J. H. & Kallenbach, E. M. F., 2016. *A literature study of human activities and pressures as well as ecosystem component layers available for Marine Spatial Planning and mapping of cumulative impacts in Swedish marine waters,* 6997-2016-DK2: NIVA Denmark Water Research.

Andersen, J. H., Murray, C., Larsen, M. M. & Green, N. W., 2016. Development and testing of a prototype tool for integrated assessment of chemical status in marine environments. Environ Monit Assess 188, 115. *Environmental Monitoring and Assessment,* Issue https://doi.org/10.1007/s10661-016-5121-x.

Andersen, J. H. et al., 2013. *Human uses, pressures and impacts in the Eastern North Sea,* Technical Report from DCE - Danish Centre for Environment and Energy No. 18.: Aarhus University, DCE - Danish Centre for Environment and Energy.

Arkema, K. K. et al., 2014. Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize. *Environmental Research Letters, 9(11), 114016.*

Arki, V., Ajanko, J., Luhtala, H. & Tolvanen, H., 2020. *BONUS BASMATI – Supporting maritime spatial planning with science. BONUS BASMATI Deliverable 7.7, September 2020, www.bonusbasmati.eu.* [Online]
Available at: https://bonusbasmati.eu/wp-content/uploads/2020/09/BONUS_BASMATI_Del_7_7_summary_report.pdf

Atkins, J. P., Burdon, D., Elliott, M. & Gregory, A. J., 2011. Management of the marine environment: Integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Marine Pollution Bulletin,* 62(2), pp. 215-226.

Ball, I. R., Possingham, H. P. & Watts, M. E., 2009. Marxan and relatives: Software for spatial conservation prioritization. In A. Moilanen, K. A. Wilson, & H. P. Possingham (Eds.), Spatial Conservation Prioritization: Quantitative Methods and Computational Tools (pp. 185–195). *Oxford University Press.*

Bekhuis, K., 2021. *Exploring the future together - A scenario analysis for the OSPAR region.* [Online]
Available at: https://www.syke.fi/en/environmental-data/calculators-and-tools#zonation-%E2%80%93-a-tool-for-biodiversity-conservation-and-land-use-planning
[Accessed 16 09 2025].

Bennun, L. et al., 2021. *Biodiversity impacts associated to offshore wind power projects. IUCN and The Biodiversity Consultancy.* [Online]
Available at: https://iucn.org/sites/default/files/2022-06/01_biodiversity_impacts_associated_to_off-shore_wind_power_projects.pdf

Bergström, L. et al., 2019. *Cumulative Impact Assessment for Maritime Spatial Planning in the Baltic Sea Region. Pan Baltic Scope.* [Online]
Available at: https://maritime-spatial-planning.ec.europa.eu/sites/default/files/pbs_cumulative_impacts_report.pdf

Bingham, C., Bond, A. & al., e., 2025. *Principles for use of AI in IA. Special Publication Series No. 16. Fargo, USA: International Assossiaction for Impact Assessment (AIAI).* [Online]
Available at: https://iaia.org/best-practice-use-of-ai-in-impact-assessment/

Blakley, J. & Russell, J., 2022. International progress in cumulative effects assessment: a review of academic literature 2008–2018. *Journal of Environmental Planning and Management.*

BLUE CONNECT, 2023. *Strict protection, restoration and co-management of Marine Protected Areas (BLUE CONNECT) 2024-2028.* [Online]

Available at: https://www.rmri.ro/Home/Downloads/Programmes/BLUECONNECT_2024-2028.pdf
[Accessed 6 10 2025].
Bonnevie, I. M., Hansen, H. S., Schrøder, L. & Armoškaitė, A., 2022. Utilising MYTILUS for active learning to compare cumulative impacts on the marine environment in different planning scenarios. Sustainability, 14(19), 12606.
BONUS BASMATI, 2000. *The BONUS BASMATI project.* [Online]
Available at: https://bonusbasmati.eu/
Borja, A. et al., 2024. Addressing the cumulative impacts of multiple human pressures in marine systems, for the sustainable use of the seas. *Ocean Sustain.*
Caine, C. A., 2019. The Race to the Water for Offshore Renewable Energy: Assessing Cumulative and In-combination Impacts for Offshore Renewable Energy Developments. *Journal of Environmental Law, 32(1), 83–109.*
Casimiro, D. et al., 2021. *Cumulative impacts and Strategic Environmental Assessment: Literature review. In support of Deliverable 3.2 of the SIMAtlantic project (EASME/EMFF/2018/1.2.1.5/SI2.806423). 26pp.* [Online]
Available at: https://maritime-spatial-planning.ec.europa.eu/sites/default/files/d3.2-cumulative-impacts-and-sea-literature-review.pdf
CLEAN, 2025. *NIVA Projects. CLEAN.* [Online]
Available at: https://www.niva.no/en/projects/clean
[Accessed 10 10 2025].
Columbia University, 2024. *Global Human Footprint Index.* [Online]
Available at: https://hub.arcgis.com/maps/65518e782be04e7db31de65d53d591a9/about
[Accessed 16 09 2025].
CSIC, 2024. *EU Project "ONE-BLUE" tackles the level and impact of emerging marine pollutants on ecosystems.* [Online]
Available at: https://www.icm.csic.es/en/news/eu-project-one-blue-tackles-level-and-impact-emerging-marine-pollutants-ecosystems
Danish Maritime Authority, 2023. *Havplansredegørelse.* [Online]
Available at: https://havplan.dk/content/api/latest/files/fec07ca1-9b74-40c0-a271-e60aa7d920aa/file
Danish Maritime Authority, 2024. *Danmarks Havplan.* [Online]
Available at: https://havplan.dk/da/om-havplanen
de Jong, C. A. F., Heinis, F., von Benda-Beckmann, A. M. & Binnerts, B., 2019. *Testing CEAF in SEANSE Case Studies: Impact of Piling for Wind Farms on North Sea Harbour Porpoise Population,* Den Haag: TNO Report R11563.
de Vries, P., Karman, C. & van Overzee, H., 2011. CUMELEO: Cumulative effects of human activities on the ecosystem of the Dutch North Sea and the Wadden Sea (IMARES Report No. C002/11). Wageningen UR.
de Vries, P. et al., 2011. Scaling human-induced pressures to population level impacts in the marine environment: Implementation of the prototype CUMULEO-RAM model. *Wageningen: Wettelijke Onderzoekstaken Natuur & Milieu, WOt-werkdocument 285.*
Declerck, M. et al., 2022a. A new strategic framework to structure Cumulative Impact Assessment (CIA). *International Marine Energy Journal*, 5(3), p. 339–347.
Dibo, A. P. A. et al., 2025. Guiding Elements for Strengthening Cumulative Impact Assessment Regulations for Offshore Wind Energy. *Environmental Management*, Issue 75, p. 3025–3043.
Edelvang, K. et al., 2017. *Analysis of marine protected areas – in the Danish part of the North Sea and the Central Baltic around Bornholm Part 1: The coherence of the present network of MPAs,* DTU Aqua Report No. 325: National Institute for Aquatic Resources, Technical University of Denmark.
Eklipse Expert Working Group, 2025. *Knowledge synthesis report. Impacts of offshore wind farm expansion: what are the consequences for achieving Good Environmental Status across European marine waters?.* [Online]
Available at: https://eklipse.eu/wp-content/uploads/2025/10/2025-10-27-Eklipse_Report_WindFarm_Final.pdf

Elliott, M. et al., 2017. “And DAPSIR begat DAPSI(W)R(M)!” - A unifying framework for marine environmental management. *Marine Pollution Bulletin*, 118(1-2), pp. 27-40.
European Commission, 1999. *Guidelines for the Assessment of Indirect and Cumulative Impacts as well as Impact Interactions.* [Online]
Available at: https://wayback.archive-it.org/12090/20151221014945/http://ec.europa.eu/environment/archives/eia/eia-studies-and-reports/pdf/guidel.pdf
European Commission, 2020. *Guidance document on wind energy developments and EU nature legislation.* [Online]
Available at: https://op.europa.eu/en/publication-detail/-/publication/2b08de80-5ad4-11eb-b59f-01aa75ed71a1/langua
European Commission, 2021. *Commission notice - Assessment of plans and projects in relation to Natura 2000 sites – Methodological guidance on the provisions of Article 6(3) and (4) of the Habitats Directive 92/43/EEC.* [Online]
Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=oj:JOC_2021_437_R_0001
European Commission, 2022. *ACTNOW 2023-2027 Advancing understanding of Cumulative Impacts on European marine biodiversity, ecosystem functions and services for human wellbeing.* [Online]
Available at: https://cordis.europa.eu/project/id/101060072
European Commission, 2022. *Report from the Commission to the European Parliament and the Council outlining the progress made in implementing Directive 2014/89/EU establishing a framework for maritime spatial planning.* [Online]
Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0185
European Commission, 2025a. *Energy, Climate change, Environment. Climate strategies & targets.* [Online]
Available at: https://climate.ec.europa.eu/eu-action/climate-strategies-targets_en
[Accessed 5 10 2025].
European Commission, 2025b. *Energy and the Green Deal.* [Online]
Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en
European Commission, 2025c. *REPowerEU Affordable, secure and sustainable energy for Europe.* [Online]
Available at: https://commission.europa.eu/topics/energy/repowereu_en
European Commission, 2025d. *European Commission. Environment. Marine and Coastal Environment.* [Online]
Available at: https://environment.ec.europa.eu/topics/marine-environment_en
[Accessed 8 September 2025].
European Commission, 2025e. *Horizon Europe.* [Online]
Available at: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en
[Accessed 5 11 2025].
European MSP Platform, 2018. *Applying Marxan for offshore wind power in the western Baltic Sea.* [Online]
Available at: https://maritime-spatial-planning.ec.europa.eu/practices/applying-marxan-offshore-wind-power-western-baltic-sea
Finnova Foundation, 2024. *Finnova Foundation presents ONE-BLUE project at the CILAC 2024 Forum in Colombia.* [Online]
Available at: https://finnova.eu/en/finnova-foundation-presents-one-blue-project-at-the-cilac-2024-forum-in-colombia/
[Accessed 10 10 2025].
Foley, M. M. et al., 2017. The challenges and opportunities in cumulative effects assessment. *Environmental Impact Assessment Review*, pp. 122-134.
Furlan, E. et al., 2020. Multscenario analysis in the Adriatic Sea: a GIS-based Bayesian network to support maritime spatial planning. *Sci Total Environ*, 703(134972).

Furlan, E. et al., 2019. Cumulative impact index for the Adriatic Sea: accounting for interactions among climate and anthropogenic pressures. *Sci Total Environ 670:379–397.*
Gallagher, C. F. et al., 2026. *Cumulative impacts of offshore wind and commercial vessels on harbour porpoise populations in Danish waters. Scientific Report from DCE – Danish Centre for Environment and Energy No. 690.* Aarhus University: DCE – Danish Centre for Environment and Energy.
GES4SEAS, 2024. *GES4SEAS.* [Online]
Available at: https://www.ges4seas.eu/toolbox/
GitHub, 2025. *Cumulative-impact-Assessment-Toolbox.* [Online]
Available at: https://github.com/helcomsecretariat/Cumulative-impact-Assessment-Toolbox
Griffiths, E., Jensen, F. & Tougaard, J., 2026. *Cumulative effects of large-scale offshore wind development on underwater noise in Danish waters. Scientific Report from DCE - Danish Centre for Environment and Energy No. 692.* Aarhus Univerity: DCE - Danish Centre for Environment and Energy.
Guerry, A. D. et al., 2012. Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 8(1-2), p. 107–121.
Göke, C., Dahl, K. & Mohn, C., 2018. Maritime Spatial Planning supported by systematic site selection: Applying Marxan for offshore wind power in the western Baltic Sea. *PLoS ONE*, 13(3).
Hague, E. L. et al., 2022. Same Space, Different Standards: A Review of Cumulative Effects Assessment Practice for Marine Mammals. *Frontiers in Marine Science*, 9(822467).
Hahmann, A. N. et al., 2025. *Environmental Mapping and Screening of the Offshore Wind Potential in Denmark. Sensitivity mapping: Wind.* DTU: Department of Wind and Energy Systems.
Halpern, B. S. et al., 2025. Cumulative impacts to global marine ecosystems projected to more than double by mid-century. *MARINE ECOLOGY,* 389(6766), pp. 1216-1219.
Halpern, B. S. et al., 2015b. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications,* 6(7615).
Halpern, B. S. & Fujita, R., 2013. Assumptions, challenges, and future directions in cumulative impact analysis. *Ecosphere,* 4(10).
Halpern, B. S. et al., 2008. A global map of human impact on marine ecosystems. *Science*, 319(5865), p. 948–952.
Hammar, L. et al., 2020. Cumulative impact assessment for ecosystembased marine spatial planning. *Science of The Total Environment*, 734(139024).
Hansen, H. S., 2019. Cumulative Impact of Societal Activities on Marine Ecosystems and Their Services. In: S. Misra, et al. eds. *Computational Science and Its Applications – ICCSA 2019.* Saint Petersburg: Springer, pp. 577-590.
Hansen, H. S., 2020. MYTILUS – a tool for assessing the cumulative impact of human pressures on ecosystems. BONUS BASMATI Project.
Heath, M. R., 2008. Comment on "A Global Map of Human Impact on Marine Ecosystems". *Science,* 321(5895), p. 1446.
HELCOM, 2010. *Ecosystem Health of the Baltic Sea 2003–2007: HELCOM Initial Holistic Assessment,* Baltic Sea Environment Proceedings: No. 122.
HELCOM, 2010. *Hazardous substances in the Baltic Sea: An integrated thematic assessment of hazardous substances in the Baltic Sea,* Helsinki Commission: Balt. Sea Environ. Proc. No. 120B.
HELCOM, 2017. The assessment of cumulative impacts using the Baltic Sea Pressure Index and the Baltic Sea Impact Index – Supplementary report to the first version of the HELCOM 'State of the Baltic Sea' report 2017.
HELCOM, 2023. *HOLAS3 State of the Baltic Sea 2023.* [Online]
Available at: https://helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2023/
Hogdson, E. & Halpern, B., 2019. Investigating cumulative effects across ecological scales. *Conservation Biology*, 33(1), pp. 22-32.

ICES, 2025. *EU request on economic, social, and ecological impacts of offshore wind farms (OWFs) and floating offshore wind farms (FLOWs) on fisheries in the Baltic Sea, Celtic Seas, and Greater North Sea,* ICES Advice: Special Requests. Report.
Isojunno, et al., 2026. *Relative risk to seabirds from future offshore wind energy developments in Danish waters: spatial distribution and cumulative development scenarios. Technical Report from DCE – Danish Centre for Environment and Energy No. 367.* Aarhus University: DCE – Danish Centre for Environment and Energy.
Isojunno, S. et al., 2025. *Mapping relative risk to seabirds from offshore wind energy developments in Danish waters,* Aarhus University: DCE – Danish Centre for Environment and Energy. 101 pp. Technical Report No. 331.
Jones, 2016. Cumulative effects assessment: theoretical underpinnings and big problems. *Environmental Reviews*, 24(2), pp. 187-204.
JPI Oceans, 2024. A common handbook: Cumulative effects asessment in the marine environment. *JPI Ocens Knowledge Hub on Cumulative effects of human ectivities in the marine environment*.
Järnberg, L., Vulturius, G. & Ek, F., 2023. Strategic agency and learning in sustainability initiatives driving transformation: the symphony tool for ecosystem-based marine spatial planning. *Sustainability Science.*
Karman, C. C. & Jongbloed, R. H., 2008. *Assessment of the cumulative effects of activities in the maritime area: Overview of relevant legislation and proposal for a harmonised approach,* Den Helder: Wageningen IMARES.
Korpinen, S., Meski, L., Andersen, J. & Laamanen, M., 2012. Human pressures and their potential impact on the Baltic Sea ecosystem. *Ecological Indicators,* pp. 105-114.
Kuempel, C. D. et al., 2025. Frameworks and best practices for cumulative impact accounting in offshore energy development. *Marine Policy.*
Leemans, J., Middelveld, R. & Gyimesi, A., 2019. *Testing the CEAF modelling tool on three SEANSE scenarios: collision mortality and displacement of four seabird species. Bureau Waardenburg Report,* Culemborg: Bureau Waardenburg. pp. 19-122.
Lonsdale, J. A. et al., 2020. A novel approach for cumulative impacts assessment for marine spatial planning. *Environmental Science & Policy, 106*, pp. 125-135.
Lukic, I. et al., 2020. *Project Interim Findings, NorthSEE project, INTERREG North Sea Region Programme, Grant agreement 38-2-2-15.* [Online]
Available at: https://www.sustainable-projects.eu/images/publications/sub-north-see-project-findings-brochure-WEB-200420.pdf
Masden, E. A. et al., 2010. Cumulative impact assessments and bird/wind farm interactions: Developing a conceptual framework. *Environmental Impact Assessment Review*, 30(1), pp. 1-7.
Menegon, S. et al., 2018. Tools4MSP: an open source software package to support Maritime Spatial Planning. *PeerJ Computer Science.*
Minin, E. et al., 2014. A quick introduction to Zonation. *Helsingin yliopisto, Helsinki.*
Mohn, C. et al., 2015. *SYMBIOSE. Ecologically relevant data for marine strategies,* DCE - Nationalt Center for Miljø og Energi: Aarhus University.
Moilanen, A. et al., 2005. Prioritizing multiple-use landscapes for conservation: Methods for large multi-species planning problems.. *Proceedings of the Royal Society B: Biological Sciences, 272(1575), 1885–1891.*
Moilanen, A., Kujala, H. & & Leathwick, J. R., 2009. The Zonation framework and software for conservation prioritization. In: A. Moilanen, K. A. Wilson & H. Possingham, eds. *Spatial Conservation Prioritization: Quantitative Methods and Computational Tools.* Oxford: Oxford University Press, pp. 196-210.
Morejón, V., González Del Campo, A., Galparsoro, I. & Pedreschi, D., 2025. A new ecosystem-based cumulative effects assessment framework to enhance strategic environmental assessment of marine spatial plans. *Environmental Management.*
Maar, M. et al., 2025. *Spatial impacts of offshore wind farms on hydrodynamics and biogeochemical environment. Scientific Report from DCE – Danish Centre for Environment and Energy No. 658.* Aarhus University: DCE – Danish Centre for Environment and Energy.
Natural Capital Project, 2025. *Natural Capital Project. InVEST 3.17.0. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience*

Centre and the Royal Swedish Academy of Sciences. [Online]
Available at: https://natcap.github.io/invest.release-metadata/3.17.0.html
[Accessed 9 10 2025].
Nelson, R. & Shirley, L. M., 2022. The Latent Potential of Cumulative Effects Concepts in National and International Environmental Impact Assessment Regimes.. *Transnational Environmental Law*, 12(1), p. 150–174.
NINA, 2023. *MARCIS Newsletter n.4 – September 2023.* [Online]
Available at: https://www.nina.no/english/About-NINA/News/article/marcis-newsletter-n4-september-2023
[Accessed 10 10 2025].
NINA, 2025. *MARCIS marine spatial planning and cumulative impacts of blue growth on seabirds.* [Online]
Available at: https://www.nina.no/english/Sustainable-society/Marcis
NIRAS, 2025. *Impacts of offshore wind farms on waves and sediment transport,* Report requested by: Danish Energy Agency.
Nordic Energy Research, 2022. *Accommodating Biodiversity in Nordic Offshore Wind Projects.* [Online]
Available at: https://pub.norden.org/nordicenergyresearch2022-01/nordicenergyresearch2022-01.pdf
NorthSEE, 2019. *A North Sea Perspective on Shipping, Energy and Environmental Aspects in Maritime Spatial Planning (NorthSEE).* [Online]
Available at: https://northsearegion.eu/northsee/
OECD, 1993. *OECD Core Set of Indicators for Environmental Performance Reviews. A Synthesis Report by the Group on the State of the Environment,* Paris: Environment Monograph, Organization for the Economic Co-Operation and Development.
OSPAR, 2023a. *OSPAR Assessments. Quality Status Reports. QSR 2023. Synthesis Report. 5. OSPAR Tackles Cumulative Pressures.* [Online]
Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/synthesis-report/cumulative-pressures/
OSPAR, 2023b. *Quality Status Reports QSR 2023 - Assessing the State of the North-East Atlantic.* [Online]
Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/synthesis-report/assessing-state-ne-atlantic/#:~:text=The%20collaboration%20on%20the%202023%20Quality%20Status%20Report,the%20relationships%20between%20people%E2%80%99s%20actions%2
OSPAR, 2025. *OSPAR Commission.* [Online]
Available at: https://www.ospar.org/
Piet, G. et al., 2023. A spatial cumulative assessment of impact risk for management. *Ecological Indicators,* p. 157.
Rijkswaterstaat, 2018. *Common environmental assessment framework - an instrumnet for assessing cumulative impacts from offshore wind. Presentation.* [Online]
Available at: https://www.france-energies-marines.org/wp-content/uploads/2021/11/flyer-ceaf-EN.pdf
Rijkswaterstaat, 2022. *Framework for Assessing Ecological and Cumulative Effects (KEC) 4.0 for the roll-out of offshore wind energy and wind farm zones (Éxtra Task 2030+).* [Online]
Available at: https://noordzeeloket.nl/en/functions-use/offshore-wind-energy/ecology/offshore-wind-ecological-programme-wozep/framework-assessing-ecological-cumulative-effects/
Rijkswaterstaat, 2023. *Wozep ecological programme.* [Online]
Available at: https://noordzeeloket.nl/en/functions-use/offshore-wind-energy/ecology/offshore-wind-ecological-programme-wozep/
Rijkswaterstaat, 2025. *KEC 5.0 Framework for Assessing Ecological and Cumulative Effects (KEC).* [Online]
Available at: https://noordzeeloket.nl/en/functions-use/offshore-wind-energy/ecology/offshore-wind-ecological-programme-wozep/framework-assessing-ecological-cumulative-effects/kec-5-0/
Sanderson, E. W. et al., 2002. The Human Footprint and the Last of the Wild: The human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not. *BioScience, Volume 52, Issue 10, October 2002, Pages 891–904.*

Santos, C. et al., 2020. A Digital Game-Based Simulation Platform for Integrated Marine Spatial Planning: Design Challenges and Technical Innovations. *Journal of Ocean Technology.*
SEANSE project partners, 2018. *Planning Criteria for Offshore Wind Energy – North Sea Region Overview,* SEANSE: WP1 Report.
Sharp, R. et al., 2018. *InVEST 3.6.0 User's Guide,* Stanford University: The Natural Capital Project.
SIMAtlantc, 2021. *SIMAtlantic: Final brochure.* [Online]
Available at: https://www.marei.ie/wp-content/uploads/2023/02/Final-Brochure-SIMAtlantic.pdf
Simeoni, C. et al., 2023. Evaluating the combined effect of climate and anthropogenic stressors on marine coastal ecosystems: Insights from a systematic review of cumulative impact assessment approaches. *Science of The Total Environment,* 861(160687).
Sinclair, R. R., 2025. *Challenges and Solutions for Offshore Wind Farm Cumulative Effects Assessments for Marine Mammals,* PrePARED Report: No. 007.
Steenbeek, J. et al., 2020. Combining ecosystem modeling with serious gaming in support of transboundary maritime spatial planning. *Ecology & Society,* p. 25(2):21.
Stock, A., 2016. Open Source Software for Mapping Human Impacts on Marine Ecosystems with an Additive Model. *Journal of Open Research Software*, Volume 4.
Stokholm, I. et al., 2025. *Sensitivity mapping of harbour seals, grey seals and harbour porpoises to the construction and operation of offshore windfarms in Danish waters,* DCE – Danish Centre for Environment and Energy, 63 pp. Scientific Report No. 644: Aarhus University.
Studwell, A., Hines, E., Nur, N. & Jahncke, J., 2021. Using habitat risk assessment to assess disturbance from maritime activities to inform seabird conservation in a coastal marine ecosystem. *Ocean & Coastal Management, 212, 105821.*
SwAM, 2020. *Symphony – a tool for ecosystem-based marine spatial planning. Swedish Agency Marine and Water Managment.* [Online]
Available at: https://www.havochvatten.se/en/eu-and-international/marine-spatial-planning/swedish-marine-spatial-planning/the-marine-spatial-planning-process/development-of-plan-proposals/symphony---a-tool-for-ecosystem-based-marine-spatial-planning.html#hav-content
[Accessed 2025].
Sørensen, T. K., Vinther, M., Rindorf, A. & Hartvig, M., 2012. *DTU Orbit Development and demonstration of Marine Strategy Framework Directive (MSFD) tools for harmonization of the initial assessment in the eastern parts of the Greater North Sea sub-region (HARMONY) (38894).* [Online]
Available at: https://orbit.dtu.dk/en/projects/development-and-demonstration-of-marine-strategy-framework-direct/
Tallis, H. et al., 2013. *InVEST 2.5.6 User's Guide. Integrated Valuation of Environmental Services and Tradeoffs. A modeling suite developed by the Natural Capital Project to support environmental decision-making.,* Stanford: The Natural Capital Project.
Tamis, J. E. et al., 2024. Assessing the potential of multi-use to reduce cumulative impacts in the marine environment. *Frontiers in Marine Science,* 11(Article 1420095).
The Danish Energy Agency, 2025. *Planlægning af fremtidens havvindmølleparker.* [Online]
Available at: https://ens.dk/energikilder/planlaegning-af-fremtidens-havvindmoelleparker
The Danish Environmental Protection Agency, 2020. *Habitatvejledningen. Vejledning til bekendtgørelse nr. 1595 af 6. december 2018 om udpegning og administration af internationale naturbeskyttelsesområder samt beskyttelse af visse arter.* [Online]
Available at: https://www2.mst.dk/Udgiv/publikationer/2020/12/978-87-7038-248-9.pdf
The Danish Ministry of Environment and Gender Equality, 2023a. *Bekendtgørelse af lov om miljøvurdering af planer og programmer og af konkrete projekter (VVM). LBK nr 4 af 03/01/2023.* [Online].
The Danish Ministry of Environment and Gender Equality, 2023b. *Vejledninger til miljøvurderingsloven.* [Online]
Available at: https://mim.dk/nyheder/faglige-nyheder/2023/september/vejledninger-til-miljoevurderingsloven

The Danish Ministry of Food, Agriculture and Fisheries, 2019. *Danmarks Havstrategi II. Første del. God miljøtilstand. Basisanalyse. Miljømål.*. [Online]
Available at: https://mst.dk/media/ntjg4vgv/hsd_ii_foerste_del__basisanalyseplusmiljoemaal_2019.pdf
Thomassen, J. A.-C. et al., 2025. Case-dependent impacts of offshore wind farms on ecosystems: A systematic review and meta-analysis. *Ocean and Coastal Management.*
UNITED, 2023. *UNITED.* [Online]
Available at: https://www.h2020united.eu/about
van der Wal, J. T. & Tamis, J. E., 2014. *Comparing methods to approach cumulative effects in the North-East Atlantic: CUMULEO case study,* IMARES: Report number C178/ 13.
van Duren, L. A. et al., 2021. *Ecosystem effects of large upscaling of offshore wind on the North Sea - Synthesis report.* [Online]
Available at: https://www.scribd.com/document/718534786/synthesis-ecosystem-effects-of-large-upscaling-of-offshore-wind-on-the-north-sea
van Oostveen, M., Sierdsma, F., Kwakkel, J. & van Mastrigt, A., 2018. *Inventory and assessment of models and methods used for describing, quantifying and assessing cumulative effects of offshore wind farms,* Royal HaskoningDHV: Project related No. WATBF8129R001F1.0.
VASAB Workshop Report, 2021. Cumulative impacts of maritime activities: Workshop report..
Willsteed, E. A., Collin, S. & Koehler, L., 2024. *Cumulative effects assessment to support marine plan development,* Peterborough: JNCC Report 768 (Project report) ISSN 0963-8091.
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*, Volume 82, p. 2332–2345.
Willsteed, E. A. et al., 2023. Advances in cumulative effects assessment and application in marine and coastal management.. *Cambridge Prisms: Coastal Futures, 1, e18.*.
Wåhlström, I. et al., 2022. Projected climate change impact on a coastal sea—as significant as all current pressurescombined.. *Glob Change Biol 28(17):5310–5319.*