SYNERGIES & TRADE-OFFS OF WAGENINGEN CLIMATE SOLUTIONS IN PRIMARY PRODUCTION SYSTEMS

CASE STUDY: MARINE

LOW TROPHIC MARINE PRODUCTION SYSTEMS IN OFFSHORE WIND FARMS AT THE NORTH SEA

WAGENINGEN UNIVERSITY & RESEARCH

KB 34 Circular and climate neutral society

FACTSHEET
JULY, 2024

Introduction

With a world population reaching 10 billion in 2050, the pressure on our food system, the impact on the ecological carrying capacity as well as the need for global food security is more apparent than ever. A fossil fuel transition towards more renewable energy, in this case wind energy, embodies a crucial point in this.

Nowadays, we face grand challenges for both land and marine systems. Zooming more into the marine realm, four trends are ongoing:

1. Regarding the energy transition, wind-driven approaches are followed with innovations in multi-use wind energy systems in offshore wind farms (hereafter named OWF) on the North Sea combined with added value energy, including socio-economic costs versus nature-inclusive benefits.
2. Furthermore, resource use transitions entail protein and biomass value chain development and value-added aquaculture and fisheries alternatives.
3. Climate change transitions encompass integrated marine production systems and add value for nature.
4. This can be interlinked with the last trend, namely marine nature ambitions and boundaries which concern circular food systems.

New energy production zones are developed in the free-market, where the government sets the guidelines and ambitions. So far, a maximum of two use functions (energy and biodiversity) are included, while the current use functions, mainly fisheries, are reconsidered.

Integrating alternative uses with renewable energy, such as food production, and in particular low trophic marine (LTM) food production possesses high potential, especially when aiming for climate-smart, resilient and circular marine systems. Adding up to this, new OWF are developed further offshore. There, nutrient availability is lower, ultimately resulting in a limited (secondary) primary production potential. More opportunities for low trophic marine production, one might ask?

In this case study we concentrate in more detail, on the primary production of food production (e.g. seaweed and/or shellfish) in OWF. Regarding the spatial and temporal boundaries of this case study, we use the Prinses Amalia WindPark and the Egmond aan Zee (see figure 1) as a reference case (due to data availability and decommissioning in the next decade).

Figure 1. Wind energy area Offshore Wind Farm Egmond aan Zee (Source: Noordzeeloket, De Rijksoverheid voor Nederland)

Current barriers and enablers regarding integrating LTM production into circular food systems are explored. The overall objective of this research is to understand to what extent low trophic marine systems in offshore energy parks in the North Sea can contribute to a more sustainable, circular and climate-smart food system which might simultaneously offer scenarios and possible approaches for other domains, such as agriculture and urban settings. This case study has a future outlook towards 2050.

The methodology used in this case study included a general description based on literature review complemented with expert knowledge. Moreover, two workshops were organized with a multidisciplinary group of Wageningen Research experts as primary data collection for this study. Approximately 12 to 15 selected participants attended both workshops. The workshops addressed the importance of combining food production with renewable energy production, as well as the identification of barriers, enablers, synergies and trade-offs using the SDGs as a framework.

Climate mitigation solution

The development of such OWF is the driving element for climate change mitigation strategies, in this case renewable energy production, where other spatial co-use functions are following. This marine case study presents a climate mitigation solution combining low trophic food production and nature restoration in renewable energy OWF.

Renewable energy

To start with, this case study proposes renewable energy production in form of offshore wind parks in the Dutch North Sea, one of the most intensively used seas in the world (Programma Noordzee, 2022).

Table 1. Overview characteristics wind park Amalia, OWEZ, and Hollandse Kust North (for comparison) , including a calculation of the potential production of mussels (based on a very conservative productivity estimate).

Location: Off the coast of Noord-Holland	Offshore Windpark Egmond aan Zee (OWEZ)	Kavel V Hollandse Kust (North)	Prinses Amalia Windpark (PAWP)	Total ambitions Dutch Climate Agreement
In operation since	2007	2023	2008	Ambition 2050
In operation until	2027	2050	2028	N.A.
Number of turbines	36	69	60	Not calculated
Turbine power (MW)	3	11	2	Not calculated
Power for number of households (in mln)	0.1	1	0.125	6.4
Power windpark (MW)	108	759	120	70000
Surface area (km2)	27	92	14	4335 - 7745
Calculated mussel production space at a productivity of 100 tons/km2 (Boogaart, et al., 2020)	2,700 tons	Not calculated	1,400 tons	Not calculated

The aim is that in 2050, there will be OWF covering one sixth to one quarter of the Dutch North Sea surface (see column to the right). This wind energy transition is a societal choice so that compliance with the objectives of the Paris Agreement can be achieved (Het Akkoord voor de Noordzee, 2018). The agreements also point out that the North Sea gas production is finite and declining. This embodies a major step away from fossil fuels and towards a climate neutral society.

Low trophic marine food production

Now, we will come to the 'primary production' component of the climate mitigation solution. LTM food production is routing to replace, contribute or complement current marine production. Marine food production with seaweed and shellfish/mussel, besides alternative fisheries, is considered as a challenging, but feasible (limiting in space and capacity) option. The total fish landings (live weight) of the Dutch cutter fleet decreased 8% to the previous year from 63 mln. kg to 58 mln. kg in 2021. The five-year average for 2014-2018 was much higher with landings of about 80 mln. kg. (Agrimatie 19-7-2023). Landings of mussels in the 2021/2022 season showed a slight increase to 33.4 mln. kg, which is still very low for recent years. The average mussel price increased further this season to 1.97 euros per kg (+37% compared to last season). As a result of price highs, the total value of mussels landed rose from 45.3 million euros to 65.9 million euros (ibid).

Over the last years, various ecosystem services have been recognized regarding LTM food production. Shellfish maintain water quality and function as natural coastal protection. Seaweed stimulates nutrient uptake and wave regulation. Nowadays, our global seafood system is dominated by a few species, for example salmon, shrimps and tuna, often originating from unsustainable fisheries and overfishing (Crona, 2023).

Our blue economy needs a major shift towards a broader range of marine species, especially lower trophic levels. In other words, we should not consume the large predators tuna, which prey on squid, shellfish and other fish, but it would be more sustainable to eat the prey of the tuna, or the prey of the prey. Figure 1 shows research results carried out in OWF regarding opportunities for seaweed and shellfish farming. The coloured patches are OWF. Yellow index colours demonstrate highest suitability.

Especially Southern OWFs possess suitable conditions for seaweed aquaculture. For shellfish, the majority of OWF are suitable, except the ones in the North West. The Egmond aan Zee (OWEZ) and Prinses Amalia WindPark (PAWP) (23 kilometres offshore IJmuiden) are both marked yellow with highest probability for seaweed and shellfish opportunities, therefore also chosen for this case study. The chlorophyl availability due to the North South flow in combination with the rhine plume yields results in an estimated relatively high productivity.

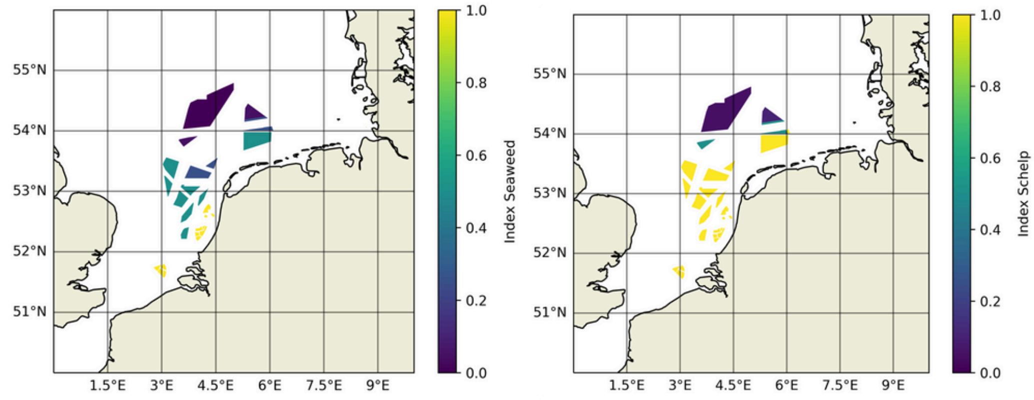


Figure 1. Opportunities for seaweed (left) & shellfish (right) farming in OWF (Steenbergen et al., 2023)

Nature restoration

While transitioning from fossil fuels to renewable wind energy in OWF, one major co-development focuses on nature restoration. There is a shift towards nature-inclusive shellfish farming in the North Sea. Due to the OWEZ and PAWP, being established in 2008, ecological ecosystem impacts are known. Nature and marine biodiversity restoration is considered to co-develop as co-use principle in the marine wind domain. Development of fixed reefs, hard substrate habitats and Halfweg gravity-based structures (GBS) are proven to increase biodiversity and biomass (Coolen, et al. 2020) and to enhance nutrient flows to benefit primary production.

Figure 1. Opportunities for seaweed (left) & shellfish (right) farming in OWF (Steenbergen et al., 2023)

Alternatively, development of fixation routes may contribute to the facilitation of C in bottom systems. In OWF, bottom-trawling is prohibited, hence allowing marine species to recover. On the Dutch Continental Shelf (DCS), the following natural reef builders occur: the flat oyster (*Ostrea edulis*) (3D printed structures for flat oyster formation), the common horse mussel (*Modiolus modiolus*), the sand tubeworm (*Sabellaria spinulosa*), the honeycomb sand tubeworm (*Sabellaria alveolata*) and the shell tubeworm (*Lanice conchilega*) (van Duren et al., 2016).

Recent research has also shown that stones surrounding wind turbines create habitat and shelter for various marine species. Researchers identified the mackerel (Scomber scombus), cod (Gadus morhua) and the European lobster (Homarus gammarus) being attracted to those hard stones substrates and higher aggregations are to be expected (Steenbergen, et al., 2023).

Another research on benthic community aggregations in four OWF in the North Sea identified a total of 47 species from seven different phyla from video footage. An abundance and diversity of benthos in OWF offer food sources for higher trophic levels such as fish, mammals and birds (Ter Hofstede, et al., 2022). However, one of the core challenges embodies finding a balance between the ecological carrying capacity of the North Sea ecosystem and the economic feasibility of OWF and LTM food production. Future-related agreements ought to pay attention not only to the economic potential, but should incorporate an ecosystem-inclusive perspective right from the beginning.

Enablers and barriers

Enablers

Increasing the demand for sustainable food production at sea, part of the North Sea agreement (2018) and expanding the current mussel sector in the Voordelta is key for the blue economy (Blue Deal, 2022). Seaweed and shellfish are resource-efficient and go hand in hand with the food vision for the North Sea (Ministry of Agriculture, Nature and Food Quality).

Ecological footprint: GHG production per serving of protein was found to be lowest for shellfish aquaculture (20 times higher for beef). Concerning eutrophication, most production methods release nutrients, however aquaculture absorbs nutrients. Acidification is also lowest for shellfish aquaculture (Hilborn et al., 2018).

Space use: Coastal and offshore waters are highly intensively used with energy, food and nature transitions upcoming. The greatest physical space available in the future for LTM food production could be within OWF.

Co-development and multi-use systems: Shipping, oil, gas, fisheries and wind energy sectors are driving forces for spatial and resource use. By co-developing other sectors, including LTM and re-thinking spatial use options, optimal use of climate solutions can be made.

Spatial limitations of agriculture production on land, freshwater shortages, Nitrogen limitations (legal framework) and Phosphorus (depletion) limitations are urgent issues on the current agenda. Connecting circular production principles of marine production to agricultural systems can have mutually beneficial effects.

Enabler for other case studies: LTM production does not require input of unnatural substances, antibiotics while being lower in the food chain → low carbon footprint and alternative protein source → less land-use → unburdening the land through more production at sea.

Robust and resilient nature: The Dutch ministry's food vision and policy making (Het Akkord van de Noordzee, 2018) – Ecological impact known for OWEZ and PAWP and can be built upon, their decommissiong is now a chance for nature, aquaculture and (passive) fisheries.

Barriers

The carrying capacity (physical, ecological, socio-economic and production-wise) embodies a major barrier to LTM production. Production space for mussels is max. 0.5 million tons in the whole North Sea (Foekema, 2024). Production space for seaweed is estimated at 145.000 ton dw (10 ton dw production/ha) with 145km2 production areal over the North Sea) (Boogaart, 2020).

Technological challenges of processing large volumes of harvested biomass at location or in a port persist to date. This also includes the challenge of having various extraction processes and the processing of large volumes of salt waste water.

Large investments are required for large-scale seaweed farming / shellfish farming. The practice is however not yet demonstrated. Adding up to this, suitable vessels are needed. The distance to OWF also demands higher transport and fuel costs.

Lack of organization and management in bringing actors and policy makers together – food vision for the North Sea results in a target, willingness and capacities of stakeholders to cooperate, innovate and change to production in OWF.

Wind farms depreciation period of 20-25 years (Wind op Zee), decommissioning according to OSPAR Guidance on Environmental Considerations for Offshore Wind Farm Development (2008) → economic factors and costs-effectiveness → ecological impact on species including noise pollution and disturbance.

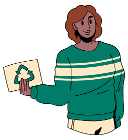
Carbon storage through shell formation has recently been reevaluated → considered to release CO2 rather than sequestrate, other processes (mainly linking to reef formation) not yet considered.

Little knowledge on carbon in marine soils and interaction shellfish and sediment.

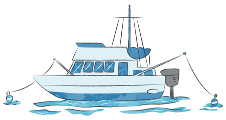
Stakeholders

The stakeholders involved in LTM production in offshore wind renewable energy farms come from a broad range of sectors, with diverse expertise and user functions. Multi-use and marina spatial planning are therefore of key importance (Steins et al., 2021).

Adding up to this, a 'Community of Practice' has been set up in the North Sea for this reason, aimed at bringing stakeholders together, sharing knowledge and learning from one another, while balancing offshore wind energy transitions with seafood production and nature development (ibid). Stakeholders active in this transition are as follows :



Nature Domain
-Stichting de Noordzee
-Stichting Anemoon
-ARK Rewilding
-Additional nature organisations and NGO's



LTM food production domain
-Conventional mussel farmers
-Innovative mussel farmers
-North Sea Farmers
-Passive fisheries

Wind energy domain
-Wind park operators
-Wind park maintenance and construction

Knowledge institutes and research domain
-University of Applied Sciences Hogeschool Zeeland
-Wageningen Marine Research
-Deltares
-MARIN
-NIOZ
-Bureau Waardenburg

Policy domain
-Ministry of Agriculture, Nature and Food Quality
-Ministry of Economic Affairs and Climate
-Ministry of Infrastructure and Water Management
-Rijkswaterstaat
-Province Zeeland

Sustainable Development Goals as a framework

The seventeen Sustainable Development Goals (SDGs) came into force on the 1st of January 2016 and have been adopted by world leaders to fulfil the 2030 Agenda for Sustainable Development (see Figure 5).

The SDGs offer a well-known framework for dialogue on international level and a good channel towards circular economy. These goals recognise that ending poverty, inequality, and tackling climate change, must go hand in hand with strategies which build economic growth while addressing social needs, education, health, social protection and job opportunities and environmental protection (van Eijk and van Kruchten, 2020).

The effective incorporation of sustainability is complex and requires all stakeholders in the value chain to be involved, therefore using common frameworks that drives understanding and effectiveness is important. The SDG framework is a shared plan for promoting sustainable economic growth, advancing social inclusion, and safeguarding the natural environment. This framework provides the basis for initiating and developing a common ground and facilitate international, national, or regional dialogues (van Eijk and van Kruchten, 2020, Sustainable Development Goals, n.d.).

Figure 5: Sustainable Development Goals (Source: UN SDG's)

The goals universally apply to all and although they are not legally binding, governments are expected to take ownership and establish national frameworks for the achievement of the 17 Goals. Countries have the primary responsibility for follow-up and review of the progress made in implementing the Goals, which will require quality, accessible and timely data collection. Countries and businesses should mobilize their efforts to end all forms of poverty, fight inequality and tackle climate change, while ensuring that no one is left behind (van Eijk and van Kruchten, 2020, Sustainable Development Goals, n.d.).

Identification of synergies and trade-offs

Identifying synergies and trade-offs of low trophic marine systems in offshore energy parks in the North Sea with the SDGs (see Figure 6 and Figure 7) is crucial for informed decision-making. Therefore, a workshop with experts has been organised to discuss synergies and trade-offs of the proposed climate solution on the SDGs. The workshop resulted in multiple synergies on the case with all discussed SDG targets. Meanwhile, trade-offs on several SDGs were identified as well. Recognizing synergies enables us to define the potential of the proposed case study. Understanding the trade-offs will help to identify potential unintended consequences. Therefore, the climate solution can be aligned better with overarching SDGs, foster inclusive development, and mitigate any negative impacts. This assessment could guide policymakers, stakeholders, and communities in making choices that balance economic, environmental, and social objectives for a more sustainable production and consumption pattern.

Figure 6: Identified synergies of low trophic marine systems in offshore wind farms in the North Sea relevant to the SDGs (Selected).

2 ZERO HUNGER

Food security:
Increasing mussel production on the North Sea offers options for more protein-rich food sources from the sea. Such low trophic marine food production diversifies human food intake. It is nutrient-rich, a local production system and does not require additional fertilizer input.

4 QUALITY EDUCATION

New opportunities for education:
Potential synergy because the North Sea food system is in a transition towards low trophic marine food production, thus new opportunities for education for the hanging rope mussel production system emerge.

8 DECENT WORK AND ECONOMIC GROWTH

Emerging developments:
Potential syngery because there are ecosystem-based mussel prodution developments ongoing which offer sustainable economic opportunities.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Food production for the future:
This case study ensures robust and resilient food production for the future. It is crucial to act sustainable and responsible towards the ecosystem.

14 LIFE BELOW WATER

Habitat creation and lower trophic species:
Increasing mussel culture has the potential to reduce the demand on other species while creating new habitat. This provides an alternative to the 'traditional' Dutch food production at sea.

3 GOOD HEALTH AND WELL-BEING

Ecosystem services:
A synergy for marine ecosystems if it is done in a nature-based, ecosystem-based or ecosystem-inclusive manner.

7 AFFORDABLE AND CLEAN ENERGY

Sustainable energy production:
This case study has a clear syngery with this SDG since mussel production is in this case developed in offshore wind farms.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Optimalization and biodiversity:
This case study aims for sustainable industrialization by upgrading already used offshore wind farms. When executed well, space can be optimally used and ecosystem recovery can be stimulated.

13 CLIMATE ACTION

Reducing impact on climate change:
Low trophic marine food production contributes to more sustainable food production, lower GHG production per protein serving as compared to conventional livestock

15 LIFE ON LAND

Releasing pressure:
A synergy can be identified since this case study has the potential to release pressure of the terrestrial ecosystem while stimulating more biodiversity increase.

Figure 7: Identified trade-offs of low trophic marine systems in offshore wind farms in the North Sea relevant to the SDGs (Selected).

SDG 1, 3, 8 and 9

1 NO POVERTY

Large companies profit:
A trade-off regarding inequality might be present since building and maintaining offshore windfarms is often done by large and resourceful companies.

3 GOOD HEALTH AND WELL-BEING

Labour risks:
Rather a trade-off for workers and mussel producers in the sector due to demanding health and working conditions offshore.

8 DECENT WORK AND ECONOMIC GROWTH

Economic and regulatory challenges:
Working conditions, sound business models and spatial arrangements are hurdles for this case study.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Financial and infrastructure constraints:
Current mussel farmers (industry) might not be equipped (financially and infrastructure wise) to transitioning towards offshore entrepreneurship and offshore mussel production.

SDG 13 and 16

13 CLIMATE ACTION

Monoculture risks:
When executed poorly, risks related to growing a monoculture population (diseases etc.) are high.

Technology and decommissiong:
Furthermore, research gaps are apparent, in particular questions surrounding the carrying capacity of the ecosystem, the technology needed for harvesting close as well as the consequences for mussel rope culture system during the decommission period.

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

Decision-making
Potential trade-off due to high competitiveness, diverging interests and unclear governance

Research questions for other domain experts

The following questions are potential topics for other domain experts to explore in this case study:

- How to assign marine development benefits to land based circular food systems?
- Which marine trade-offs can be directly used to land based case studies?
- How can multiple indicators (nitrogen, carbon, biodiversity etc.) in synergy and trade off analysis be used?
- How much Nitrogen/Phosphorus and which ratios are we expecting in future circular food scenarios? (Will this alter current marine productivity?).
- How can ecosystem services be integrated in synergy and trade-off analysis?
- How is this case linked to the carbon sequestration and food waste case in relation to closing nutrient loops (as a trade-off)?

Terminology for Wageningen Climate Dictionary

The proposed climate solution contributes to essential terminology and practical concepts for the Wageningen climate dictionary, enriching the discourse on climate mitigation and adaptation. The terms and definitions can be found in Annex 1.

Conclusions

Integrating low trophic marine systems, such as mussel farming, with offshore wind farms in the North Sea represents an innovative approach to contribute to multiple Sustainable Development Goals (SDGs). This integration offers numerous synergies (on SDG 2-4, 7-9 and 12-15) but also involves certain trade-offs (on SDG 1-3, 8, 9 and 16) that must be carefully managed to ensure overall sustainability.

One of the primary benefits of this case study is its contribution to a robust and resilient food production, aligning with SDG 12 (Responsible Consumption and Production). By farming mussels in conjunction with wind farms, this approach ensures a steady and sustainable food supply that does not require additional fertilizers, thereby promoting responsible production practices. This approach also supports SDG 14 (Life Below Water) by reducing pressure on higher trophic species and fostering habitat creation.

In terms of energy production, the integration aligns well with SDG 7 (Affordable and Clean Energy). Mussel farming within offshore wind farms exemplifies the synergy between clean energy and sustainable food production. It optimizes the use of maritime space and reduces the carbon footprint associated with food production, thus supporting the goal of affordable and clean energy.

Increasing mussel production also contributes to SDG 2 (Zero Hunger) by enhancing food security. Mussels offer a local, nutrient-rich food source that diversifies the human diet and contributes to a more resilient food system. This production can take place alongside the high-efficient farming systems as known in the Netherlands. This is especially important as global food demand continues to rise.

Several trade-offs on SDGs are associated with the implementation of this case study as well. Questions remain about the ecosystem's carrying capacity and the technological requirements for harvesting mussels during decommissioning periods. Economic and regulatory challenges are at issue. Ensuring the economic viability of offshore mussel production involves overcoming difficult working conditions, establishing sound business models, and addressing spatial planning issues. Regulatory frameworks need to evolve to support these new practices effectively.

Technological and knowledge gaps can also complicate the integration. More research is needed to enhance the resilience of rope culture systems under rough offshore conditions and to understand the economic impacts of these innovations. Poorly managed monoculture can lead to disease outbreaks and other environmental impacts. Education and training programs must address these gaps to support successful implementation.

In summary, integrating low trophic marine systems with offshore wind farms in the North Sea presents significant potential for sustainable development. It can enhance food security, promote biodiversity, and contribute to clean energy goals. However, addressing the financial, infrastructural, and regulatory challenges is crucial to fully realizing these benefits.

Authors: Poelman, M. and Pulskens, A. (2024). Marine Case Study. Low trophic marine production systems in offshore wind farms at the North Sea. Project: Synergies & trade-offs of Wageningen climate solutions in primary production systems . Wageningen University & Research. Factsheet, July 2024.

Acknowledgements:
Special thanks to Daan Verstand, Cheng Liu, Naomi Dam, Jan Verschoor, Trond Selnes, Martine Trip, Lesly Garcia Chavez, Noortje Pellens, Kelly Niermans, Rosa Safitri, Josien Steenbergen and Monserrat Budding-Polo Ballinas.

This research was funded by the Dutch Ministry of Agriculture, Nature and Food Quality
(Project number 5200047569- Synergies & trade-offs of Wageningen climate solutions in primary production systems. KB34 Circular and climate neutral society).
KB-34-002-004

References

Agrimatie, 2023: https://agrimatie.nl/PublicatiePage.aspx?subpubID=2526&themaID=2857&indicatorID=2881&sectorID=2863

Alongi, D.M., Robertson, A.I. Factors regulating benthic food chains in tropical river deltas and adjacent shelf areas. Geo-Marine Letters 15, 145–152 (1995). https://doi.org/10.1007/BF01204456

van den Bogaart, L., van der Wal, J. T., Tonk, L., Bos, O., Coolen, J., Poelman, M., ... & Timmermans, K. (2020). Geschiktheid zeewindparken voor maricultuur en passieve visserij: een kwantitatieve beoordeling van de kansrijkheid van de gebieden voor de potentiële productiviteit van een selectie aan commercieel interessante soorten (No. C127/19A). Wageningen Marine Research.

Byron, C.J. & Costa-Pierce, B.A. 2013. Carrying capacity tools for use in the implementation of an ecosystems approach to aquaculture. In L.G. Ross, T.C. Telfer, L. Falconer, D. Soto & J. Aguilar-Manjarrez, eds. Site selection and carrying capacities for inland and coastal aquaculture, pp. 87–101. FAO/Institute of Aquaculture, University of Stirling, Expert Workshop, 6–8 December 2010. Stirling, the United Kingdom of Great Britain and Northern Ireland. FAO Fisheries and Aquaculture Proceedings No. 21. Rome, FAO. 282 pp.

Cao L., Naylor R., Henriksson P., Leadbitter D., Metian M.,M. Troell M. et al. (2015) China's aquaculture and the world's wild fisheries. Science 347: 133–135.

Coolen, J. W. P., Van Der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G. W. N. M., Faasse, M. A., Bos, O. G., Degraer, S. & Lindeboom, H. J., May (2020) Benthic biodiversity on old platforms, young wind farms, and rocky reefs, In: ICES Journal of Marine Science. 77, 3, p. 1250-1265 16 p., fsy092.

Corell, H., Bradshaw, C., M. Sköld (2023) Sediment suspended by bottom trawling can reduce reproductive success in a broadcast spawning fish, Estuarine, Coastal and Shelf Science, Volume 282, 108232, ISSN 0272-7714

Crona, B. I., Wassénius, E., Jonell, M., Koehn, J. Z., Short, R., Tigchelaar, M., ... & Wabnitz, C. C. (2023). Four ways blue foods can help achieve food system ambitions across nations. Nature, 616(7955), 104-112.

van Duren, L., Gittenberger A., Smaal, A.C., Van Koningsveld, M., Osinga, R., Cado van der Lelij, J.A., de Vries, M.B., (2016), Rijke riffen in de Noordzee: verkenning naar het stimuleren van natuurlijke riffen en gebruik van kunstmatig hard substraat
FAO. 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO.

Foekema, E., Poiesz, S., Poelman, M., Kootstra, M., & Geerdink, P. (2024). Mariene bouwstenen: Een verkenning van de mogelijkheden van benutting van schelpen in cement-en betonproductie (No. C002/24). Wageningen Marine Research.
Gibbs, M.T. (2007) Sustainability performance indicators for suspended bivalve aquaculture activities. Ecological Indicators, 7: 94–107.

Hilborn, R., Banobi, J., J Hall, S., Pucylowski, T., E. Walsworth, T., (2018), The environmental cost of animal source foods
ter Hofstede, R., Driessen, F. M. F., Elzinga, P. J., Van Koningsveld, M., & Schutter, M. (2022). Offshore wind farms contribute to epibenthic biodiversity in the North Sea. Journal of Sea Research, 185, 102229.

Kruchten, S. van., en F. van Eijk, (2020), Circular Economy & SDGs -How circular economy practices help to achieve the Sustainable Development Goals, Netherlands.

Lilienthal, P., Lambert, T., P. Gilman (2004) Computer Modeling of Renewable Power Systems, Encyclopedia of Energy, Elsevier, 2004, Pages 633-647.

Lotze H.K. (2021) Marine biodiversity conservation Curr. Biol., 31 (2021), pp. R1190-R1195, https://doi.org/10.1016/j.cub.2021.06.084
Mayerle, R., Sugama, K., van der Wulp, S., & Runte, K. H. (2022). Decision tool for assessing marine finfish aquaculture sites in Southeast Asia. In Science for the Protection of Indonesian Coastal Ecosystems (SPICE) (pp. 371-387). Elsevier.

Nikitas G., Bhattacharya, S., N. Vimalan (2020) Wind Energy, Book chapter 16: Future Energy (Third Edition), Editor(s): Trevor M. Letcher, Elsevier, 2020, Pages 331-355, ISBN 9780081028865,

Noordzeeloket, (2024), https://www.noordzeeloket.nl/functies-gebruik/windenergie/doorvaart-medegebruik/hollandse-kust-noord-inclusief-prinses-amalia/

OFL, (2018), Het Akkoord voor de Noordzee: https://open.overheid.nl/documenten/ronl-99d46f4b-1d45-49cd-a979-2ce8bf737e22/pdf

Programma Noordzee, (2022)

Savrda, C. E. (2007). Taphonomy of trace fossils. In Trace fossils (pp. 92-109). Elsevier.

Steenbergen, J., van Hal, R., Kamermans, P., Nauta, R., Schneider, L., Vallina, T., ... & van Duren, L. (2023). Kansrijke windenergiegebieden voor maricultuur en passieve visserij: Kwalitatieve beoordeling van de geschiktheid van de bestaande, geplande en nog aan te wijzen windenergiegebieden voor zeewierkweek, schelpdierkweek en passieve visserij als medegebruiksfunctie (No. C015/23). Wageningen Marine Research.

Steins, N., Veraart, J.A., Klostermann, J.E.M., Poelman, M., (2021), Combining offshore wind farms, nature conservation and seafood: Lessons from a Dutch community of practice

Trites A.W. (2001) Marine Mammal Trophic Levels and Interactions, Editor(s): John H. Steele, Encyclopedia of Ocean Sciences (Second Edition), Academic Press, Pages 622-627, ISBN 9780123744739

Van Doorn, A., Melman, D., Westerink, J., Polman, N., Vogelzang, T., & Korevaar, H. (2016). Food-for-thought: natuurinclusieve landbouw. Wageningen University & Research.

Zeeland 2022, Blue Deal: https://www.zeeland.nl/actueel/nieuws?categorie=All&field_type_target_id=All&created%5Bmin%5D=2022-03-13&created%5Bmax%5D=2022-04-13&page=1

Annex I

TERMINOLOGY	DESCRIPTION	SOURCE
OFFSHORE WIND FARMS	As offshore wind farm can be defined as a power plant that contains all the facilities needed to capture the wind power, transform it into electricity and supply it to the main electricity network.	Nikitas, 2020
WIND ENERGY	Wind turbines generate alternating or direct current (AC or DC) power, in sizes ranging from a few watts to several megawatts. Each wind turbine has a characteristic power curve that describes its power output as a function of the wind speed at its hub height.	Peter Lilienthal, 2004
TROPHIC LEVELS	Trophic levels are a hierarchical way of classifying organisms according to their feeding relationships within an ecosystem. By convention, detritus and producers (such as phytoplankton and algae) are assigned a trophic level of 1. The herbivores and detritivores that feed on the plants and detritus make up trophic level 2. Higher order carnivores, such as most marine mammals, are assigned trophic levels ranging from 3 to 5. Knowing what an animal eats is all that is needed to calculate its trophic level.	Trites, 2001
LOW TROPHIC AQUACULTURE	Low Trophic Aquaculture (LTA) can include unfed shellfish, seaweed and some species of finfish, and can also include fed species that primarily depend on plant products in their feeds.	Cao, 2015
BENTHIC COMMUNITY	Benthic communities are the organisms that reside on the sediments of aquatic habitats. They are very diverse and also, they can occur in a wide range of habitats. According to their size, they are subdivided into macrofauna, meiofauna, and microfauna. Aquatic habitats possess a diverse range of benthic communities and they have an important role in maintaining the food web and primary production.	Alongi & Christoffersen, 1992
MARINE BIODIVERSITY	Marine biodiversity is the key foundation for the structure and functioning of ocean ecosystems and for providing essential service and benefits for human societies, on local, regional, and global scales.	Lotze, 2021
ECOSYSTEM CARRYING CAPACITY	as the magnitude of aquaculture production that can be supported at site scale without leading to significant changes to ecological processes, species, populations, or communities in the environment (Gibbs, 2007; Byron and Costa-Pierce, 2013)	Mayerle, 2022 Gibbs, 2007 Byron and Coasta-Pierce, 2013
HARD SUBSTRATES	Hard substrates include (1) hardgrounds sensu stricto, formed by syndepositional cementation of carbonate sediments at or near the seafloor, and (2) rockgrounds, which are lithified substrates of various types that have been exhumed. 3) Artifical hard substrates are typically introduced in an exclusively soft-bottom environment	Savrda, 2007
OVERFISHING	Stock abundance fished to below the level that can produce maximum sustainable yield (MSY)	FAO, 2022
BOTTOM-TRAWLING	Bottom trawling is a fishing method used to catch fish or invertebrates living on or close to the seabed. It is performed worldwide using a range of different fishing gears, most commonly beam trawls, otter trawls and various types of dredges, which are dragged along the sea floor.	Corell, et al., 2023
NATURE-INCLUSIVE FARMING	Nature-inclusive farms are defined as having low emissions and thereby a limited negative impact on biodiversity on the farm or in the surroundings, making use of biodiversity through ecosystem services and taking care of biodiversity through landscape management.	Van Doorn et al., 2016