Combining offshore wind energy and large-scale mussel farming: background & technical, ecological and economic considerations

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Preface

Offshore wind energy production and offshore aquaculture – an unusual combination? Whether you judge it an unrealistic idea or an innovative concept within reach, the first thing to do is: find out what the points of departure are of the different actors in the field and whether it makes sense to further explore such an uncertain path. That's exactly what the Blauwdruk study does. It looks into the technical, ecological and economic challenges and risks, and simulates the feasibility of combining an offshore wind farm with offshore aquaculture, namely an offshore mussel farm. The starting point of our study was the assumption that there is a potential for synergy. Although there are still more uncertainties than certainties, looking at this final report, we believe that our considerations touch the key issues and fill in a knowledge gap. We consider this report a useful source of inspiration to continue the exploration of combining offshore activities and to start up (small-scale) pilot studies. In the end: the proof of the pudding is in the eating, isn't it?

Contents

Glossary and abbreviations

AMC	Asset Management Control: a management approach to manage and control, over the life cycle, all processes (specify, design, produce, maintain and dispose) needed to achieve a capital asset capable to meet the operational need in the most effective way for the customer/user.
Blauwdruk	Dutch for blueprint, in general: an operational plan
Business case	Captures the reasoning for initiating a project, the quantifiable and unquantifiable characteristics of a proposed project.
Business scenario	One or more options considered in a business case.
Business case model	Computer model; tool for the financial analyses of a business case
CAPEX	Capital expenditures; expenditures creating future benefits. A capital expenditure is incurred when a business spends money either to buy fixed assets or to add to the value of an existing fixed asset with a useful life extending beyond the taxable year.
DM	Dry matter
DOWES	Dutch offshore wind energy services
EBIT	Earnings before interest and tax
EFRO	European Fund for Regional Development
FLOW	Far and large offshore wind farm
FTE	Full time equivalent
HAB	Harmful Algal Bloom
IMTA	Integrated Multi Trophic Aquaculture
LCA	Life-cycle analysis
NM	Nautical mile
MCN	Maritime Campus Netherlands
MIC	Microbial corrosion
MSP	Marine spatial planning
MUP	Multi-use platform
MWH	Megawatt hours
MYM	Multiyear maintenance
MYC	Multiyear confidence
O&M	Operation and maintenance
OPEX	Operational Expenditures
OWF	Offshore wind farm
OWEZ	Offshore Windfarm Egmond aan Zee
PAWP	Prinses Amalia Windfarm
ROI	Return on Investment
SMC	Seed Mussel Collector (in Dutch: MZI; Mosselzaadinvanginstallatie)
SWH	Significant wave height: usually defined as four times the standard deviation of the surface elevation (wikipedia)
WPSP	Wind power sales price
W&MF	Wind and mussel farm

Summary

This Blauwdruk project report presents background and technical, ecological and economic considerations of the potential combination of offshore wind energy production and large-scale mussel farming in offshore areas in the North Sea. The main objective of the Blauwdruk project was to study the feasibility of such a combination on the Dutch Continental Shelf.

The Blauwdruk project focused on a virtual offshore wind farm of 1000 MW, arranged in five clusters of 200 MW each, combined with an offshore mussel farming system that consists of four clusters of 1,800 mussel long line systems. The four mussel long line clusters are integrated in the empty corridors between the five wind farm clusters of the virtual wind farm and are supposed to produce 50,000 tons of mussels per year.

After a brief introduction to the project, this report describes the current perspectives of the Dutch government and the offshore industry on the concept of marine multi-use. This facilitates a broader understanding of the different stakes.

An overview is presented of the development of offshore wind energy in the Netherlands, the related Dutch policies, and the technological gaps and logistical problems that the offshore wind energy sector faces. This report zooms in particularly on operation and maintenance issues of offshore wind farms.

Offshore mussel farming is still a novelty in the North Sea; practical experiences from the field are still lacking. Hence, this report builds on literature to describe the state of the art of offshore aquaculture in general and mussel farming in particular.

The proposed combination of offshore wind energy and aquaculture production is promising, but it also involves risks. There are the technical risks of corrosion and biofouling, as well as ecological risks, such as underwater-noise disturbance of marine mammals, disturbance of the seabed sediments and seabed communities underwater, collision risks to birds and bats above water, and attraction of invasive species. Apart from risks, the combination of an offshore wind farm with and offshore mussel farming can provide ecological benefits, such as offering increased food availability and shelter, thereby attracting flora and fauna. This, in turn, enhances biological diversity and production.

This report also investigates a concrete business case, using an expanded version of the Asset Management Control (AMC) model to simulate the return on investment (ROI) of a virtual wind and mussel farm. It seems likely that a combined offshore wind and mussel farm can achieve synergy effects through savings on operation and maintenance costs of at least 10%. The scenario simulations demonstrate the potential financial benefits. Assuming unfavourable economic conditions and no synergy effects, an ROI of 4.9% should be possible. Applying a 10% synergy factor in the model raises the simulated ROI to 5.5%. When economic conditions are favourable, without assumed synergy effects , the simulated ROI is significantly higher: 8.3%,. Applying the 10% synergy factor, an ROI of 9.6% can be yielded.

Finally, the report summarizes the main findings for each of the relevant topics of this study. It concludes with recommendations for practitioners and policy makers on how to proceed in the future with combining offshore wind energy production and offshore aquaculture.

The four most important conclusions of the Blauwdruk study are:

- With regard to the Dutch part of the North Sea, currently mussel culture and seed mussel culture are considered the most promising options for offshore aquaculture.
- Concerning the technical aspects of an offshore wind farm in a combined wind/aquaculture setting, the preferred foundation type should be monopile or gravity based in order to minimize the risk of a high drag force incident.

- Type and size of the integrated aquaculture activity determine the extent of effects on water and sediment quality, which in turn effects the corrosion resistance of the materials used. This aspect should be dealt with in a dedicated risk assessment for the specific location. Appropriate measures are the application of corrosion resistant materials and/or suitable protective coatings.
- The combination of offshore wind and mussel farming poses ecological risks, but also offers potential benefits to the marine ecosystem. Since individual marine ecosystem components may be affected differently by different pressures, it is difficult to generalize conclusions concerning ecosystem impacts.

The Blauwdruk approach focused on large-scale, (semi-)intensive offshore aquaculture production and providesan overview of the potential developments. The authors realize that there are still many uncertainties concerning possibilities, risks, and benefits. We therefore recommend a stepwise learning-by-doing approach, starting with small-scale pilot projects, instead of directly jumping into large-scale implementation. It seems likely that the development from pilot studies to full-scale commercial cultures will take approximately 8-10 years. During this process other aquaculture options (fisheries, seaweed, lobsters, and/or oysters) might be considered in order to optimize spatial use within (or in the vicinity of) wind farms.

1 Introduction

1.1 MCN-Efro and the Blauwdruk project

This report is the result of Work Packages 1 and 2 of the MCN[1]-Efro[2] program 2009-2014, called the 'Blauwdruk'[3] project. The MCN-Efro program addresses three major strategic topics, namely shipping, offshore energy and offshore aquaculture. The Blauwdruk project focuses on the latter two subjects and in particular on the combination of both activities, which is a subject in itself: multi-use of marine space. The Blauwdruk report represents a feasibility study, covering technical, ecological, and economic aspects.

1.2 Aim and scope of the project

The Blauwdruk study deals with offshore wind energy production in combination with offshore aquaculture in general and mussel farming in particular, and the potential economic viability, ecological sustainability, and technical soundness thereof. If there are advantages via synergy, this could make offshore aquaculture feasible and attractive to financiers; at the same time, synergies with aquaculture could contribute to the wind industry's efforts to reduce costs, particularly operation and maintenance (O&M) costs.

The Blauwdruk investigations focus on one specific scenario[4], i.e. an exemplary case description. This scenario can be worked out in more detail and result in a real business case, which can be brought into practice in the coming five to ten years. The scenario chosen acts as a means to identify pre-conditions and constraints that are relevant for future implementations of combined marine activities (generally indicated with multi-use platforms (MUPs)) and to give recommendations for the improvement of operational processes in such offshore multi-use settings.

The Blauwdruk project team decided to focus on the 1000 MW wind farm concessions on the Dutch Continental Shelf (see chapter 3). Since several public-private partnerships have already been launched in the Province of Zeeland (e.g. Zeeuwse Offshore Wind Project (ZOWP)[5]) to discuss and develop plans for combined activities, the offshore wind farm concession Borssele was taken in mind as a possible location. Some characteristics and pre-set parameters for the combination of offshore aquaculture and offshore wind energy production are given in Table 1-1.

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1 Maritime Campus Netherlands (MCN); Its goal is to expand and strengthen the economic infrastructure in the north of the Province of Noord-Holland ('Noord Holland Noord') by establishing, developing, expanding and maintaining an authoritative international Marine, Maritime and Environmental Technological cluster based in the city of Den Helder which promotes the sustainable use of the sea and the marine environment. www.maritimecampus.nl

2 Efro; European Fund for Regional Development

3 'Blauwdruk' is the Dutch word for blueprint or template

4 We prefer to speak of a scenario to underline that the particular local circumstances always play an important part. Although the project-title is 'Blauwdruk' (in English: blueprint) we did not intend to create a blueprint meaning a guide or design that can simply be followed by 'copy & paste'.

5 www.zowp.nl/content/meervoudig-ruimtegebruik

Table 1-1. Characteristics and pre-set parameters of a possible combination of offshore wind energy production and offshore aquaculture, as used in the Blauwdruk study.

Wind farm turbines and foundations	Wind farm with 5 MW turbines and new type of foundations, suitable for deeper water *)
Aquaculture zone	The offshore aquaculture installations will only be installed in the freely accessible zones between the clusters of turbines/within the wind farm (e.g. with poles or lines and anchors). They will not be attached to the foundations of the wind turbines.
Synergy: scenarios to be evaluated with the Asset Management Control (AMC) model	0% and 10% reduction of costs through combination of offshore wind and offshore aquaculture operation and maintenance (O&M) activities
** for example jackets and gravity based constructions*	

The quantitative analyses in chapter 7 of this report are limited to mussel farming; all simulations focus on the operational phase.

The decommissioning of offshore constructions, which is regulated in several treaties and Dutch national law based on IMO Resolution A.672 (16)[6], can be a compulsory requirement, but is not specifically taken into account in this report. Another aspect that has not been dealt with in this study, is how insurance companies assess the risks arising from the operational processes when modified for combined use. Although this is of major importance, especially for financial calculations and results, this can only be examined once it is known how the operational processes in an offshore mussel farm exactly look like, and whether typical risks of combined use can be mitigated.

1.3 Reading guide

As an introduction and to facilitate a broader understanding of the different stakes and perspectives, we first describe the current perspectives of the Dutch government and the offshore industry on the concept of multi-use (chapter 2). In chapter 3, we outline the development of offshore wind energy in the Netherlands and the related Dutch policies up to the time of writing of this report (August 2014). We also point out technological gaps and logistical problems that the offshore wind energy sector faces, in order to identify potential synergy fields that advocate combined use. In chapter 4, the state of the art of offshore aquaculture is presented. Chapter 5 and 6 elaborate on the technical aspects of corrosion and biofouling, and on ecological risks and opportunities respectively, paying special attention to the combination of offshore wind energy and aquaculture. In chapter 7, a concrete business case is depicted and four scenario simulations, run with an expanded version of the Asset Management Control (AMC) model, are presented and compared. Chapter 8 concludes with recommendations for practitioners and policy makers how to proceed in the future with combining offshore wind energy production and offshore aquaculture.

6 www.imo.org/blast/mainframe.asp?topic_id=1026

2 Single and multi-use activities in the North Sea

2.1 The Dutch government perspective

The Dutch government recognizes the need for new marine activities, their particular needs and the potential competition for space. The Dutch marine spatial policy therefore does not only focus on sustainable and safe use of the North Sea, but also stresses the need for space-efficient use. The Policy Note North Sea 2009-2015[7] elaborates on the Dutch North Sea policy and explicitly mentions that co-use of offshore wind farms with other functions, for example with recreation, fisheries or aquaculture, should be stimulated, thus leading towards multi-use platforms (MUPs) in the North Sea. The Integral Management Plan for the North Sea 2015[8] (IBN 2015) expresses objectives of similar meaning, stating that the Dutch policy should be based on three pillars: a healthy, safe, and profitable sea. The two important principles of Dutch marine spatial planning policy are: multiple use and ecosystem approach.

Triggered by the European renewable energy objectives, the Dutch policy goal is to achieve 14% of sustainable energy production by 2020[9]. The switch to renewable energy should be completed in 2050. Wind energy – generated on land as well as at sea – plays an important contribution to achieve this goal. The Dutch national government's website also states that the Dutch part of the North Sea should provide space for a total installed volume of wind turbines of 4450 MW after 2020. This is roughly 20 times more than the currently (2014) installed 220 MW. Moreover, it also implies that at least 1000 km^2 of suitable marine space on the Dutch continental shelf have to be reserved for wind farm development. Originally, the Dutch government had decided to exclude the 12 NM zone for offshore wind farm concessions. Meanwhile, the government considers opening this coastal zone to offshore wind farm construction as well. Developments after 2020 might require even more marine space.

In the Integral Management Plan for the North Sea 2015 (IBN 2015), the Dutch water management authority[10] explicitly points out that aquaculture inside offshore wind farms is a possibility for smart use of space, which leads to opportunities for innovative entrepreneurship. No space has yet been indicated for offshore aquaculture in the Dutch part of the North Sea though. This means that aquaculture activities in or around offshore wind farms need to apply for permits to obtain exemption. Obtaining permits does not seem to be a preliminary off-set, as the government does not principally oppose to offshore aquaculture and the development of MUPs. Nevertheless, a regulatory framework for MUPs is yet missing, and existing guidelines are not supportive of MUPs. Anyhow, apart from the problem of space, growing world population and food consumption, and diminishing fish stocks will lead to a growing demand for marine protein from aquaculture. Therefore, it is plausible that the multi-use concept will gain ground among policymakers.

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7 Dutch: "Beleidsnota Noordzee 2009-2015": www.rijksoverheid.nl/documenten-en-publicaties/brochures/2010/08/12/beleidsnota-noordzee-2009-2015-engels.html

8 Dutch: "Integraal Beheerplan Noordzee 2015": zoek.officielebekendmakingen.nl/stcrt-2011-20771.html

9 http://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie (last accessed: 23 January 2014)

10 Dutch: "Rijkswaterstaat": http://www.rijkswaterstaat.nl/

2.2 The offshore industry’s perspective

Up till now, when it comes to multi-use, only a few individual (offshore) companies have started to develop innovative concepts, mostly through isolated activities or studies. Time seems ready now for progressing with combined offshore activities, for a number of reasons. As mentioned in section 2.1, more offshore wind farms have to be built to comply with renewable energy goals. Traditional marine sectors now have to compete for space with other new users, and they start feeling threatened in their operations. This leads to a public debate on the fair and sustainable use of marine space.

Multi-use is apparent when the potential of use conflicts is low, i.e., when overlap of activities in time and space is limited but still allows for synergies and - perhaps the most important criterion – when risks arising from combined activities are minimal in relation to the benefits. Combining activities at the same place and time can lead to increased or new risks, though. To date the offshore wind energy sector has been reluctant to allow other activities within the boundaries of their wind farms. Moreover, the offshore wind energy sector, being subsidized, has not felt the urgency to look for potential synergies and collaboration with other users in order to share, and thus reduce, costs. This situation is changing now; pressure is increasing on the offshore wind sector to become a mature industry that can stand on its own feet, i.e., survive without, or at least with less, subsidies. Due to these developments, the wind energy sector is now more inclined to seek synergies with other sectors. Surveys (MERMAID 2013, COEXIST 2011) reveal that stakeholders consider the combination of offshore wind energy and offshore aquaculture as worthy to be explored. For offshore-wind energy companies, faster licensing procedures, financial benefits, and/or the improvement of the company’s corporate social responsibility would be strong incentives. Knockdown arguments are: higher insurance costs and an increase of ecological risks. Anyway, given the current uncertainties, stakeholders advocate a level playing-field and a facilitative role of government (MERMAID 2013).

Development of offshore aquaculture is a relatively new activity in the North Sea, in contrast to the more than 40 years of experience of the offshore oil and gas industries. Culture of fish in (offshore) sea cages is commercially applied in many areas around the world; the potential for fish culture, in particular in the rather shallow Dutch part of the North sea, is low, though (Reijs et al. 2008). The Dutch aquaculture industry is therefore looking for opportunities for offshore production of shellfish and seaweed in the North Sea. There are indications that the traditional areas for shellfish culture (Eastern Scheldt, Wadden Sea) are reaching their carrying capacity, setting limits to further growth of production in those areas (Smaal et al. 2013, Schellekens et al. 2013, Brinkman 2013). Furthermore, induced by recent changes in collection of mussel seed (transition from seed fishery to collection of seed with so-called Seed Mussel Collectors; SMC), suspended spat collection measures have recently proven their technical and economic feasibility for use in inshore and near shore areas (Van Stralen 2012, 2013). The shellfish industry now wants to expand and is looking for areas outside the traditional production locations to collect mussel spat and to grow consumption mussels to a marketable size. This has led to commercial interest for development of offshore shellfish culture.

The production and sale of seaweed is less mature compared to shellfish, but increasing demand for marine natural resources, healthy food and increasing food prices have spiked interest in alternative marine production methods. Seaweed production is promising as it can provide material required for the production of (animal) feed, feed additives (alginates, protein, carbohydrates), trace minerals, source for biofuels, or novel feedstock and antibiotics in a green chemical sector.

Various small-scale research projects have investigated the viability of seaweed production onshore or near shore in the Netherlands over the past years, and demonstrated the technical potential to grow seaweeds in estuarine areas (such as experiments in the Oosterschelde, as well as nearby Texel). Using offshore oil, gas, and wind energy platforms to facilitate shellfish and seaweed production, has so far mostly remained theoretical (Reith et al. 2005), and been tested only at pilot scales on a few occasions (Buck 2004, Brandenburg 2012).The technical implementation and practicalities of production and harvesting of aquaculture products pose many questions and challenges. As newcomers, the pioneers from the Dutch offshore aquaculture sector need to collaborate with offshore wind energy companies and will have to convince other stakeholders – government and nature organizations – that good neighborhood and, even more, synergy through collaboration are possible (Stuiver et al. 2012).

Despite the still existing strong doubts about integrating offshore wind energy generation with aquaculture, especially held by wind farm operators (MERMAID 2013), there is potential for cost reduction and thus financial benefit through economies of scale (e.g. transport, shared (electrical power) installations, co-use of maintenance vessels and platforms) and economies of knowledge and experience (e.g. personnel, environmental studies, risk analyses). Clearly, both offshore wind farm operators and offshore aquaculture operators will only adopt a multi-use concept once the technical and economic feasibility has been demonstrated with a certain degree of reliability. The likelihood of collaboration in a multi-use setting not only depends on how well risks and uncertainties are addressed in feasibility studies but also on the economic and social environment (market conditions, demand for corporate social responsibility) and regulatory frameworks, which can stimulate or counteract the adoption of the multi-use concept.

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3 Offshore wind energy production

3.1 Dutch energy policy

The development of wind farms in the Netherlands is inseparable from the Dutch energy policy, which aims at stimulating sustainable energy to meet the targets under the Kyoto Protocol. In the early years of the energy discussion (2001-2004)[11], offshore wind was considered to contribute largely to achieving these policy objectives. In 2008, the Dutch government set itself the goal to realize, by 2020, an overall production capacity of 6,000 MW of wind energy on land (Rijksoverheid 2008[12]). A clear commitment for offshore wind energy, however, was not there: a target for offshore wind was lacking in that plan. In 2010, the Dutch government appointed the taskforce 'Wind Energy at Sea' in support of meeting this goal. The taskforce identified a number of bottlenecks, especially related to the supply and investment chain capacity (Taskforce Windenergie op Zee 2010; Price Waterhouse Coopers 2011)

The development of offshore wind farm technology faces enormous challenges, implying huge costs, and thus initially calling for public subsidies. In the Netherlands, the SDE+ program[13] provides subsidies for sustainable energy projects, but in 2012, offshore wind projects were expelled from this program. It was argued that offshore wind was too expensive compared to other methods of energy production and that the offshore wind energy sector should first focus on technical innovation and cost reduction. Nowadays offshore wind energy still costs about 13.5-15 Euro cent/kWh[14], which can be twice as much as onshore wind energy. A newspaper article from December 2013 on wind energy even reported 17 Euro cent/kWh, being 10 cent above the costs for energy from coal.[15] In 2013, the SDE+ program has reopened again for offshore wind energy projects; this triggered critical evaluations of the Central Bureau of Statistics (CBS) and another Dutch research institute (Planbureau voor de Leefomgeving, PBL[16]), as they doubt the efficiency of wind energy in general (onshore and offshore). According to the CBS, the recent wind energy calculations are based on assumptions that are too favorable[17]. A study of the Dutch Ministry of Economic Affairs on the costs and benefits of energy and climate policy is critical of the costs and the effect on CO_2 reduction by renewable energy such as wind power (CPB 2013). Despite all calculations, it is clear that there are conflicting messages and large uncertainties about the cost-effectiveness of wind energy.

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[11] In 2001, a management agreement on wind energy development was signed in the Netherlands (in Dutch: "Bestuursovereenkomst Landelijke Ontwikkeling Windenergie (BLOW akkoord)"): www.infomil.nl/publish/pages/86443/blow_akkoord_2001.pdf; last accessed March 2014.

[12] Rijksoverheid 2008: Nationaal Plan van Aanpak Windenergie: http://www.rijksoverheid.nl/documenten-en-publicaties/brochures/2011/03/01/nationaal-plan-van-aanpak-windenergie.html, last accessed March 2014.

[13] SDE = Stimulering Duurzame Energie (in English: Stimulation of sustainable energy); successor to the MEP-programme (MEP = Milieukwaliteit Electriciteitsproductie).

[14] ECN calculations for the purpose of SDE+ 2014; http://www.energiebusiness.nl/2013/05/17/ecn-wind-op-land-veel-goedkoper-dan-zonne-energie/, last accessed March 2014.

15 *"Zeewind vergt nog heel wat"*, Volkskrant 21 December 2013.

[16] The PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the fields of environment, nature and spatial planning.

[17] CBS Statline: http://www.cbs.nl/enGB/menu/themas/industrieenergie/publicaties/artikelen/archief/2011/2011-3321-wm.htm?Languageswitch=on, last accessed March 2014.

The Dutch government is currently funding studies that investigate additional renewable energy possibilities and measures. One study examines whether offshore wind farms could be given permits closer to the coast, i.e. in the 12 NM zone (Quickscan Haalbaarheidsstudie 2013[18]; Leopold et al. 2013a, b). Up to now, territorial waters have been excluded from wind farm development because of too many objections (for example visual pollution) raised by coastal inhabitants, environmental NGOs, etc. The stimulatory effect of a policy that allows wind farms in the 12 NM zone, arises from the fact that near shore constructions are more economical due to shorter cable routes and lower transportation costs. On the other hand, there are many use functions near the coast, and there is a risk that wind farms negatively impact the natural environment.

The development of offshore wind farms in the Dutch part of the North Sea can best be described when looking at the different 'permit rounds' in which the wind farms were and are to be realized (see Box). The interactive map (Figure 3-1), managed by the government, presents an overview of the existing and future Dutch wind farms in various stages of planning and development[19].

18 www.rijksoverheid.nl/documenten-en-publicaties/rapporten/2013/06/27/quickscan- haalbaarheidsstudie-windparken-binnen-12-mijlszone.html; last accessed March 2014.

19 Since the status of marine areas designated for wind farm development can change rapidly, we also like to refer to http://www.4coffshore.com/windfarms/windfarms.aspx?windfarmid=NL18 for the most up-to-date maps on and descriptions of offshore wind energy development in the North Sea.

Development of offshore wind farms in the Dutch part of the North Sea

Permit round 1 (2002)
The first Dutch offshore wind farms in operation are the offshore (demonstrator) wind farm Egmond aan Zee (OWEZ[20]; 10-18 km from the coast; 36 x 3MW = 108MW) and the offshore Prinses Amalia Wind Park (PAWP[21]; approx. 14 km from the coast near IJmuiden, 60 x 2MW = 120 MW).

Permit round 2 (2009)
Twelve permits were issued to wind farm developers, but only two of them were granted a subsidy: Typhoon Capital (formerly BARD), developing the wind farm 'Gemini'[22] north of Schiermonnikoog, and Eneco, developing 'Luchterduinen'[23] (Q10) off IJmuiden.
The Gemini wind farm consists of three sites. Two of them, 'Buitengaats' (300 MW) and 'ZeeEnergie' (300 MW), were granted a SDE+ subsidy (2010). Both projects are currently in the process of being brought to financial close[24] (2014). The third Gemini project, 'Clearcamp' (275 MW), is still without subsidy, so its future is uncertain. If it will be built, it may serve as a future test site for new offshore wind technologies[25].

After granting Gemini en Luchterduinen in 2011, a moratorium was declared for round 2. The government wanted to mark time and reflect on a new issuance policy for offshore wind, before starting with Round 3.

Permit round 3 (starting in 2015)
In the third round, the construction of offshore wind farms will only be allowed in designated areas ("windgebieden"[26]). The Dutch Ministry of Infrastructure and Environment is looking for suitable locations for wind farms in the Dutch part of the North Sea. When choosing these locations, the government looks for the most profitable way to use financial resources and the available space near and far offshore. The search will focus on the area 'North of the Wadden Islands' and 'Coast of North and South Holland' (see "windgebieden" and Structuurvisie Windenergie op Zee[27]).

Permit round 3 (potential area)
Two other Round 3-development zones suitable for the construction of offshore wind farms have already been identified in the National Water Plan[28] (NWP): 'IJmuiden far' (approx. 80 km from the coast) and 'Borssele' planned on the shallow 'Vlakte van de Raan', at approximately 36 km from the coast of Zeeland, in the Southwest of the Netherlands. The NWP focuses in particular on innovations that lead to cost reductions, and on an eco-design approach for offshore activities. For the Gemini site, studies are investigating the safety and stability of monopile and jacket constructions[29], and the environmental impact and application of an ecosystem approach.

[last updated: August 2014]

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20 www.noordzeewind.nl
21 www.prinsesamaliawindpark.eu/nl/index.asp
22 www.typhoonoffshore.eu/projects/gemini
23 http://projecten.eneco.nl/eneco-luchterduinen/Pages/default.aspx
24 http://cdn.vanoord.com
25 http://www.typhoonoffshore.eu/projects/gemini/
26 https://data.overheid.nl/data/search?f[0]=tags%3Awindgebied
27 https://zoek.officielebekendmakingen.nl/kst-33561-1.html
28 In Dutch: NWP = Nationaal Waterplan. http://www.rijksoverheid.nl/onderwerpen/water-en-veiligheid/documenten-en-publicaties/rapporten/2009/12/01/nationaal-waterplan-2002015%5B2%5D.html last accessed March 2014
29 See http://www.4coffshore.com/windfarms/support-structures-for-offshore-wind-turbines- aid268.html for more information on the different types of wind farm foundations, e.g. jacket or lattice structures: http://www.4coffshore.com/windfarms/jacket-or-lattice-structures-aid271.html

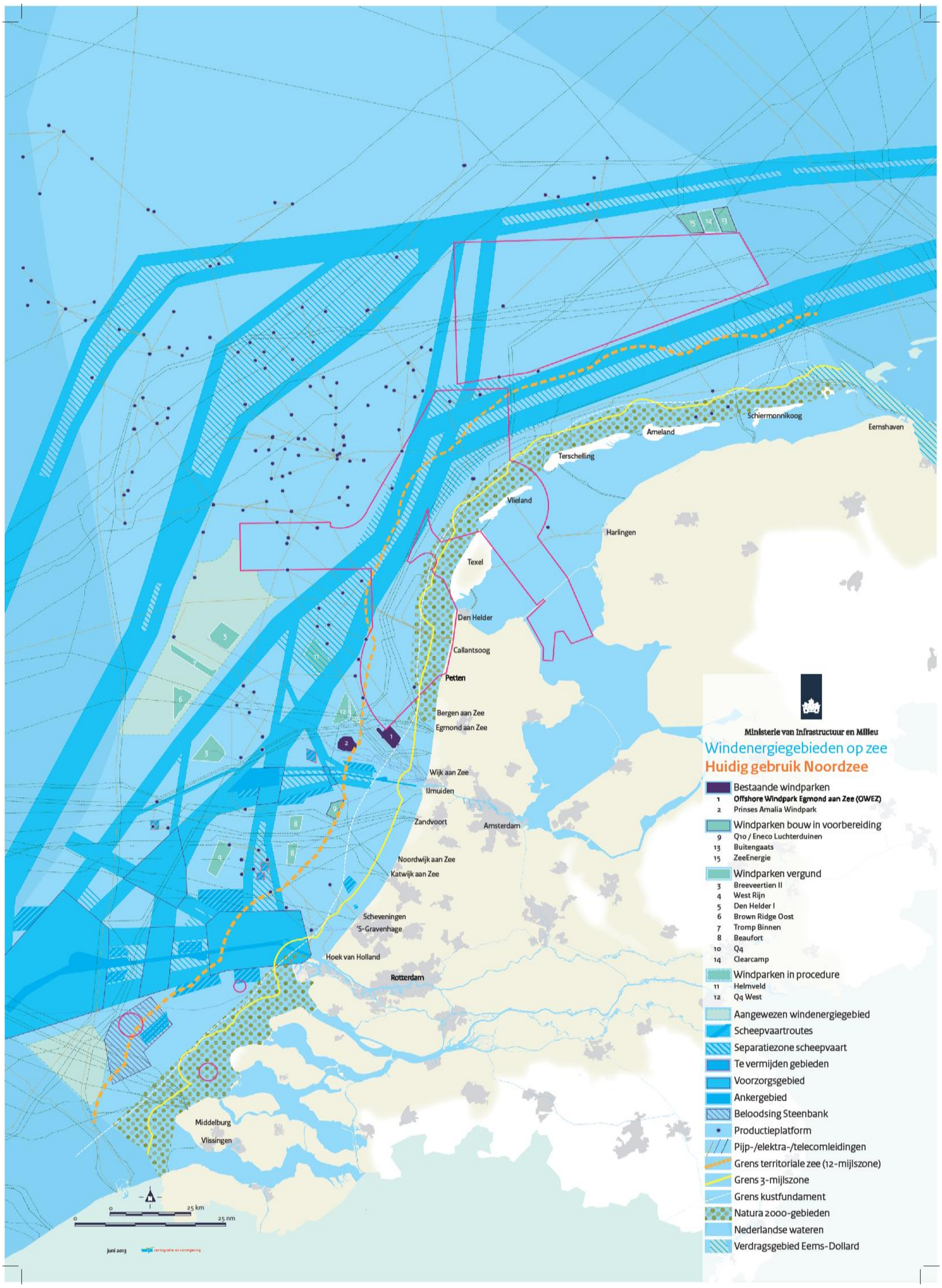

Figure 3-1. Interactive map showing offshore wind locations and other use functions in the Dutch part of the North Sea. Legend: dark blue = existing wind farms; different shades of blue-gray, numbered = future wind farm locations (www.rijksoverheid.nl; last accessed March 2014).

3.2 Government and sectoral initiatives in the Netherlands

3.2.1 *Green deal*

In 2011, the government and the Netherland Wind Energy Association (NWEA) signed a Green Deal. They strive for a 40% cost reduction of offshore wind energy in 2020 (meant are the total costs per MWh). The Green Deal describes the agreed input and actions to be taken by the government and NWEA to meet this goal. Proposed actions are: improving the licensing process, stimulation of innovation, promotion of offshore wind energy, drawing up of legislation to create electrical grids and the possible construction of an experimental and demonstrator wind farm[30]. Up to now, the turnaround time from first initiative to an operational wind farm is about ten years. The new policy intends to shorten the turnaround time. The government is ready to fund innovative research on cost reduction but will only grant SDE+ subsidies on the condition that the agreed cost reduction of 40% is achieved.[31]

3.2.2 *Far Large Offshore Wind (FLOW) program*

Due to limitations such as shipping routes, oil and gas platforms, visual impact and ecological effects, only 2,000-3,000 MW of the 6,000 MW, projected to be achieved in Dutch waters by 2020, can be installed within 50-60 km from the coast. The remaining capacity will have to be installed far offshore, in water depths of more than 30 m. These are challenging conditions. Worldwide, there is little knowledge and experience on how to build and operate a wind farm far offshore and at great depths. A fully commissioned initiative to examine the feasibility and benefits of a deepwater wind farm is the demonstrator project 'Beatrice'[32] near the Beatrice oil field 22 km offshore in the Moray Firth, which is a Special Area of Conservation. By 2017, two 5 MW turbines with a total turbine height of 170 m will be operational. The turbines are fixed to the ground at a notable depth of 45 m.

In a similar way, in 2009, nine Dutch companies and knowledge institutes took up the challenge and established the FLOW group (Far Large Offshore Wind[33]). The main objective of FLOW is to speed up the deployment of (far) offshore wind energy production. Future wind farms will be built up to 75 km offshore, mostly in more than 30 m water depth. Currently, most turbines are founded on monopiles which are less/not suitable for locations farther offshore. Therefore, in the future, more resistant foundation types, such as gravity based or floating, will have to be built there.

To achieve these challenges, a significant reduction of costs and risks of far-offshore wind energy is necessary; FLOW aims at a reduction of more than 20% to improve commercial viability of offshore wind energy. Cost and risk reduction requires the development of specific far-offshore competences.

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30 The wind energy sector has already drawn up a project proposal called 'Leeghwater-project', which is partially a demonstrator wind farm for those innovations that can already bring down the costs, and partially testing ground for the effective market launch of promising innovations which are still under development.

31 Letter of Minister Kamps to the parliament: *'Energieakkoord voor Duurzame Groei'; 6 september 2013; overheidsidentificatienr. 00000001003214369000; en 'Beantwoording vragen over het bericht dat overheidssubsidie voor duurzame energie moet worden beperkt tot bedrijven die nieuwe productiemethodes introduceren'; 9 december 2013; overheidsidentificatienr. 00000001003214369000*

32 http://www.beatricewind.co.uk/home/default.asp; last accessed March 2014

33 http://flow-offshore.nl; last accessed March 2014

The FLOW group has drawn up a Research and Development (R&D) plan that promotes the development of new technologies onshore and near-shore as well as a far-offshore demonstrator wind farm. Meanwhile, the ideas of the FLOW program have been incorporated into the project document of the public/private-partnership 'TKI Wind at sea'[34], which has been submitted for government subsidy.

3.2.3 *Dutch national energy agreement*

In July 2013, the responsible Dutch ministers and several union representatives, employers and environmental groups have reached an agreement on clean technology, saving energy and climate policy. They expect the agreement to lead to billions of euros of investment and a fully sustainable Dutch energy market by 2050. It involves the setting up of a special fund to pay for energy efficiency measures and a major focus on offshore wind energy production. However, the agreement implies a 3-year delay of the deadline to achieve at least 16% of energy from sustainable sources (i.e., from 2020 to 2023). Despite the clear vote for renewable energy sources, (offshore) wind energy will have to compete with other ways of generating renewable energy. Therefore the toughest challenge for the wind energy sector remains cost reduction.

3.3 Operation and maintenance of offshore wind farms

In this paragraph we elaborate on some technological and logistical problems the Dutch offshore wind industry will have to solve - alone or jointly with other (potential) users – in order to achieve substantial cost reduction. Large offshore wind farms farther off the cost pose high expectations because of higher average wind speeds and hence greater wind energy yield (in terms of megawatts per capital). These conditions entail additional challenges in logistics, though. It is precisely these logistical problems where most likely synergy benefits can be achieved.

3.3.1 *Accessibility of offshore wind farms*

The offshore marine environment is characterized by harsh conditions. Project developers of offshore wind farms have to cope with many logistical and safety issues that developers of wind energy projects on land do not have to contend with, or at least not to the same extent. Operation and maintenance costs make up 25-30% of the total costs of an offshore wind farm (Miedema 2012, cf. chapter 7.1). This is almost as much as the cost of the wind turbines only, or about as much as the costs of construction and installation. Offshore wind turbines currently require about five site visits per year[35]. With technological progress, this can potentially be reduced to three visits per year. Nonetheless, a future offshore wind farm comprising 200 turbines of 5 MW each will need some 3,000 offshore visits per year. Operation and maintenance (O&M) visits are carried out by boat or helicopter, which means that the personnel performing the repair, has to climb onto the turbines. Especially in rough conditions – helicopters for example are used at wind speeds of up to 20 m/s – this is a risky undertaking. Systems need to be developed to ensure the safety of staff and to expand workability. In the future, certain maintenance tasks may also be carried out remotely (see DOWES, section 3.3.4).

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[34] Innovatiecontract Wind op Zee, 2012: http://www.agentschapnl.nl/programmas-regelingen/tender-tki-wind-op-zee, last accessed March 2014.

[35] http://www.noordzeewind.nl/elektriciteit/onderhoud/; last accessed March 2014

Until now, O&M visits are carried out when the significant wave heights (SWH) are less than or equal to 1.5 m. According to Stavenuiter (2009) each support vessel has a certain maximum allowable significant wave height for several operations. Therefore, the availability of a vessel is correlated with the occurrence of certain significant wave heights. Figure 3-2 shows the cumulative frequency distribution of significant wave height measured at two Dutch offshore locations that are both close to two Dutch offshore wind farm locations (OWEZ and PAWP). Despite a distance of 40 NM between each other, the two measurement locations show almost identical measurement results of significant wave height. The cumulative occurrence of significant wave heights up to 1.5 m is 68%. The step from 1.5 to 2.0 m increases the occurrence by 15%, up to a cumulative occurrence of 83% (Stavenuiter 2009).

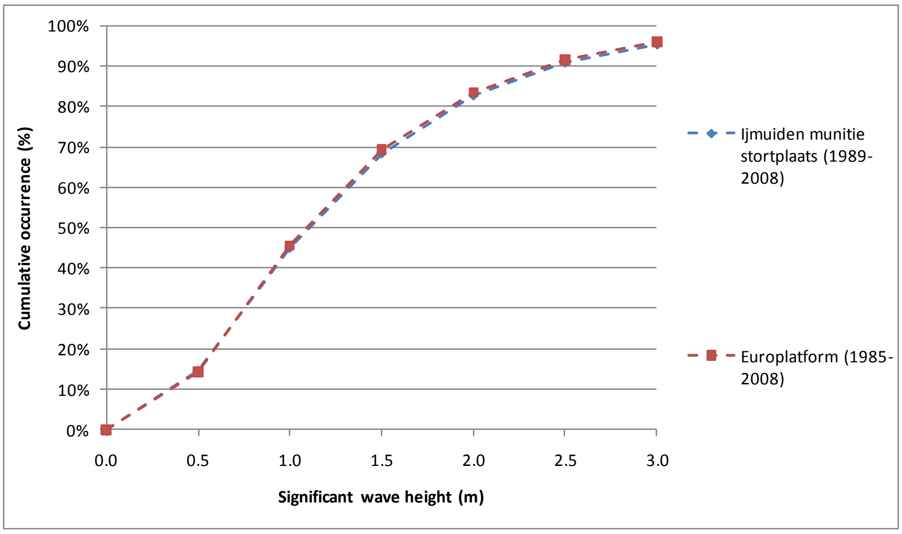

Figure 3-2. Measured wave data near the Dutch (planned) offshore wind farms (Rijkswaterstaat, 2009).

Figure 3-3 shows the number of days per month in 2009 that the two offshore locations, both very close to the Dutch offshore wind farms OWEZ and PAWP, were accessible or not due to weather downtime.

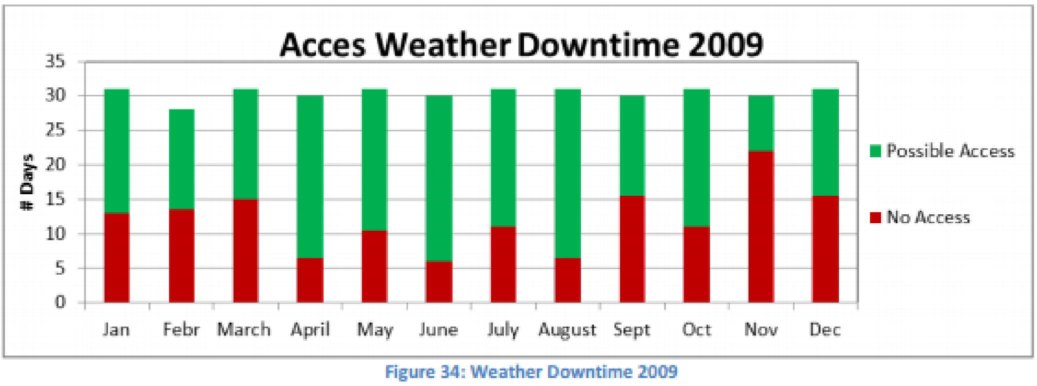

Figure 3-3. Number of days of accessibility and weather downtime of two Dutch offshore locations per month in 2009 (Stavenuiter 2009)

The chance for larger wave heights will require new systems for safe O&M personnel transfer. If transfers are to be restricted to wave heights of 1.5 m, this will limit offshore work to about 200 days a year (Noordzeewind 2010, Miedema 2012). Noordzeewind (2010) estimated a total of approximately 218 possible access days in 2009, and the remaining time of the year was considered non-productive time ('weather downtime') in 2009. Increasing the workable significant wave height from 1.5 to 2 m, could increase the accessibility of wind farms by 15% (Stavenuiter 2009). An increase of the safe working wave height to 3 m and above could increase the number of days available for transfers up to 310 days per year. Hence, increasing overall accessibility can lead to cost reduction of wind energy production. To achieve this, new ships with motion stabilizers are required to guaranty safe transfers of personnel and material. Current solutions are offshore access systems such as 'Ampelmann', a motion compensated access system, which enable safe operations, when applicable related to wave height and ship capability. But even if these new systems for operating in far-offshore conditions are developed, a constant shuttling of workboats to and from the coast is impractical and costly. Therefore, developers and offshore service providers are looking for new methods, one of which is the 'mother ship' approach. A single large vessel would then service one or more offshore wind farms staying in the neighbourhood of these farms for long periods of time and deploying multiple smaller craft for daily servicing.

3.3.2 *Infrastructure for cabling and cable repair*

Up to now, there are neither standardized practices nor procedures to procure cables as well as sharing cabling equipment, ships, and all other elements necessary for a safe and speedy repair. If developers were more willing to collaborate with each other, to share facilities, vessels, and their particular knowledge, this could lead to far more efficient procedures through economies of knowledge. So far, the desire to keep cable choices and technologies confidential, prevailed over the opportunity to develop a more efficient infrastructure for joint installation and maintenance or repair of cables. But these facilities will be necessary as bases for long-range offshore vessels and to service the offshore wind farms closer to the shore. Especially with future FLOW farms, it could be a unique asset to have manufacture and dedicated repair and storage facilities for spare parts closer to the FLOW sites. Despite the benefits to be expected, it is far from certain whether developers and offshore operators are willing to pay for collective facilities that they may not need to use.

3.3.3 *Trained staff*

To keep up with developments, companies will need to permanently invest in capacity building and training to ensure that sufficiently skilled O&M personnel are available. This holds even more for FLOW farms. A rough calculation suggests that one O&M job will be created for every two turbines installed. With 200 turbines of 5 MW each, this equates to a need of about 100 FTE of trained staff. Even if this calculation is conservative, and the number of staff can be reduced through greater efficiency, there will still be a huge need for skilled personnel. To meet that demand, operators and developers will have to set up offshore training centers and training programs. It would not be wise, if they do this just for their own purposes. As with the cabling sector, it is obvious that collaboration and joint financing have great advantages.

3.3.4 *Dutch Offshore Wind Energy Services (DOWES)*

There are three lines of intervention in a wind farm: first, scanner control with remote management; second, helicopter intervention; and third, heavy lift operations. Reactive maintenance, e.g. arranging a site visit if a turbine stops working, is always expensive and can sometimes be impossible; for instance, in bad weather conditions or if boats and crew are unavailable. This dependence on weather, crew, and boat availability increases the risk of an expensive wind generation asset being unable to produce electricity for weeks or even months. Predictive maintenance, i.e. remote surveillance, can help in constant monitoring and real time information about what is happening at a site. Key to such planned predictive maintenance is the increased deployment of sensors in offshore wind turbines. Modern offshore wind turbines, particularly those that are custom built for offshore, will contain a huge number (>1000) of sensors in key components. The ongoing Dutch Offshore Wind Energy Services (DOWES[36]) project focuses on developing an innovative ICT system to manage offshore wind parks in the Den Helder region (2008-2014). The DOWES management plan aims to lead to high wind farm availability at minimum cost. The ICT system will be capable of reading the sensors on the wind turbines using remote control, making use of the most up-to-date science.

It is possible to manage and maintain offshore wind parks in various ways. DOWES aims to safeguard offshore wind parks from a distance/at land. Constant monitoring of the state of the wind turbines can facilitate timely information of the right people. This can aid in making cost-effective choices and carrying out maintenance optimally. In the long run such systems are expected to increase the manageability of offshore wind parks and reduce maintenance costs.

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Note: see ANNEX A for more electronic references.

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36 DOWES = Dutch offshore wind energy services: www.dowes.nl; last accessed March 2014.

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4 Offshore aquaculture

4.1 Potential for offshore aquaculture

Aquaculture within offshore wind farms has been identified as one of the many possibilities of smart use of marine space, leading to opportunities for innovative entrepreneurship. Although the combination of offshore wind energy and offshore aquaculture is increasingly seen as worthy to be explored (chapter 2), the aquaculture sector – in order to be recognized as a potential partner – still has to demonstrate that aquaculture in Dutch offshore areas is feasible in the first place. This is not an easy task since offshore areas for aquaculture are exposed to a wide range of oceanographic conditions, such as high currents and high wave action (Ryan 2004). Aquaculture in offshore areas therefore faces major challenges compared to coastal (and land based) aquaculture. Ships are required to transport all inputs to and from the farm, resulting in higher operational costs than for coastal aquaculture sites. Besides these costs there is an increased risk of natural influences, such as rough seas and storms. Nevertheless, there are positive assets to offshore aquaculture as well. The main reasons to develop offshore aquaculture are the often favorable conditions for growth due to water depth and hydrodynamics (e.g. quick nutrient input and waste dispersal), and less potential for disease spread, pollution and agricultural interactions.

Offshore areas potentially pose less conflict with co-users than onshore. With increasing marine activities and uses, however, this situation is currently changing. Open water aquaculture interacts with the surrounding ecosystem and the aim for offshore aquaculture is therefore not only to develop technically and economically feasible systems but also to develop ecologically sustainable production systems.

Aquaculture is a broad term and includes the culture of fin fish, crustaceans, bivalves, and aquatic plants, as well as other emerging culture species. Generally we distinguish between culture types based on the feed requirements of the species. Fish culture typically relies on external feed supply (fed species) while bivalves and seaweeds (extractive species) rely on naturally available resources. At this moment, mainly because of technical reasons, offshore aquaculture in the North Sea is absent.

In the next section we outline a selection of species with potential for offshore production in the Dutch part of the North Sea.

4.2 Species selection for offshore aquaculture in the Dutch part of the North Sea[37]

4.2.1 *Fish culture*

Offshore fish culture started approximately 40 years ago in Asia, and soon after that a number of marine species have been taken into production in fish cages. Many of these species are raised in specially designed cages, of which the configuration depends on the fish species and the geographical location. In 2012, offshore fish culture was commercially performed in Australia, Canada, Chile, China, Croatia, Greece, Ireland, Italy, Japan, Malta, New Zealand, Norway, Russia, the Shetland Islands, Spain and Turkey. As to date, no fish culture activities take place in the open North Sea. The conditions in the North Sea differ from the conditions in locations where typically most of the European aquaculture production is realized nowadays (e.g. Norway, Mediterranean Sea).

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[37] This section is mainly based on Burg et al. (2013).

Therefore it is not possible to directly apply common culture techniques to the North Sea situation. A study by Reijs et al. (2008) concluded that commercial fish culture appears to be challenging in the Dutch North Sea as there are technical and biological constrains for most areas. The study took into account the economic potential of finfish culture based on the biological growth performance. For commercially interesting species temperature was found either too high in summer (e.g. for species like cod) or too low in winter (e.g. for species like Bluefin Tuna), and the relative shallowness of the North Sea does not allow culture cages to be submerged (minimum depth 40m) at most locations. Hence, just a few sites are potentially suitable for fish culture, with a high estimated risk in terms of economic feasibility[38]. At this moment the economic and technological advancements are not considered far enough to overcome the biological boundaries for growth and production.

4.2.2 *Bivalve culture*[39]

Four shellfish species have been identified as 'promising for culture in the Dutch North Sea': the blue mussel (*Mytilus edulis*), flat oyster (*Ostrea edulis*), Pacific oyster (*Crassostrea gigas*), and scallop (*Pecten maximus*) (Reijs et al. 2008). In the current study we focus on mussel culture because this is an important and well established industry in the Netherlands. The Dutch mussel culture sector has an average yearly production of 50,000-60,000 tons[40], but the total production ambition is 100,000 tons; the difference is currently partially supplied by import of mussels from other EU member states (BluePort Oosterschelde innovation program 2012). There is commercial interest to expand mussel culture from the Wadden Sea and Delta towards offshore areas, as carrying capacity and environmental pressure hinder further direct production growth in the former mentioned areas (Sas 2011). Theoretically it is possible to culture mussels at any location in the Dutch North Sea. There are pilot scale examples in other countries providing some data and reference material for mussels (UK, Canada, New Zealand), while information on e.g. suspended offshore oyster and scallop culture are currently not available. Note that the research on offshore mussel culture is dominated by reviews and desk studies. Only few resources have been invested in field-scale trials to identify the best offshore production concepts, thereby improving the quality of the knowledge to the current topic. Commercially viable culture systems for offshore production of mussels are in operation for green lipped mussels in New Zealand (Cheney et al. 2012). There are initiatives for pilot scale offshore mussel culture in Belgium, Germany, UK, Ireland, Denmark, France, Italy (for details see Kamermans et al. 2011), but technical feasibility at commercial scale still needs to be proven.

4.2.3 *Seaweed culture*

Reith et al. (2005) concluded that *Ulva* sp., *Laminaria* sp. and *Palmaria* sp. have highest potential for successful culture in the North Sea. This was confirmed by Burg et al. (2013) who performed a feasibility study to further investigate the potential for offshore seaweed culture in the North Sea.

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38 The German Thünen Institue currently carries out a study to develop criteria for the site selection for offshore aquaculture systems in combination with offshore windfarms: http://www.ti.bund.de/index.php?id=4833&detail_id=238496&L=2&llang=en&stichw_suche=selection&zeilenzahl_zaehler=4

39 This section is based on/partially adopted from Burg et al. (2013).

40 Metric tons; not to be confused with "mosseltonnen" (Dutch for mussel tons) which is 100 kg.

Their study concluded that there is a significant potential for seaweed culture, however there are still many unknowns, for example regarding technical solutions to large-scale commercial production, variable chemical composition of seaweed, and therefore uncertainties concerning ways of processing. These uncertainties and the large spread in production and processing estimates make it difficult to project the economic feasibility of seaweed culture at this moment. A preliminary simulation exercise, comparing scenarios of offshore mussel and offshore seaweed culture, is depicted in Annex C. This exercise triggered us to focus our Blauwdruk business scenario on mussel aquaculture only. The progressing research on seaweed culture should clarify the exact potential for future commercial sea weed farming in the North Sea.

4.2.4 *Bioremediation and integrated culture*[41]

Marine protein production in open water systems per definition interacts with the surrounding aquatic ecosystem. Whether and to what degree this affects ecological sustainability depends on the type of culture and the extent of integration between different culture types and other activities. Extractive species such as seaweeds and bivalves remove (in)organic nutrients from the water column; in coastal eutrophic waters (rather coastal) they can therefore be applied as bioremediation measure. Lindal et al. (2005) suggested nutrients can be removed from the water column by harvest of bivalves and they proposed that bivalves therefore can be incorporated into a nutrient trading system as an alternative to nutrient (nitrogen) reduction for improving coastal water quality. Similar concepts apply to seaweeds.

A special approach that exploits the extractive properties of bivalves and seaweed is Integrated Multi Trophic Aquaculture (IMTA). In IMTA systems the extractive species are introduced to remove the excess nutrients discharged from fish cage aquaculture (Figure 4-1) in order to create a more sustainable production system and simultaneously increase the economic profitability. In open seas, IMTA fits with the concept of 'ecosystem based management' as each activity is placed in a wider ecosystem context and managed so that it contributes to the sustainable development (Ryther et al. 1975). However, as concluded above, commercial fish culture in the North Sea seems unviable at this moment, which takes away the principle basis for the IMTA approach in this area (that is, having a fed component). Figure 4-1 also shows that limited (bio-chemical) interaction between bivalves (shellfish) and seaweeds exists, as they rely on different types of nutrients (organic versus inorganic, respectively) as food source. Integrated production systems where two or more species are cultured at the same location without any apparent positive or negative biological influence are often referred to as co-culture. Advantages for co-culture are related to finding synergies in work-activities and expenses for the co-cultured cultivation which may lead to increased economic benefits compared to single-species cultivation sites. Challenges associated with IMTA and/or co-culture relate to 1) marketing and processing of two or more completely different types of products, 2) variable nutrient removal by the extractive species, 3) mismatch in seasonality and production rates of different trophic levels, 4) logistical problems associated with shared space and equipment.

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[41] This section is based on Burg et al. (2013).

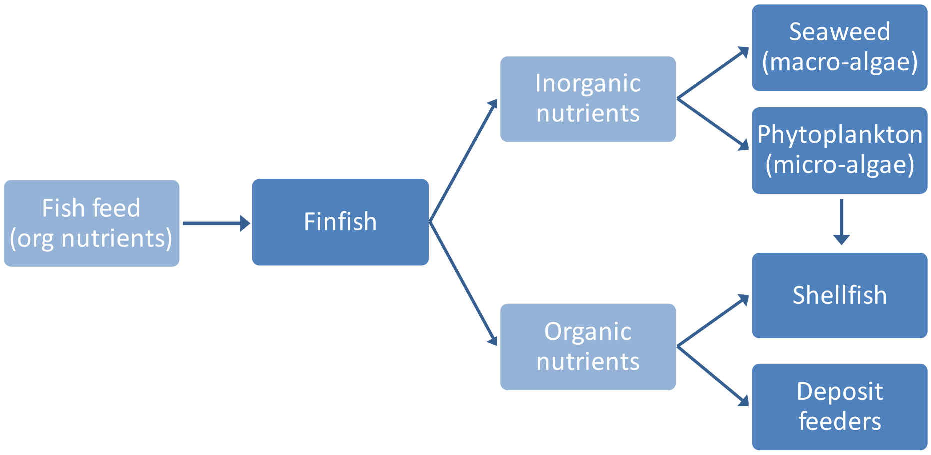

Figure 4-1. Overview of nutrient fluxes in Integrated Multi Trophic Aquaculture (IMTA) system for open water fish cage aquaculture (adopted from Burg et al. 2013).

4.2.5 *Prospective*

In the context of our study, the main opportunities for offshore aquaculture in the Dutch North Sea are related to the production of mussels. Diversification of species, however, should eventually be pursued in order to optimize economic output. Development of technical solutions for offshore culture of mussels, other bivalves, seaweeds and even fish culture are a key issue for implementation of aquaculture in offshore areas. Moreover, further roll-out of offshore aquaculture should also focus on sustainability aspects of the production.

4.3 Mussel farming and mussel seed collection

Considering the high potential for offshore mussel farming we now further elaborate on site selection, culture techniques, production rates, physical and ecological boundaries, revenues, problems and challenges specifically related to offshore farming. Statistics presented in the current section form the basis for the scenario analyses presented in section 7. Tables presenting background data for the AMC model are included in Annex B.

4.3.1 *Site suitability*

Experience with offshore shellfish culture in field-scale trials is too limited to identify the best offshore production concepts. Specific requirements for mussel culture in offshore areas can therefore not yet be defined (Kamermans et al. 2011). However, based on some general assumptions about current speeds (max-min) and the fact that water depth should be at least 10 m it can be concluded that the entire Dutch North Sea, except for a few areas (the most Southern part of the Dutch North Sea was not studied) is potentially suitable for offshore bivalve culture. However, productivity of the systems highly depend on local conditions. Natural occurrence of mussels in relation to food (Chlorophyll *a*) conditions were studied for the North Sea (Steenbergen et al. 2005), resulting in a map indicating areas where mussel culture has the highest potential (in Dutch: *Mosselkansenkaart;* Figure 4-2).

4.3.2 *Seed mussel collectors (SMCs)*

Traditionally the Dutch shellfish sector has been based on culture and fishery on bottom plots. However, since the last decade suspended culture systems (Seed Mussel Collectors – SMCs) have been taken into use to relieve fishing pressure on natural seed beds. SMCs are mainly floating buoys and tubes on which a collector substrate is deployed. This substrate may vary from a net (mesh size 10-15 cm) to different types of collector ropes, e.g. (continuous) long lines. All systems are anchored using offshore anchors or, more recently, using poles. The systems are deployed in the water from February till May. The SMCs are inspected throughout the following months for growth and predation. SMCs applying nets as collector substrate may be harvested (thinned out) once or twice during the process. All SMCs are harvested (end product) between July and September/October; subsequently, the mussel seed is (most often) transferred to the bottom plots in the Wadden Sea or Eastern Scheldt. In 2014, the first trials of SMC are expected to be deployed in the North Sea "Voordelta"(cf. Figure 4-2).

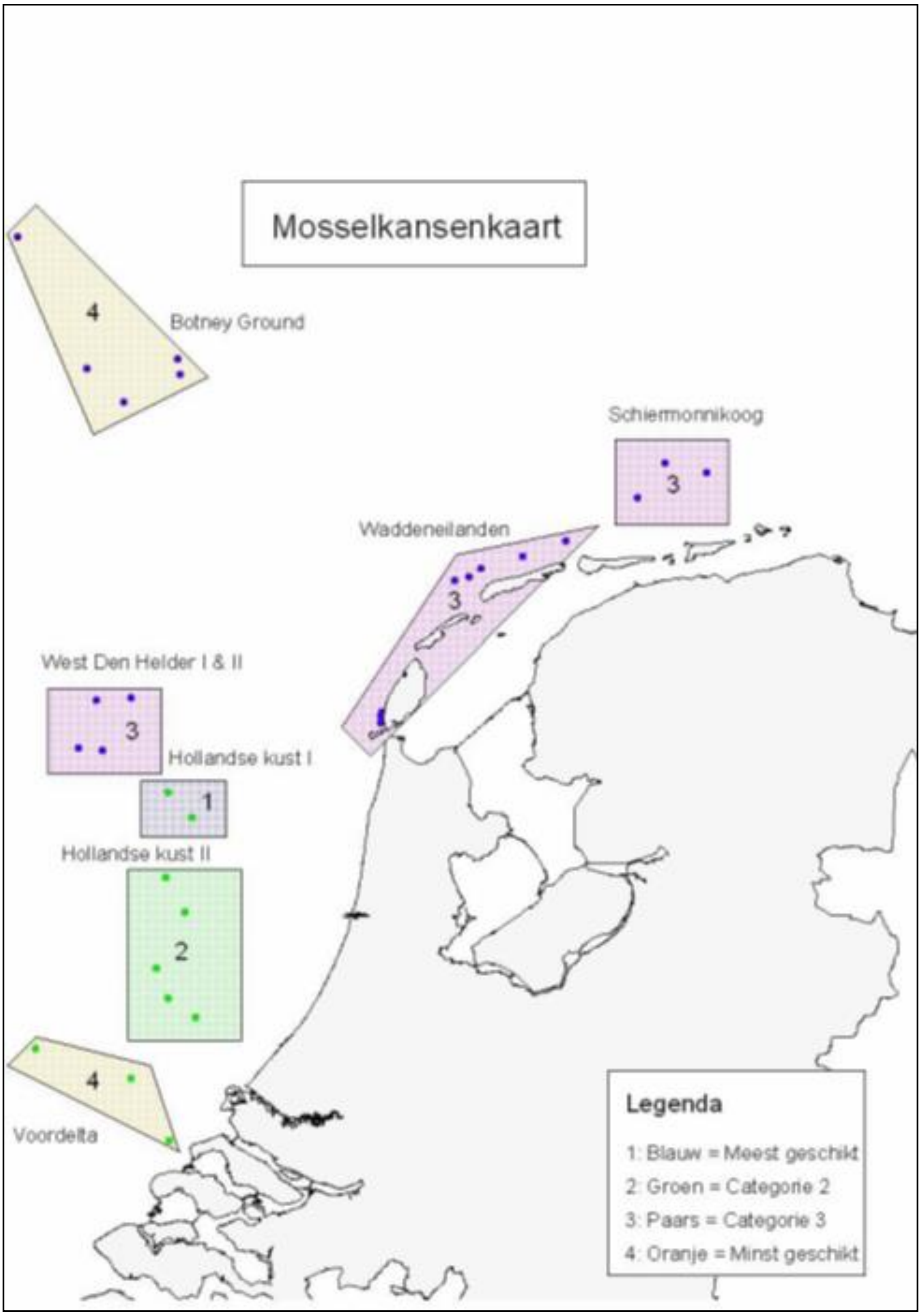

Figure 4-2. Analysis of the most suitable mussel production areas (Mosselkansenkaart; source: Steenbergen et al. 2005). The "mosselkansenkaart" gives a first impression on the potential suitable locations for offshore mussel production. Legend: the classification runs form category 1: blue (= most suitable), via category 2: green, and category 3: pink to category 4: yellow (= least suitable).

4.3.3 *System requirements/prerequisites*

Selection of culture techniques and system types depends largely on the desires of the entrepreneur and opportunities for development. The most applied technique for offshore mussel culture is currently the submerged long line system. Submerged long lines may be used for mussel seed production, grow-out products (1-4.5 cm) or consumption size (> 4.5 cm) products.

Figure 4-3 presents the growth/production cycle for mussel culture. Seed production can be realized once a year starting from April/May until August-October, at densities of approximately 2.8 kg m^{-1} (Stralen 2013). This is followed by harvest and/or socking to other long lines for further production (grow out). During this period the mussels should be resocked at least once more to allow the mussels to grow further. This allows harvesting of grow-out products (for example for other locations or as stocking material for bottom cultures), after 12 months. If no resocking of the long lines is applied, the mussels will grow too densely, resulting in lower production, due to food and space competition. Maximum densities of 3-10 kg m^{-1} long line may be achieved (Stralen2013, Buck 2011; W. Bakker, pers. comm.). In such a production cycle 1 kg of mussel seed can be grown to 4-8 kg of consumption mussels during a period of 1½-2 years, dependent on local conditions (food availability and stress; W. Bakker, pers. comm.). Data on the characteristics of a fictional mussel production farm are shown in Annex B-1. Note that these data derive from estuarine areas.

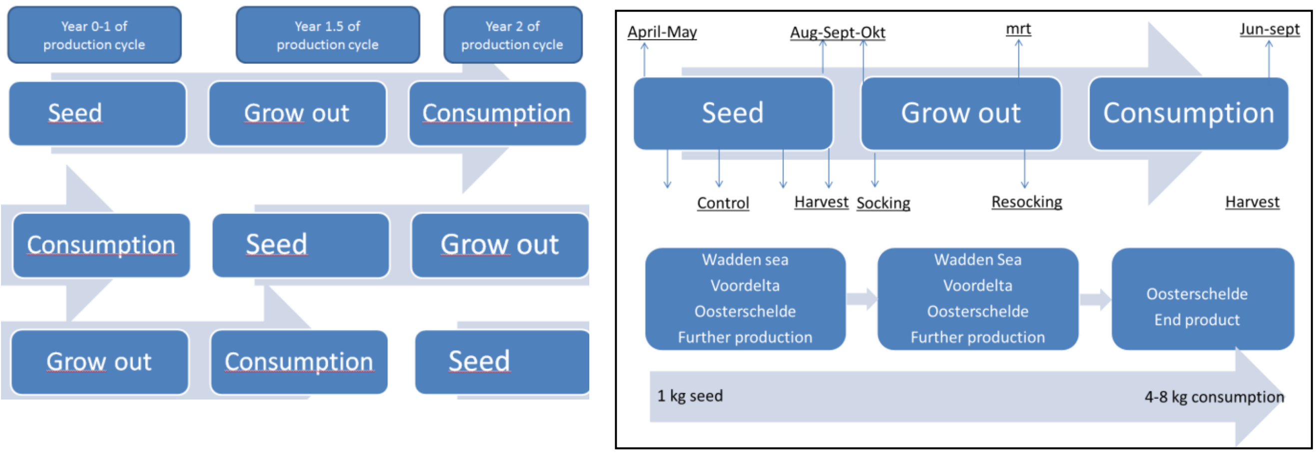

Figure 4-3. Left panel: Schematic presentation of mussel growth production cycle. Right panel: Overview and timing of mussel production activities in the Dutch Delta and Wadden Sea. The areas mentioned indicate the possible routings for the end product of this phase.

Mussel harvest from long lines takes place by mechanical removal using water pressure (spray off) or brushes. At this moment the long lines need to be taken on board of the vessel for harvesting. Socking of mussels is done by specialized equipment, which facilitates the introduction of a standard mussel rope with a mussel sock in which the mussels are stocked. The mussels attach to the culture rope using their byssus threats.

In the process of producing consumption mussels (from grow out to harvest), it is important that culture structures, such as long lines, are not affected by settlement of new mussel seed.

Mussel seed will suffocate the already available mussels in their competition for space. Production of consumption mussels is therefore preferred in areas with low or absent spat fall. It is thus advised to perform a feasibility pilot study before implementing a new culture site in offshore areas. A pilot study should provide insight in site specific parameters on which production and commercial viability can be assessed. This is essential to prove the feasibility of mussel culture in the North Sea.

The Dutch shellfish industry has gained experience with suspended cultures. Van Stralen (2012, 2013) demonstrated that a mussel production of 72 tons ha^{-1} via seed mussel capture devices can be realized in the Wadden Sea applying long lines (Annex B-2), using 95 ha and 427 production systems. The total production in 2012, including all production systems (not only long lines), was 11.5 Mtons (585 net systems, and 646 rope systems on 267 ha; Van Stralen 2013).

Based on available literature the following set of requirements for successful offshore mussel farming are identified:

- Fully resistant construction to withstand weather, use and cross over (Buck 2007b)
- Fully balanced floatation (Daley 2010)
- Sufficient spat fall (but balanced, to avoid suffocation) (Van Nieuwenhove 2008)
- Sufficient growth (Langan & Horton 2003)
- No excessive fouling of other organisms (Cheney et al. 2010)
- No excessive predation (Mille & Blachier 2009)
- No pollution: neither contaminants nor parasites (Buck 2007a, Van Nieuwenhove 2008)
- Avoidance of loss of mussels that fall off the ropes (Mille & Blachier 2009)
- Reliable and robust harvest method (Cheney et al. 2010)
- Clear agreements and clear marking to allow sailing traffic (Buck 2007b, Van Nieuwenhove 2008)
- Infrastructure (logistics) (Reijs et al. 2008)
- Capital of stakeholders/participants (Reijs et al. 2008)

4.3.4 *Physical potential*

A review of global offshore cultivation experiences, published by Kamermans et al. (2011), indicated that, in theory, offshore mussel production in the Dutch part of the North Sea is feasible. Depth, wave height, current speed and wind direction define which type of system is best to use. The conditions in the Dutch part of the North Sea are extreme for aquaculture practices, both in terms of maximum wave height and current speed. However, even for such extreme conditions it has been proven that submerged long-line systems can sucessfully be implemented (Langan & Horton, 2003). Submerged systems are deployed at 10 m depth to avoid wave action. The systems consist of a horizontal main long-line, which droppers (mussel cultivation rope) are attached to. Droppers generally have a length of up to 10 m. Thismeans that mussels are cultured at a depth between 10-20 m below the surface. Hence, depth at the forseen culture site should be more than 20 m, in order to leave sufficient space underneath the droppers and to compensate for tidal variation.

Sufficient flow rates are necessary to avoid sedimentation of (pseudo)faces and to guarantee the supply of nutrients/food to the bivalves. Sedimentation effects should be predicted prior to implementation of a new culture site. This can be done by predictive modelling, for example, based on current patterns and bathymetry of the area (e.g. Weise et al. 2009, Keeley et al. 2013). However, too high current speeds also set limitations to system design.

Table 4-1. Overview of physical conditions in the Dutch North Sea in comparison to the conditions in other offshore areas (derived from Kamermans (2011), based on Reeds Nautical Almanac 2009).

Area	**Depth (m)**	**Maximum wave height (m)**	**Maximum current speed during spring tide (m s^{-1})**
Dutch North Sea	11-40	8	2
Belgian North Sea	7-11	5	2
German Bight	12-15	6.5	1.5
UK	30	6	0.5
France (Languedoc-Roussillon)	20-30	10	1.5
France (Pertuis-Breton)	8-18		
Italy	10-30	4	
New-Zealand	30-50	3-4	0.3-0.5
VS (New Hampshire)	52	9	0.9
VS (Californie)	27	6	
Canada (Baie de Cascapédia)	18	1.5	0.3

4.3.5 *Ecological potential and challenges*

There are still many unknowns concerning the ecological performance of offshore mussel culture. Spat fall is important for obtaining resource material, however, during the grow-out phase of consumption mussels one would like to avoid spat fall. A study on the abundance and growth of mussels on buoys revealed that the highest abundance of mussels was found at the Dutch coast. Other locations in which mussel seed was found are west of Den Helder and Schiermonnikoog. Spat fall seems less for the areas in Botney Ground, although at this location mussels were found at 20 m depth (and thus suitable for submerged systems; Steenbergen et al. 2005; cf. Figure 4-2). Good mussel growth depends on the supply of sufficient food, particularly the supply of phytoplankton. Phytoplankton availability in the North Sea is largely unknown as national monitoring programs only provide information on phytoplankton concentrations in the surface water, while information on spatio-temporal dynamics in phytoplankton concentrations at 10-20 m depth, where the mussels would be cultured, is largely unknown. Harmful algal blooms (HAB's) are not expected to become problematic; according to monitoring observations of algae in the surface waters at several locations in the North Sea, thresholds have never been exceeded so far (Koeman et al. 2006). The absence of toxic algae is of particular importance during harvesting of mussels for human consumption. Despite absence in current monitoring programs, a food safety program should be set in place once commercial production of bivalves starts in the North sea (like in other bivalve production areas such as the Eastern Scheldt and Wadden Sea). Toxic compounds in the water, monitored by national monitoring programs, have been below the threshold for different inorganic and organic micro-pollutants (http://live.waterbase.nl). Negative effects of predation, diseases and parasites on mussel growth and survival in the North Sea are largely unknown.

4.3.6 *Economic feasibility*

Buck et al. (2010) provided an economic feasibility study for offshore mussel culture within areas used by wind-farms in the Germany Bight (theoretical, based on results of a pilot scale culture). From this study it can be concluded that suspended mussel culture with longlines in offshore areas can be profitable. The extent of profitability depends on the possibility of using existing equipment and the type of culture chosen (consumption mussels, seed mussels).

The break-even-points for consumption mussels (cf. Table 4-2) are below the auction price in Yerseke averaged over the past years (Visserijnieuws 2011). As mussel seed is not sold at the market, it is difficult to put a value to it. Mussel seed collectors in the Waddensea and Eastern Scheldt yield between 2-3 kg m^{-1} on average (MarinX 2011), which is below the break-even-yield shown by Buck et al. (2010; Table 4-2).

Table 4-2. Profitability of offshore long line culture of mussels indicated by Break-even-points (Source: Buck et al. 2010)

	Consumption mussels		**Seed mussels**	
	new vessel + land facility	**using existing equipment**	**new vessel + land facility**	**using existing equipment**
Break-even-price (assuming harvest of 10 kg m^{-1} longline)	0.52 €	0.37 €		
Break-even-yield (assuming 1€ kg^{-1} consumption mussel)	5.2 kg	3.7 kg		
Break-even-price (assuming harvest of 5 kg m^{-1} longline)			0.49 €	0.34 €
Break-even-yield (assuming 0.5€ kg^{-1} seed mussel)			4.9 kg	3.4 kg

In chapter 7 of this report, we investigate the feasibility of offshore mussel culture when carried out within an offshore wind farm. We focus on the question to what extent operation and maintenance (O&M) costs can be shared between these two activities to reduce costs. As long as there are no adverse non-economic effects of the combination that create new unforeseen costs, our simulations (presented in chapter 7) show that cost sharing can result in other break-even-prices/yields of aquaculture production than those presented by Buck et al. (2010; Table 4-2).

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5 Technical aspects of offshore structures

5.1 Introduction

For the successful operation of a wind farm and the successful combination of a wind farm with aquaculture, it is essential that the expected lifetime of the constructions used is acceptable. The expected lifetime of an offshore structure is to a great extent determined by the risk of failures. These failures can be the result of many different problems. This section focuses on two aspects: damage mechanisms of corrosion and bio-fouling, and damage risks of mechanical loads. These are risks typically associated with a combination of wind farming and aquaculture. There are additional risks, which are not dealt with in this report. The risk of collision with ships is also there, and it may even be slightly elevated, but in terms of possible damage it does not substantially differ from the single-use situation (wind farm). Impacts of foreign (drifting) objects are also not taken into account.

The findings presented in the following sections are based on literature data. Mechanical risks are described in some more detail in Janssen & van der Putten (2013). Although the prime subject of our study is the combination of offshore wind energy with mussel farming, risks arising from seaweed culture and using fish cages are also presented here because information on technical aspects of offshore structures, available in current literature, is scarce and often does not discriminate between the different types of aquaculture.

5.2 Corrosion aspects and biofouling

5.2.1 *Basic aspects of seawater chemistry*

The salinity of ambient sea water at open sea is 3.0-3.6% in most cases. The pH of seawater is relatively stable whereas temperature, dissolved oxygen, and nutrients may vary strongly (Bartoli et al. 2005, Mantzavrakos et al. 2007). Seawater is generally at a pH of 7.5 to 8.5 due to its buffering capacity with many ions and interaction with carbon dioxide and water. Oxygen levels can range from zero to over 20 ppm in temperate waters (Valdemarsen et al. 2012).

5.2.2 *Corrosion mechanisms and corrosivity zones for offshore structures*

The offshore wind turbine and foundation structure is exposed to different and varying corrosive environmental conditions. Based on theory and practical experience with offshore structures, in total eleven different corrosion zones of offshore wind structures can be identified. The most critical zones are the splash/tidal zone and closed compartments filled with seawater (e.g. the internal of a monopile or jacket foundation structure).

In general, the same mechanisms that can damage offshore structures like wind turbines and platforms can also damage aquaculture structures that are made of the same or similar material.

Design specifications for steel structures define a corrosion allowance. In case of uniform corrosion this is an applicable design tool.
However, when local corrosion mechanisms like microbial corrosion (MIC), galvanic corrosion or corrosion fatigue occur, the structural integrity of the steel structure must be evaluated.

The offshore wind structure design is determined by fatigue load. Local defects like pitting attack may act as initiation sites for fatigue cracking. For this reason special attention should be given to local defects in the foundation and the tower structure.

5.2.3 *Corrosion risks in currently used offshore wind turbines*

The offshore wind energy market is young, compared to the offshore oil and gas and shipment markets; the first offshore wind farm was installed in 1991. The most important lesson learned from the first generation offshore wind turbines is: wind turbines based on onshore technology are not suitable for offshore application. The first offshore wind farm, Horns Rev (D), suffered from a major coating failure of eighty wind turbine foundations. The coating on the transition pieces broke down and resulted in unexpected repair and maintenance costs. The reason was a combination of wrong coating selection and improper application of the coating. The key issue is a lack of conformity between the manufacturer, coating applicator, and coating supplier.

Other corrosion related problems reported are failing cathodic protection systems, corroding boat landings by combination of wear, impact and seawater, and corroding secondary structure components like ladders and railings. The impact of corrosion damage varied from increased safety risks for maintenance personnel to re-evaluating the structural integrity of the foundation structure because of local pitting attack.

Local corrosion attack by MIC has been noticed on the internal surface of different monopile foundations on different locations in the North Sea. With grouting failure repair of several monopile foundations, local corrosion attack was detected on the internal surface area of the unprotected monopile. Until then the internal area had been a black box. The hedge was sealed to reduce and stop the internal corrosion process.

Specification of corrosion protection for specific offshore wind structures is still an issue. The applied standards for European offshore wind farms vary from onshore related specifications to those deriving from offshore oil and gas specifications. Based on the experiences with coating and cathodic protection failures, there is a need for an accepted uniform specification. Up to date, such a specification is lacking.

5.2.4 *Biofouling on offshore structures*

Offshore constructions are attractive to biofouling species. Biofouling may result in increased costs due to antifouling measures that have to be taken: extensive inspection and maintenance, creation of micro-environments discouraging microbial corrosion, and heightened design criteria as a consequence of the extra hydrodynamic and weight loading (Figure 5-1, Figure 5-2, Figure 5-3).

Figure 5-1. Biofouling on an offshore jacket foundation.

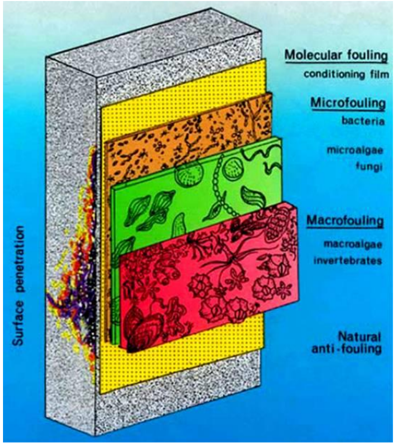

Figure 5-2. Schematic representation of different stages in marine biofouling process (NERC News 1995).

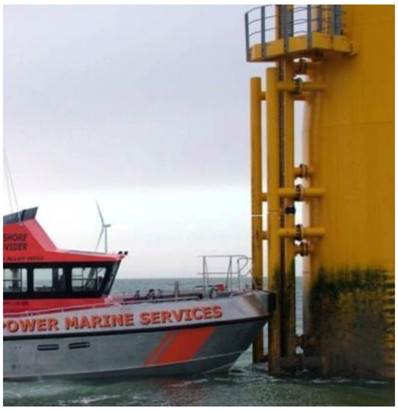

Figure 5-3. Access to a wind turbine foundation for maintenance. Biofouling is visible on the stairs and on the boat landing structure in the tidal zone.

Generally four different process stages of bio-fouling in seawater are described (Figure 5-2). These may take place in different time frames. The first stage starts almost instantly upon immersion with the formation of a conditioning layer of dissolved organic matter such as glycoproteins and polysaccharides. Subsequently a so-called biofilm can be formed with colonizing bacteria and micro-algae. Hours to days later a more complex community may form including multicellular primary producers and grazers, for instance algal spores, marine fungi and larvae of hydroids, bryozoans, and barnacles. If time and environmental conditions allow for, such communities may evolve to diverse and sometimes very thick layers with both hard fouling organisms (barnacles, mussels, tube worms, corals, etc.) and large populations of soft fouling such as ascidians, hydroids and macro algae. However, it should be explicitly mentioned that in a natural environment the biofouling process is very variable and never follows exactly this schematic representation. The process is influenced by many abiotic factors as well, such as salinity, nutrient content, sunlight intensity and duration, currents, and temperature.

In existing wind farms, no antifouling techniques are currently applied on the foundations. In this situation, the uncoated steel subsea zone and the coating system on the transition piece are both susceptible to biofouling.

Biofouling on floating foundations as well as the tether ropes should be taken into account when assessing the lifetime of the construction. Calculations of design loads of offshore wind turbine foundations commonly apply a maximum biofouling layer thickness of about 200 mm for extreme load conditions. A load calculation model would also take into account weight and hydrodynamic loading (current and wave load) by biofouling.

At first glance, a value of 200 mm of maximum biofouling layer thickness seems sufficient. However, in order to deduce a more reliable biofouling layer thickness depending on the location, regular checks over a twenty year period must take place. Biofouling on tether ropes can additionally influence the hydrodynamic behavior by the increased diameter of these tether ropes.

Biofouling can pose a risk to offshore wind foundations in the following cases:

- **Increased drag load.** The hydrodynamic profile of a biofouling layer strongly deviates from that of the flat surface of a foundation. Extensive growth, in the form of long trail-like colonies of mussels, algae and other soft elongated macro-organisms that move along with the current, may sometimes result in unexpectedly high drag loading. Biofouling may, however not necessarily pose a risk to the mechanical load on the foundations in moderate tidal current conditions.
- **Influence on cathodic protection.** Another effect of biofouling is coverage of anodes, which affects the function of the cathodic corrosion protection system. For visual inspection on site (weld inspection, wall thickness measurements) a biofouling layer must be removed.
- **Influence on MIC.** Biofouling creates micro-environments encouraging microbial corrosion (MIC)
- **Safety and accessibility.** For safety reasons biofouling must be prevented on stairs and boat landing, to ensure safe access of maintenance personnel to the foundation and wind turbine (Figure 5-3).

There are several techniques that can be applied to prevent or clean biofouling on surfaces: antifouling coatings, electrochemical and physical methods for fouling control, cleaning of surfaces by robots or handheld tools. It is recommended to inspect the foundation and anodes after a period of 5–10 years. Visual inspection and quantification of fouling composition and thickness can be combined with regular cleaning of the external surface.

Considering the three types of wind turbine foundations (see Table 5-1) no clear differences in biofouling settlement and/or development are expected. The basic materials used in the foundation are equally susceptible to fouling under immersion. Fouling control coatings can be applied to all types of materials. Also cleaning techniques for removal of fouling do not substantially differ between the three types of foundation structures.

5.2.5 *Potential influence of offshore aquaculture on the corrosion of unprotected steel structures*

Seaweed farms influence the seawater chemistry. Seaweed photosynthesis increases dissolved oxygen in the water: The oxygen concentration in seaweed tanks can vary from 7.0 to 13.0 ppm, while in ambient seawater it varies from 8.0 to 10.3; Msuya & Neori 2008). The increased level of dissolved oxygen in the water might result in an increased corrosion rate of unprotected steel structures at sea. The corrosion rate of steel under a calcite film (deposited by seawater on cathodic areas of metal) is 250% higher in the presence of seaweeds than without (Buzovkina et al. 1992). Seaweeds may raise the pH of the water by 0.1 to 0.4 pH units (Robertson-Andersson et al. 2008). This variation may have an influence on scale formation on steel structures and thereby induce or change localized corrosion processes (Beech et al. 2008). Careful monitoring of scale formation and appropriate maintenance measures will help to keep corrosion risks below critical levels.

Fish farms cause metal enrichment in the bottom of the sea, e.g. extreme high concentrations of Zn, Cu and Cd in sediments and pore water (Dean et al. 2007, Kalantzi et al. 2013, Loucks et al. 2012, Nordvarg & Johansson 2002).

Such high concentrations may also increase the corrosion risk of steel due to higher conductivity of the electrolyte and creation of galvanic effects. Additionally, oxygen consumption because of biodegradation may create an anoxic or anaerobic environment that stimulates MIC by microorganisms such as sulfate reducing bacteria (SRB; Kawahara et al. 2008). Increase of carbon oxides and nitric oxides can also increase the corrosion of steels (Beech et al. 2008).

No literature data have been found on effects of mussel farms on environmental parameters that can be associated with corrosion risks. A priori such risks cannot be fully excluded, depending on type of materials used in mussel farms. If similar phenomena occur as described above for fish farms, e.g. metal enrichment and/or anoxic conditions in the near environment, then similar potential risks can be expected.

5.3 Mechanical risks of wind farms due to the presence of offshore aquaculture constructions

Offshore wind farms are constructed and developed to withstand the forces of the oceans. Wind and waves cause the highest loads on a wind turbine (tower and foundation). The presence of an offshore aquaculture may pose an additional threat to the wind farm. The research question is: What are the effects of aquaculture constructions and activities on the (mechanical) safety of offshore wind turbines?

To grow seaweed or mussels, usually nets or ropes are used; fish farms usually apply special cages (see Figure 5-4).

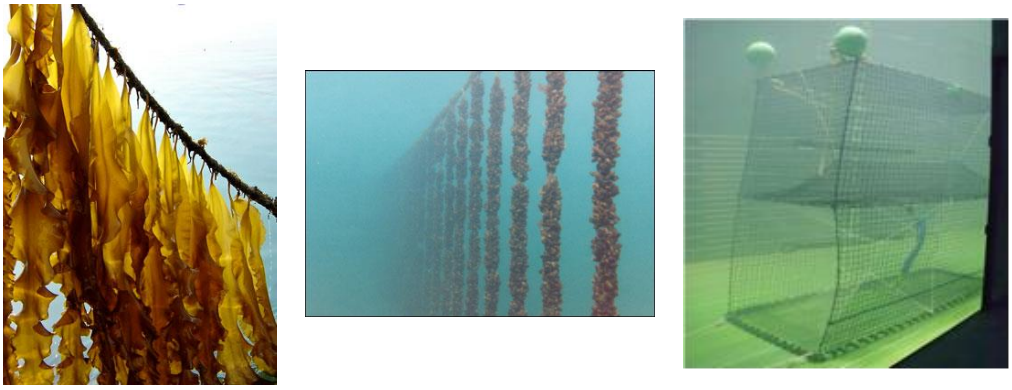

Figure 5-4. Three types of aquaculture: seaweed (left), mussels (middle) and fish (right).

The next section discusses scenarios that may occur and could lead to mechanical risks to the turbine foundation when offshore aquaculture is carried out within or in close vicinity of an offshore wind farm. Because the risks can be different depending on the type of foundation, three commonly used structures and their properties are considered: monopile, jacket and gravity based (Table 5-1).

Table 5-1. Typical design properties of three different wind turbine foundations.

	Monopile	**Jacket**	**Gravity based**
Weight	500 tonnes	800 tonnes	5,000 tonnes
Main Material	Steel	Steel	Concrete
Water depth	30 m	30 m	40 m
Max. wave height (H_{max})	13.7 m	16.2 m	17.5
Max overturning moment at seabed	200MNm		450MNm

5.3.1 *Scenario analyses*

Our analyses focus on scenarios that may lead to mechanical (and corrosion) damage to the wind turbine foundation. Scenarios that could lead to damage of the aquaculture construction or the supply/maintenance vessels are not (yet) included. These risks can only be investigated at a later stage when the operational processes of maintenance and harvesting are known in detail.

Two scenarios that may occur and questions that arise are:

1. Impact. Drifting aquaculture construction **strikes** the turbine foundation.
   Is there a risk of significant damage to the foundation?
2. Extra drag force. Drifting aquaculture construction **gets stuck around** the turbine foundation, increasing its surface area.
   Can the foundation handle the extra (drag) forces involved?

The answers to these questions depend on the type of aquaculture (mussel, seaweed, fish) and corresponding constructions, and on the specific turbine foundation (i.e. monopile, jacket or gravity based). Therefore, the scenarios are presented in matrix tables. The two different scenarios and their possible risks are described below.

Scenario 1: Impact. Drifting aquaculture strikes the turbine foundation
It is possible that a drifting aquaculture (e.g. the longline construction, whether or not overgrown) strikes a turbine foundation. In such a case there are three main parameters that determine the risk of damage to the foundation:

1. the mass
2. the impact velocity
3. the deformability/ robustness of the aquaculture construction

As mussel and seaweed farms mainly consist of nets and ropes, the deformability of such structures is large. In case of an accident, it is the aquaculture construction that deforms, and not the foundation. Probably this also holds for most fish cages. Fish cages as shown in Figure 5-4 will not damage the foundation structure; only larger, more rigid cages have the potential to do so.

Damage to the protective coating of the foundation structures when they are hit, is possible in all cases. On a longer term, this could induce additional corrosion risks and negatively influence the safety of the construction. Inspections are required and possible repair of the coating may be necessary. Table 5-2 summarizes the effects, which do not differ for the three different foundation types.

Table 5-2. Scenario 1: Drifting aquaculture strikes the turbine foundation. Orange cells indicate the worst case scenario.

	Mussels	Seaweed	Fish
Monopile	No significant structural impact damage expected	No significant structural impact damage expected	Damage depends on mass, velocity and deformability of fish cage
Jacket			
Gravity based			

Scenario 2: Extra drag force. Drifting aquaculture construction gets stuck around the turbine foundation, increasing its surface area

It is possible that a drifting aquaculture does not only strike, but gets stuck around a turbine foundation. In the case of a monopile or gravity based foundation, the stuck aquaculture construction will not significantly increase the frontal surface area of the structure. The frontal surface area is an important parameter in the determination of drag forces. With increasing frontal surface, drag forces due to current and surface waves increase. In the case of a jacket consisting of a lattice structure with many beams, it is possible that an aquaculture construction gets stuck around the beams and significantly increases the frontal surface area. In this case, the local force on such a beam, and the overall drag forces on the whole structure certainly increase. The effects are summarized in Table 5-3.

Table 5-3. Scenario 2: Drifting of the aquaculture. The aquaculture is stuck around the turbine foundation. Orange cells indicate the worst case scenario.

	Mussels	Seaweed	Fish
Monopile	No significant increase in loads expected		
Jacket	Increase in drag force		
Gravity based	No significant increase in loads expected		

Possible effects of the 'worst case' scenario (orange cells in Tables 5-2 and 5-3) are preliminarily analyzed in Janssen & Van der Putten (2013).

A preliminary qualitative assessment of scenario 1 and 2 yields that scenario 1 (impact between offshore aquaculture and wind turbine foundation) is not a real threat in case of mussel and seaweed farms. Damage to the (anticorrosive) paint of the turbine foundation is possible in case of an impact, but this will not lead to short term structural damage. In order to prevent corrosion and damage risks in the long term, appropriate actions (i.e. repair) can and should be taken. For fish farms the situation in scenario 1 may vary with the type and size of cages that are used and the way they are constructed. Potential risks of consequences of the impact should be assessed already in the design phase of such combined infrastructure.

Scenario 2 (extra drag force due to stuck aquaculture constructions) poses a risk especially to jacket constructions because it may lead to (strong) increase of frontal surface area of the immersed structure and thereby give increased drag forces. With monopiles and gravity based constructions the stuck aquaculture material may attach to the turbine foundation at a single point only with insignificant increase of frontal surface area and minimal increase in such drag force.

For a jacket construction, in the extreme case of a 100% coverage of its underwater surface by stuck aquaculture material during a storm, the overturning moment at the seabed could increase by 200-300 MNm (Janssen & van der Putten, 2013), and eventually lead to the collapse of the wind turbine.

However, this risk is merely theoretical, considering the type and construction of aquaculture materials being far less massive than the foundation itself and the unrealistic assumption of a 100% coverage. Nevertheless, appropriate methods to avoid this small risk can be investigated in the design phase of such infrastructure, for instance modular aquaculture structures that fall apart in case of drifting under severe conditions.

In severe storms with extremely high waves, an intact aquaculture structure that is physically directly connected to the turbine foundation could theoretically lead to the collapse of the turbine if the overturning moment at the seabed becomes too large. For this reason, the investigated Blauwdruk scenarios only consider aquaculture installations that are not attached to any wind turbine foundations. Nonetheless, if a connected wind farm-aquaculture infrastructure is considered and designed, methods to reduce and prevent high tensile forces on the turbine foundation should be taken into account. For example, use of suitable anchors to hold the aquaculture structure in place, or application of so-called safety wires that break at predefined tensile forces. Although the aquaculture farm will be lost in the latter case, the turbine foundation will stay intact.

5.4 References

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6 Ecological risks and opportunities

6.1 Introduction

This section describes the potential effects of wind farms and of mussel farming on the marine ecosystem. First we consider both activities separately, based on recent literature, then we try to assess the potential effects when both activities are combined. An assessment of the ecological impact(s) of a combination that does not yet exist remains highly speculative. Therefore we can only discuss some areas of concern in a more general way.

Note that the financial analyses (chapter 7) focus on the operational phase. In this ecological chapter, it is relevant to also look at the construction phase, because potential negative ecological effects can prevent a Wind & Mussel Farm (W&MF) from being built, simply because the necessary permits will not be issued.

6.2 Impacts of offshore wind farms

Potential key effects of offshore wind farms are: noise disturbance to marine mammals, collision risks to birds and bats, displacement of mammals and seabirds, attraction of fish and epibenthos[42], damage to seabed communities (Lindeboom et al. 2011, Degraer et al. 2012), and potential effects on fish, fish eggs or larvae caused by underwater noise or electromagnetic fields (experimental studies have shown that some fish species are sensitive to electricity).

6.2.1 *Construction phase*

Potential effects during the construction phase relate to the sound produced by preparatory subsea works, and construction activities, including vessel traffic. Piling of wind turbine foundations, for example, introduces very high levels of underwater sound into the environment and has the most marked impacts. Although many accompanying research programmes have been carried out in the North Sea, there is still a great knowledge gap about the impacts of offshore wind farms on the ecosystem, in particular with regard to the impact of noise in the construction phase. Only limited evidence is available. Measurable impacts arising in the construction phase (e.g. displacement of animals) are usually temporary and reversible, and more or less confined to the period in which the construction activities take place. However, permanent effects on individual animals cannot be excluded. Depending on how many individuals are affected and how resilient the population is, there may be an impact on the population level, too. Based on a recent review of scientific literature and reports (Lindeboom et al. 2011; Leopold et al. 2013a), some general conclusions can be drawn for the species groups fish, marine mammals and birds. Note that these studies concern wind farms in the shallow coastal zone of the North Sea and not in the offshore area considered in this report. Since no large far-offshore wind farms have been completed yet, there is almost no scientific knowledge available on potential ecological impacts of wind farms in deeper North Sea waters.

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[42] Community of organisms living on the top of the marine sediment.

The (initial) environmental impact assessments[43] that were carried out for the demonstrator project 'Beatrice' (see section 3.2), only briefly address the aspects that typically play a role in deep-water areas, but they do provide some insight in specific concerns.

Fish

Fish are at risk of physical damage in the vicinity of piling operations, and of possible behavioural changes in a wider spatial range (references in Leopold et al. 2013a). Significant physical impacts mainly occur to fish with swim bladders at high sound exposure levels. Whereas adult fish may be able to avoid exposure by leaving the area, larval and young fish – passively drifting – cannot escape from (possible) harmful sound levels and are likely to be adversely affected. Since small fish are prey for other species, including larger fish and birds (e.g. terns), food availability for these species may be affected during the construction phase in a limited area but also at larger distances, if fish larvae drift past the piling site to a nursery area downstream (Arends et al. 2008).

Marine mammals

The construction phase is considered to be the most disturbing period for sea mammals. Within several hundreds of meters from the piling site, depending on the noise level, underwater sound may result in avoidance behaviour or even (permanent or temporary) hearing loss (Seamarco 2011[44]).

Harbour porpoises. In Belgian waters Haelters et al. (2012) measured "that immediately upon the start of piling activities, harbour porpoise detections at a few km from the piling site fell to virtually zero. After the cessation of piling it took hours to days before new detections were made at this location." Researchers who investigated the spatial distribution pattern of harbour porpoises in a German wind farm by carrying out two aerial surveys three weeks before and exactly during pile-driving operations demonstrated a strong avoidance response of the animals within 20 km distance of the noise source (Dähne et al. 2013). Negative long-term effects (avoidance) and slow recovery were found by Teilmann & Carstensen (2012) for a large-scale offshore wind farm in the Baltic.

Harbour seals. Based on a short period of overlap between piling operations and seal tagging data, Brasseur et al. (2012) observed that the tagged harbour seals stayed away several tens of kilometres from the construction area. This telemetry study concerns the coastal zone, and it is not clear how these results can be extrapolated to (far)offshore areas. Seals can also be disturbed by the physical presence of installation vessels. During the construction of an offshore wind farm in the United Kingdom (Scroby Sands) harbour seals on a haul-out location nearby were adversely affected by shipping activities (Skeate et al. 2012). It is unknown yet whether severe peak sound noise pollution has long-term effects. A study on the effects of a commercial two-dimensional seismic survey in the central Moray Firth (Scotland, the Beatrice area) did not find any such effects (Thompson et al. 2013).

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43 http://www.beatricewind.co.uk/environmental_statement.pdf; last accessed March 2014

44 http://www.informatiehuismarien.nl/Images/Final%20%28short%29%20report%20on%20TTS%20in%20seals%20%26%20a%20porpoise_2025.pdf; last accessed March 2014

Seabirds
Underwater sound due to pile driving operations or seismic surveys may disturb seabirds as they dive down to forage. Although not much is known about the effects (Turnpenny & Nedwell 1994), it is generally assumed that there are no effects on population level. Local seabirds are likely displaced from the building site during construction.

Seabed organisms
Construction activities like pile driving, and trenching and burying of cables destroy and modify the present benthic habitat on the construction site and along the cable routes. Due to the disruption of the seabed sediments, existing benthos will be affected but only in the immediate area, which is relatively small. Lindeboom et al. (2011) carried out a monitoring study in the OWEZ wind farm, and drew the following preliminary conclusion (based on two years: there were "no short-term effects on the benthos in the sandy area between the generators, while the new hard substratum of the monopiles and the scouring protection led to the establishment of new species and new fauna communities".

6.2.2 *Operational phase*

During the operational phase impacts can arise from the physical presence of the wind farm, including disturbance of the seabed sediments. Furthermore, when in operation, turbines generate noise and introduce energy in the seafloor by the tower and via the subsea cables.

Fish
On a larger scale, the construction of a wind farm will most probably not lead to detectable changes in the abundance of fish (Van Hal et al. 2012). However, on the scale of the wind farm (OWEZ: 24 km^2; PAWP: 17 km^2) clear differences were observed between the new, artificial hard-substrate habitat and the sandy seabed. Van Hal et al. (2012) found higher densities of a.o. horse mackerel and cod, on the scour protection of the monopiles, while lower abundances were observed of flatfish and whiting. Note that fisheries was prohibited inside these two wind farms. Possible negative impacts on migrating fish species (e.g. salmonids) and elasmobranchs (lampreys, sharks and rays) may occur due to the electromagnetic fields around cables, but evidence for this is scarce (Gill 2010, and references in Leopold et al. 2013a).

Marine mammals
Harbour porpoises. Concluding from an acoustic activity monitoring carried out in wind farms in Dutch nearshore waters, harbour porpoises did not seem to avoid these farms. Inside the farms higher acoustic activity was recorded than outside, which may be linked to increased food availability due to the reef effect of the turbine foundations and the exclusion of fishery from the wind farm (Scheidat et al. 2012). However, the opposite (avoidance of the wind farm) was found in a Danish study (Teilmann & Carstensen 2012).

Seals. Seals mainly live and forage in the coastal zone but also make long foraging excursions across the North Sea. They may be attracted by increased levels of food (fish, benthos) that may occur within wind farms when fisheries are excluded inside the farm (Van Hal et al. 2012). Noise levels of operational wind farms are not considered detrimental to seals (Madsen et al. 2006).
On the other hand, there are concerns that high densities of wind farms in the coastal zone may create barriers for the migration of seals from one habitat to another, which may (partly) be due to the underwater sound created by turning turbines (Leopold et al. 2013a).

Bats

Bats have been found on oil platforms in the North Sea (Boshamer & Bekker, 2008) and have been observed during surveys at sea (S. Lagerveld; pers. comm.). A recent study has shown that bats occur regularly in the Dutch offshore wind farms, up to 23 km off the coast (Jonge Poerink et al. 2013). The first firm evidence that bats actually migrate over sea came from a 'Nathusius pipistrelle', which was banded in the United Kingdom and was found 600 km to the east in the Netherlands[45].

Several studies in Europe, South Africa and the United States have shown that wind turbines can cause high fatality rates amongst bats (Osborne et al. 1996, Bach et al. 1999, Rahmel et al. 1999, Rodrigues et al. 2008, Brinkmann et al. 2006, Arnet 2005, Johnson 2005, Fiedler et al. 2007, Dürr & Bach 2004, Doty & Martin 2012). The causes of death are collisions with rotating blades (Kunz et al. 2007) and barotrauma: internal injuries due to sudden pressure fluctuations near moving turbine blades (Baerwald 2008). It is not known whether offshore wind turbines cause fatalities as well, but the risks might be comparable to onshore wind turbines (Ahlen et al. 2007).

Seabirds

Some bird species appear to be indifferent to the presence of wind farms (especially gulls), or are even attracted by them. Other birds, particularly divers, seaducks and auks avoid wind farms (Petersen et al. 2011, Dierschke et al. 2012, Leopold et al. 2013b). The species composition at sea is mainly determined by the distance from shore. Nearshore species include divers, grebes and seaducks; offshore species include northern fulmar, northern gannet, black-legged kittiwake and auks. Several species with a wider distribution, including the northern gannet and gulls, are attracted by fishing vessels and will be displaced from wind farm sites, if fisheries are banned from wind farms (Hartman et al. 2012). In general, seabirds may be impacted directly by collisions, and indirectly by behavioural responses, i.e. avoidance/ attraction. Collisions are most likely where fluxes of (flying) birds are high, and when species do not show avoidance behaviour. However, if collision rates are at such a low level that impacts on population level are unlikely for most species. On the other hand, when vulnerable species are involved, also small death rates can have a great impact on the population. Pelagic seabirds[46] show strongest avoidance behaviour. However, if collisions occur, the population may be impacted because of the longevity of these offshore/ pelagic seabirds.

In general, where wind farms increase in number and area, the risks of barrier effects and disturbance increase. Avoidance may further lead to a reduction of suitable feeding grounds. Seaducks, for example, forage in shallow areas where shellfish densities are very high and a wind farm in such habitats may displace large numbers of birds (Petersen et al. 2011); however, the combination of shallow grounds and high shellfish densities do not occur in the offshore areas considered in this report.

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[45] http://www.bats.org.uk/pages/amazing_journey_for_a_tiny_bat.html; last accessed May 2014.

[46] These are birds that live in the pelagic zone. The word pelagic is derived from Ancient Greek pélagos, meaning "open sea". The pelagic zone can be thought of in terms of an imaginary cylinder or water column that goes from the surface of the sea almost to the bottom. Conditions change deeper down the water column; the pressure increases, the temperature drops and there is less light (Wikipedia).

Migrating birds are at risk of collisions, particularly near shore, because they use the coastal zone as navigation guidance and they occur in high densities and fly lower than further offshore (Krijgsveld et al. 2011).

Seabed organisms
Wind turbine foundations, if fixed to the seafloor, occupy a certain area of the seabed and also may have an impact on seabed currents and patterns of scouring, e.g. re-suspension of sediment in the water column or coverage of nearby benthos. These effects are considered to be small, because they are very localised (Lindeboom et al. 2011).

Changes on ecosystem level
Offshore wind farm constructions can create a new (type of) habitat under water (Lindeboom et al. 2011). In an area of sandy sediment, turbine foundations form a new type of hard substrate. Sessile flora and fauna colonize these substrates, thereby enhancing biological diversity and production and creating (micro-)habitats where organisms may find shelter in addition to food. This new community also attracts mobile species, including fish and at a final stage, possibly larger piscivores such as large fish, seabirds, and marine mammals. However, there is also the risk of introducing unwanted invasive species, since constructions in general provide a good habitat or substrate for invasive epibenthic species.

6.3 Impacts of offshore mussel farming

Since no offshore aquaculture takes place in the Dutch part of the North Sea, only general information about ecological impacts of mussel farming is reported here. For the same reason we do not distinguish between the construction and operational phase. Even if longline constructions need heavy foundations, it is still unlikely that the impact of placing them is greater than that of wind farm construction activities (see section 6.2). Offshore mussel farming (on suspended longlines) results in several impacts on the environment (McKindsey et al. 2011). The physical environment is altered by the mechanical farming construction and the presence of mussels, leading to altered hydro-sedimentary processes, e.g. locally modified currents and increased sedimentation. In addition, the longline-construction provides a habitat for other invertebrates by providing refuge from predation and adverse environmental conditions, and by increasing food availability (in the form of other invertebrates or algae). The deposition of (pseudo)faecal material from the mussels, and settlement of particles from the water column as a result of reduced water mixing, increases the organic load of the sediment. This in turn changes biochemical processes in the seabed, leading to changes in oxygen levels, pH, redox potential, dissolved sulphides and other sediment parameters. Depending on the local current speeds, the organic load can also be transported to other areas. The effect of this process is considered to be very small (H. Lindeboom; pers. comm.)

Seabed organisms
Changed sediment conditions alter the benthic community. As the level of organic input increases, typical soft sediment communities dominated by large filter-feeders are replaced by smaller, more deposit-feeding organisms, mainly polychaetes and nematodes (McKindsey et al. 2011). At high organic loading rates, the sediment may become anoxic and only bacteria may be present. However, since the Southern Bight of the North Sea is a very dynamic environment, anoxic sediment conditions are unlikely to occur.

Constructions in general may provide an additional habitat or substrate for exotic species. It has been shown that suspended bivalve culture sites are hotspots for invasive species, including tunicate ascidians[47], algae and molluscs (McKindsey et al. 2011). Since mussels and associated fauna may drop off from the constructions, the natural benthic soft-sediment habitat may adapt features of a biogenic reef. This may enhance the amount of food available to benthic predators and scavengers.

Fish

Suspended mussel culture may also provide benefits for fish, including the availability of food by the enriched hard-substrate fauna, and shelter from predators. It appears that mainly demersal fish[48] are associated with mussel lines (McKindsey et al. 2011). Some of these species are predators of the cultured mussels. In general, it is unknown whether the fish are attracted by the vertical structures, the farmed product, or the associated organisms. Fish and other species attracted to aquaculture may also remove fouling organisms, thereby improving the mussel farming performance.

Seals and seabirds

Roycoft et al. (2004) studied the occurrence of bird species and seals in a mussel culture area in comparison to a reference area. The study was performed in a large bay in Southwest Ireland, where mussels were cultured using suspended longlines at less than 20 m above the sediment. It appeared that cormorants, gulls and auks were present in higher numbers at the mussel sites than outside. The abundance of divers (Gaviidae) and harbour seals did not show spatial variation related to aquaculture sites. No adverse effects from suspended mussel culture on the numbers of seabirds and harbour seal were observed. Particularly gulls made use of the floating devices to rest. Similar observations were made around mussel culture plots in the Wadden Sea, where eiders flock together in large numbers and where mussels are abundantly available on the seafloor (Cervencl et al. in prep.). Sea ducks are only rarely observed offshore, probably because the water is too deep for feeding and stocks of suitable bivalves are generally low. Still, sea ducks do migrate across the North Sea (Offringa 1993, Wernham et al. 2002) and if suitable feeding conditions are present they may in time learn to exploit these.

Bats

Aquaculture structures, which do not have rotating parts, are not likely to affect bats.

Plankton

In addition to the impacts on benthos, fish, birds, and marine mammals, described above, mussel farming may reduce the availability of food in the water column by filtering phytoplankton and zooplankton. While the biomass of plankton may be reduced due to mussel grazing, the production of phytoplankton may be enhanced by the recycling of nutrients. This could result in a shift in the plankton species composition towards fast growing species, which are/might be less favoured as food by predators.

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[47] In Dutch: zakvormige manteldieren.

[48] Fish that live and feed on or near the bottom of seas.

Changes on ecosystem level

Carrying capacity refers to the maximum amount of mussels that might be farmed without causing any negative impact to the surrounding ecosystem. For bivalve farms carrying capacity is often related to primary production and phytoplankton concentration. If carrying capacity is exceeded, changes in phytoplankton availability may lead to cascading effects on other trophic levels such as fish, birds and even sea mammals. Lower phytoplankton levels limit bivalve growth itself and should therefore be avoided for commercial purposes. The open nature of offshore mussel farming, and thus the availability of currents supplying new fluxes of nutrients and phytoplankton to the culture site, indicate that negative impacts are not likely to occur rapidly. However, for planning and up-scaling of mussel farming, potential carrying capacity models should provide insight in the maximum level that can be sustained in a given area. Such ecosystem models should also take bio-deposition and potential benthic effects into account.

Shipping

The physical presence of operation and maintenance vessels on the culture sites (anchoring or passing through) may cause disturbance. Disturbance of birds and sea mammals may give rise to concerns, if boat activity greatly increases. Seed mussel culture (SMC) requires more boat operations than bottom cultures. However, in the Wadden Sea there are no indications that shelducks or eider ducks are adversely affected by the presence of SMC (Kamermans et al. 2014). Other studies also demonstrated that effects of boat activities are minor/absent (Cheney et al. 2010). This may, however, vary per farming system, and the type and condition of the vessels used.

6.4 Impacts of a Wind & Mussel Farm

This section deals with the question whether a Wind & Mussel Farm (as described in chapter 7) can lead to impacts that have not been described in the previous sections of this chapter. In other words: Does the combined use of an offshore area for generating wind energy and farming mussels cause other potential synergistic effects (including the individual effects but to another extent), as compared to the situation in which the two activities are carried out singly.

6.4.1 *Construction phase*

It is likely to assume that the construction of a Wind & Mussel Farm does not take more time than would be required when building the wind farm and the mussel farm separately (at two comparable locations). Unless there are synergy effects allowing the construction period to be shortened, negative cumulative effects may however occur because when building a Wind & Mussel Farm, the period of continuous construction activity in one and the same area is longer. It is speculative whether an extended construction phase leads to the accumulation and aggravation of adverse effects. Short-term, reversible effects could become permanent, because the disturbances persist over a too long period of time. On the other hand, habituation may also occur. If synergy in the construction phase is possible and installation activities can be carried out simultaneously, negative cumulative effects can still occur because of increased intensity of disturbance. Although a typical property of (underwater) noise is that it does not simply add up, critical noise levels could be reached. An obvious advantage of multi-use is that the disturbed area where the most marked adverse effects occur, the construction site itself, is likely smaller because of the combined use.

6.4.2 *Operational phase*

The physical structures of the Wind & Mussel Farm may act as shelter for several species, including fish and mobile invertebrates. They add a different type of substrate, a hard one, to sandy seabed, thereby enabling fouling organisms to settle. This leads to a different type of (sessile) community. The fouling community attracts other invertebrate species and (mainly) demersal fish. These fish may attract predatory fish, sea birds and marine mammals. In addition, the hard substrate from the Wind & Mussel Farm structures may form an attractive habitat for non-indigenous species, thus increasing the risk of establishment of invasive species.

The presence of mussel farming constructions within a wind farm might hypothetically result in a barrier effect, since the 'open' wind farm is now 'filled' with longlines which is more of a closed construction. Some species of seabirds may be attracted by the mussel farm, but this is unlikely to result in significantly more bird strikes as these birds will quickly become "locals" with good knowledge of their surroundings. In a similar way, marine mammals could be attracted by increased food availability, in particular fish, ignoring temporary disturbance, which eventually can have negative long-term effects for their well-being depending on the levels and duration of noise exposure (but see Madsen et al. 2006: operational noise levels may be too low to present real danger).

Regardless whether the operation of a wind farm or of a mussel farm is concerned, both farms require maintenance, involving transport by vessel and/or helicopter. These activities cause various disturbances like underwater noise, marine litter, introduction of contaminants, and visual disturbance. Underwater noise and visual disturbance may lead to avoidance of the area by seabirds and sea mammals during the period of time in which these operations take place. If synergy advantages can be achieved through sharing of transport and access facilities (see section 3.3 and chapter 7), e.g. when maintenance activities in the wind farm and the mussel farm can be carried out in a same window of opportunity, it may be assumed that compared to single-use less potential disturbances occur, since a vessel then needs to make the trip from the coast to the farm only once.

Table 6-1 summarizes the potential effects in the operational phase described above.

Table 6-1. The main potential impacts of a wind farm and a mussel farm in the operational phase when used singly and in combination. Red = potential negative impact, green= potential beneficial impact; light-/darkness of colours indicates degree of expected impact.

	Single use	Single use	Combined use
Ecosystem component	Wind farm	Mussel farm	Wind & Mussel Farm
Plankton	n/a	Change in species composition due to grazing/filtering, **reduced biomass**	
	n/a	**Increased production** of phytoplankton	
Benthos	n/a	Organic enriched sediment with **opportunistic species**	
Seabed	**Risk** of invasive species settlement	**Increased risk** of invasive species settlement	
	Introduction of hard-substrate fauna**, increased production** (in each situations probably of different composition.		
	Shelter when fisheries or other (ground) activities are excluded.		
Fish	**Habitat** and **increased** food availability		**Habitat** and **increased** food availability
	Shelter when fisheries or other (ground) activities are excluded.		In the absence of fisheries: **more shelter.** Refugium function here holds for fish species attracted by the wind farm **and** the mussel farm.
Birds	**Avoidance** and **collision risk** for some species, possible **barrier effect**	**Avoidance** due to disturbance by maintenance vessel activities	**Increased Avoidance**, **collisions risk** for some species and possible **barrier effect**
	Increased food availability for some species**; new habitat** for some species		
Marine mammals	Possible **barrier effect** when built large-scale/ in high densities in coastal zone	Possible barrier effect due to **'closed' construction**	
	Increased food availability (in the absence of fisheries)		**Increased food** availability (in the absence of fisheries)
Bats	**Collision** and **barotrauma risks**	n/a	**Collision** and **barotrauma** risks

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7 Towards a business case – one scenario

The business case of a combined wind and mussel farm (W&MF) was evaluated using a generic Asset Management Control (AMC) model. The fictive W&MF was modelled as one system, composed of individual subsystems and installations that are characterized by specific parameters (listed in Annex D). The main purpose of the scenario analyses is to demonstrate the economic feasibility of a combination of wind- and mussel farming.

Four scenarios, characterized by specific parameters and variables, as explained further below in this chapter, were investigated.

7.1 Analysis of operation and maintenance costs

Offshore wind energy production is a complex and relatively small industry in the Netherlands, but it is considered an industry with promising features for the public and private sector. As described in chapter 3, one of the main hurdles that hinders use of offshore wind energy is the high cost for operation and maintenance (O&M) that typically amount to 25-30% of the total lifecycle costs of offshore wind farms (Miedema 2012). The offshore wind energy industry is eagerly looking for technical innovations. Until now they mostly sought the solutions in their own circles. But if the combination of offshore wind energy and offshore aquaculture proofs to be feasible and profitable in practice, there may be an additional possibility to reduce the O&M costs by synergy effects of the combined operations. Logistic waiting times can result in substantial revenue losses, whereas timely spare-parts supply or the availability of jack-up vessels is beneficial.

The next sections describe the fictive wind mussel farm (W&MF) in more detail and how the Asset Management Control (AMC) model is build and applied to simulate different O&M scenarios of 20 years. To get more insight in the O&M cost structure of OWFs, the total O&M costs are split over specific O&M disciplines. It starts with the breakdown of the operational expenditures (OPEX) (Figure 7-1).

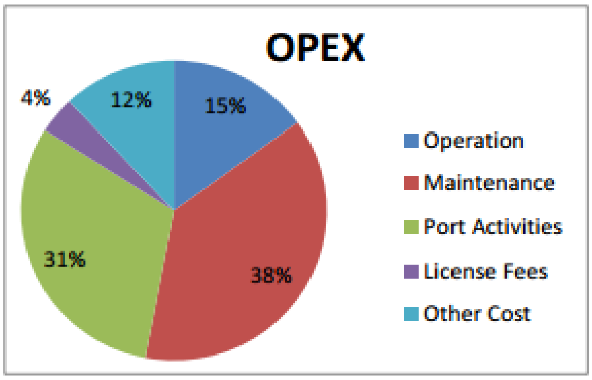

Figure 7-1. Breakdown of operational expenditures (OPEX) of an offshore wind farm, according to Board (2010).

This breakdown shows that the O&M costs represent 53% of the OPEX (15% "Operation" + 38% "Maintenance", figure 7.1). In the Asset Management Control (AMC) approach (Stavenuiter 2002) the discipline "Maintenance" is considered to be the combination of all technical, logistic, administrative and managerial actions during the life cycle of an asset/object, intended to retain the asset or restore it to a state, in which it can perform the required function. Therefore the activity "Port Activities" is considered a part of "Maintenance". For the UK's seabed, the Crown Estate applies license fees. However, this aspect is not applicable for the offshore wind industry in the Netherlands. For this reason the cost for license fees are also included under "Maintenance". "Other cost" which are not specified by Board (2010; Figure 7-1) are distributed among the O&M disciplines: 5% are placed under "Operation" and 7% under "Maintenance" since this discipline holds more variable and unspecified costs.

The next objective is to validate a realistic average annual O&M cost for offshore wind farms. For this purpose, a specific annual O&M cost analysis has been carried out. Figure 7-2 illustrates the spread of O&M cost, as applied in several reports (Board 2010, Feargal 2009, Pieterman et al. 2011, Kjeldsen 2009, Musial & Ram 2010, Rademakers & Braam 2002). The total annual O&M cost varies between 15 and 45 €/MWh. The cited reports do not mention the size of the wind farms, nor the distance to shore. It seems likely though, that these aspects have great influence on the O&M cost. An average (orange line in Figure 7-2) for O&M cost is determined at 30 €/MWh (€ 0,03 per kWh), by calculating a boxplot based on the middle 50%, omitting the maximum and minimum outliers, which are considered as unreliable or exceptional (Miedema 2012).

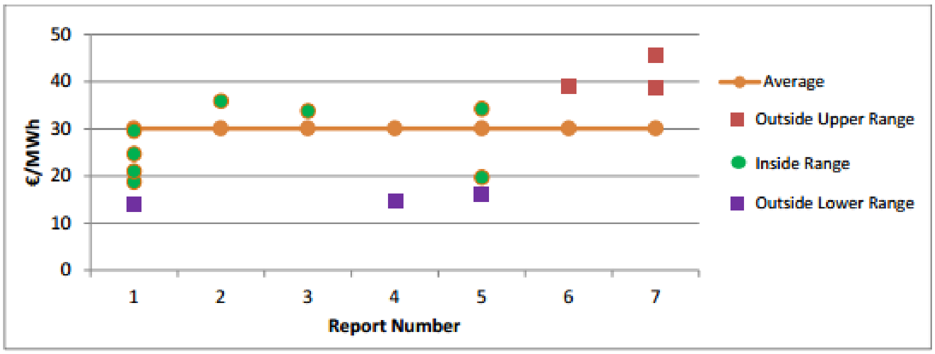

Figure 7-2. Spread of the O&M cost of offshore wind farms of seven different studies (Miedema 2012).

To identify possibilities for synergy, a more refined O&M OPEX distribution is necessary to identify activities which can be executed more efficiently by combining wind energy production and mussel farming. For this purpose we used a cost distribution (Table 7-1), as elaborated by Miedema (2012), according to the AMC approach (Stavenuiter 2002).

Table 7-1. Cost share (in % of total O&M costs) and explanation of the different O&M disciplines in the total life cycle management of offshore wind farms (Miedema 2012).

Operations [11%]	In this distribution 'Operations' purely deals with the primary process; by moving 3% to 'Life Cycle Management' (LCM) and 6% to 'Inspective Maintenance', 'Operations' (usually 20%; ref. fig. 7-2) is reduced to 11%.
Life Cycle Management [7%]	'Life Cycle Management' (LCM) is used for the benefit of both operations and maintenance. LCM takes care of maintenance schedules and planning (3%) and covers activities that are normally housed under 'Maintenance' (ref. fig. 7-2), thereby leading to a transfer of 4% from 'Maintenance' to 'LCM'.
Inspective [10%], Preventive [12%] Corrective [35%] Maintenance	The overall activity 'Maintenance' (usually 80%; ref. figure 7-2) is split up into three specific maintenance types and 'Improvement', which covers refit, overhauls and modification programs. 'Inspective Maintenance' is often seen as an operational activity or part of preventive maintenance. In this study it is recognized as a specific maintenance type with a total share of 10%, composed of 6% 'Operations' and 4% 'Maintenance' (ref. fig. 7-2). Although most studies apply a preventive/corrective maintenance ratio of app. 1:2, in this study it is this set at app. 1:3, because inspective maintenance is usually considered to be part of preventive maintenance. [49]
Improvement [25%]	Total O&M cost includes refits, major overhauls and modifications, to maintain optimal performance of the wind farm. With a total O&M cost distribution of 21 to 34 €/MWh, the share of 'Improvement' O&M is set at 25%. According to the Validation Team (2012), this is a realistic estimate.

Figure 7-3 presents a summary of the three consecutive approaches of allocating costs to the different operation and maintenance disciplines.

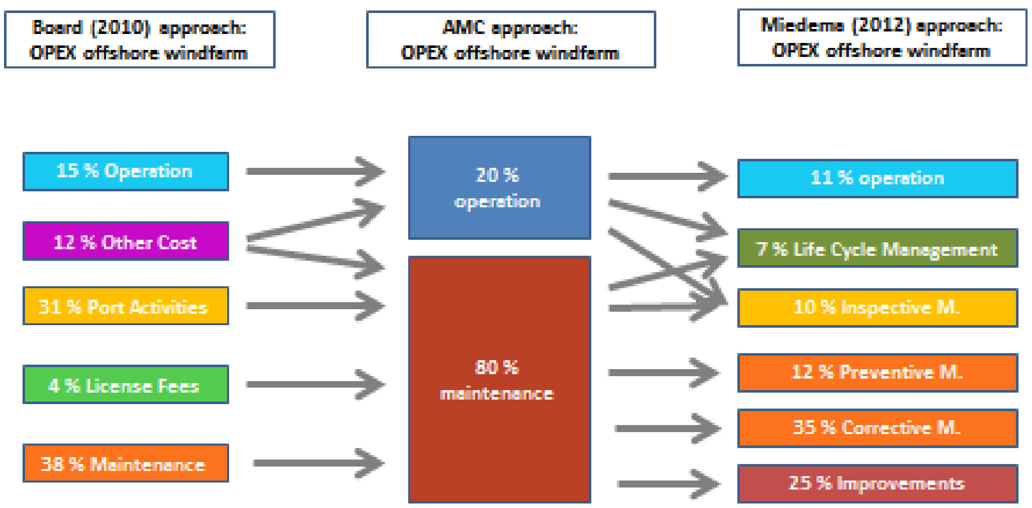

Figure 7-3. OPEX breakdown. Left: distribution according to Board (2010); right: distribution used in this study; adopted from DGAME (AMC Centre 2011).

49 According to Rademakers et al. (2003), the preventive maintenance cost dispersion is 3 to 6 €/MWh, where the corrective cost dispersion is 5 to 10 €/MWh.

7.2 Potential for synergy

To estimate the potential synergy through combining wind and mussel farming, the following assumptions apply[50]:

Operations & Life Cycle Management
For OWFs larger than 200MW, it is common to have a control room ashore, 24 hours and 7 days a week staffed by two to four people. In this study, the assumption is made that with little extra effort this team can also manage the mussel farm, if it is integrated in the wind farm environment.

Inspective, Preventive, Corrective Maintenance and Improvement Maintenance
Previous studies and practical experiences (Thomsen 2012) have shown that in general 50% of the charged maintenance labour are non-productive time because of waiting for e.g. specific certified personnel, transport opportunities, acceptable weather windows, adequate spares, tools and equipment. It is assumed that by combining wind energy and mussel production these 'lost hours' can be reduced to at least 25% of the charged maintenance labour. This means that, when the labour cost is 60% of the total O&M cost of a wind farm, a cost reduction of 15% is attainable.

To reduce the waiting time related to O&M of wind farms, and thus reduce O&M costs, , the project team has discussed several logistical opportunities for synergy. For example, when a multi-purpose ship sails out for a week to transport a maintenance crew to and from the wind turbines, it can inspect the longline-installations and/or harvest the mussels, while the crew is busy carrying out the maintenance work. When tasks are finished, the ship takes the crew on board again and brings the harvest ashore.

To achieve the pursued cost reductions, the following aspects of synergy are seen as prerequisites:

- Clusters of aquaculture integrated with, or between, clusters of wind turbines
- Combined Operations and Life Cycle Management
- Use of multi-purpose support vessels, capable to operate under significant wave-height conditions of up to 3 m
- Well-trained staff, capable to operate and maintain all installations
- No additional staff needed for the control room

The previously mentioned assumptions are expected to lead to an overall reduction of O&M costs by at least 10%. The following cost breakdown (in % of the total O&M cost of wind energy; see Table 7-1) is considered to be an adequate estimation for offshore mussel farming and the combination of offshore wind and mussel farming. The figures derived serve as set targets and baselines or references for a first analysis in the LCA model (Table 7-2).

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50 These assumptions were formulated and agreed on in an expert workshop consisting of Ramses Alma (AMC T&T), Nico Bolleman (Blue-H), Henk Braam (ECN), Wim de Goede (HVA), Ko Hartog (HVA), Bertrand van Leersum (ATO NH), Tom Obdam (ECN), Luc Rademakers (ECN), Hein Sabelis (Peterson), John Stavenuiter (AMC Centre) & Frans Veenstra (IMARES).

Table 7-2. Estimation of cost shares for wind farming when carried out singly and in combination with mussel farming, based on the expert workshop. Baseline (bl) is the O&M OPEX distribution according to Miedema (2010).

O&M Disciplines	Wind farming	Combination wind & mussel farming
Operations	11%	9%
Life Cycle Management	7%	6%
Inspective Maintenance	10%	9%
Preventive Maintenance	12%	11%
Corrective Maintenance	35%	32%
Improvement	25%	23%
Cost reduction	**-**	10%
Total	**100%**	**100%**

Although the cost breakdown for offshore wind farming is fairly well-founded, it must be taken into account that the estimations for combined wind and mussel farming are indicative and used as a first estimated baseline for running the AMC model.

7.3 Practical implementation of the virtual wind and mussel farm

An offshore Wind & Mussel Farm (W&MF) is a complex system which does not yet exist. Based on practical issues, availability of data, expert opinion, and consultation with and experience of relevant business partners (mussel sector), we focus on one scenario, or rather on one conceptual design that is currently recognized as the most feasible configuration because it is based on proven technology. We call it the '1,000x50,000 Cash Flow Farm' (Figure 7-4.).

It is a 1,000 MW wind farm, consisting of 5 clusters of 200 x 5 MW wind turbines, combined with a 50,000 ton/year mussel farm, consisting of 4 clusters with 1,800 longline systems, located between the 5 wind clusters and producing 50,000 tons of mussels per year in total. To minimize technical risks, the mussel farming longline systems are not detached to any of the wind turbine foundations; they are kept in place either by poles or gravity based anchors.

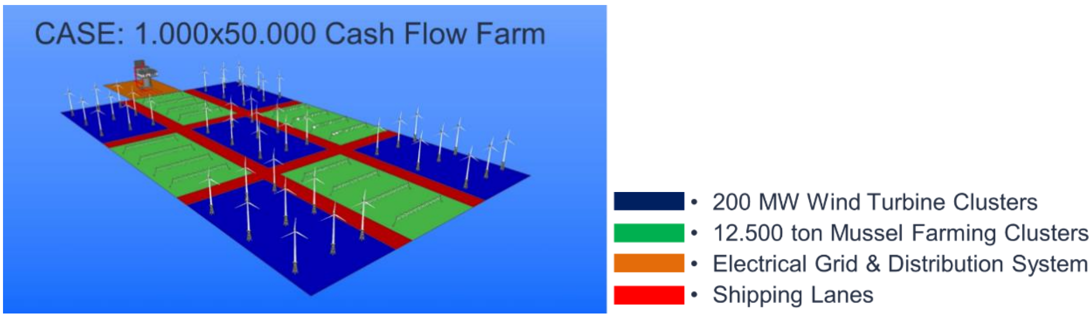


Figure 7-4. 'Cash Flow Farm' with a production capacity of 1,000 MW wind and 50,000 tons of mussels.

Since the analyses in this report are based on data derived from traditional offshore wind farms where turbines are lined up in rows, we also assume this type of arrangement for our W&MF. In the future, other – cost reducing – arrangements may be chosen to minimize wake effect losses.

Such effects that significantly reduce the mean wind speed as the wind flow passes through large wind farms, have been measured by satellite (being 8-9%; Christiansen & Hasager 2005) and modelled (e.g. Francesca Davidson[51]). Solutions under investigation are: controlling the pitch angle and the tip speed ratio of each one of the wind turbines.

Needless to say that more actors in the O&M process will lead to a more complex organization and more uncertainty and financial risk for the asset owner. A model that oversees all actors and processes, involved in the O&M of OWFs, will prove to be essential to determine the cost-effectiveness of the W&MF system over the design lifecycle. The results of our cost benefit analysis are presented in section 7.5.

In this desk study, a system approach is chosen that gives sufficient insight and at the same time is kept manageable. The prime operational functions, namely wind energy production and mussel farming, are the main components of the system identification diagram (see Figure 7-5). The diagram illustrates the two main systems, their support systems, and the system boundaries. The two main systems are supported by three support systems:

1. Operations & Maintenance System
2. Meteo & Nautical Navigation System
3. Transport System

The physical building blocks of the systems (dashed lines) are defined as 'functional packages'. The functions: power distribution onshore, mussel unload, factoring, and distribution, are not included because it is assumed that these (sub)systems are available in adequate capacity.

51 http://www.renewableenergyworld.com/rea/news/article/2013/10/next-generation-approaches-to-wind-turbine-wake-modeling

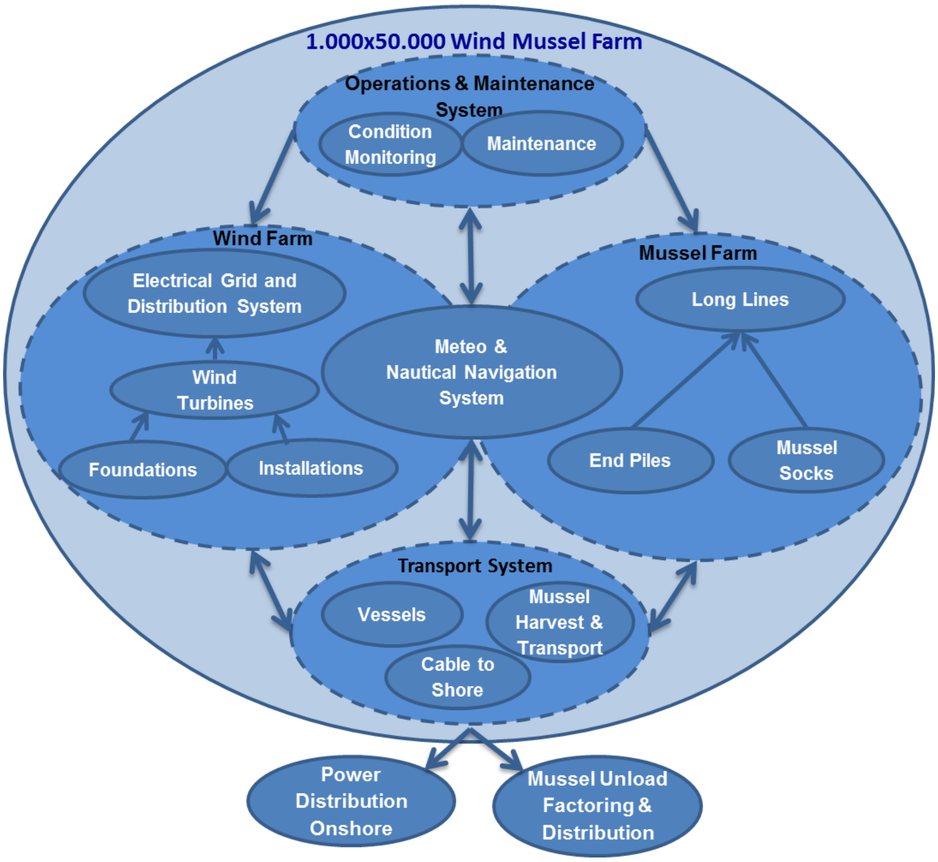


Figure 7-5. Wind & Mussel Farm (W&MF) system identification diagram.

Based on the identification diagram and our assumptions on how a W&MF system like this could be realized in the North Sea, the following physical concepts are worked out:

1. Wind & Mussel Farm outline
2. Operation and Wind farm clusters, including auxiliary systems
3. Auxiliary systems
4. Mussel farm clusters
5. Transport system
6. maintenance management system

Optional: economic input parameters can be added; please refer to Annex C.

Ad 1. Wind & Mussel Farm outline

The W&MF (Figure 7-6) exists of:

- 5 wind clusters of 10 x 4 km each, with 40 x 5 MW wind turbines
- mussel clusters of 10 x 4 km each, with 3 sub-clusters x 40 lanes x 15 systems = 1,800 mussel long line systems
- main shipping lanes of 1 km wide

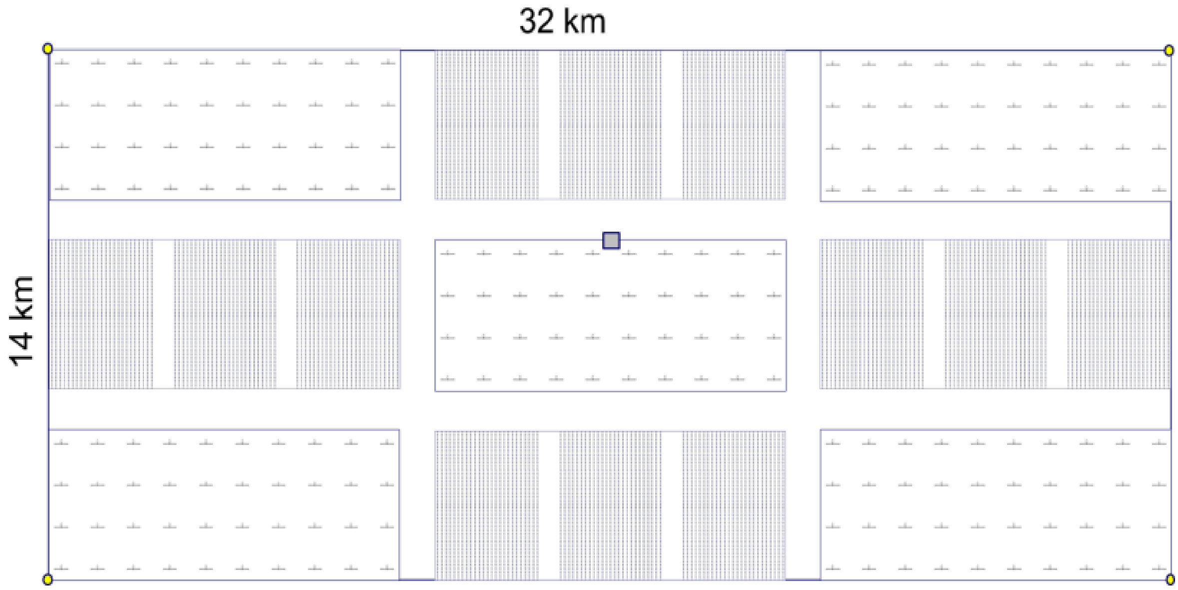


Figure 7-6. Wind & Mussel Farm (W&MF) outline.

The dimensions are determined by the design distance between the wind turbines of 3 km. The spacing should ensure that the wind turbines are minimally disturbed by one another (wake effects). For mussel farming on this scale, this size of farm area seems to be realistic to guaranty sufficient nutrients for feeding the mussels. The shipping lanes are considered necessary to provide an acceptable 'freedom to shipping'.

Ad 2. Wind farm clusters including auxiliary systems

The five wind farm clusters contain 40 wind turbines of 5 MW per cluster (Figure 7-7). Based on this configuration the most important auxiliary systems are defined (BVG Associates 2011):

- 5 x 50 km wind farm grid subsea cable
- 1 x wind farm sub-station;
- 4 x wind farm meteorological and navigation mast

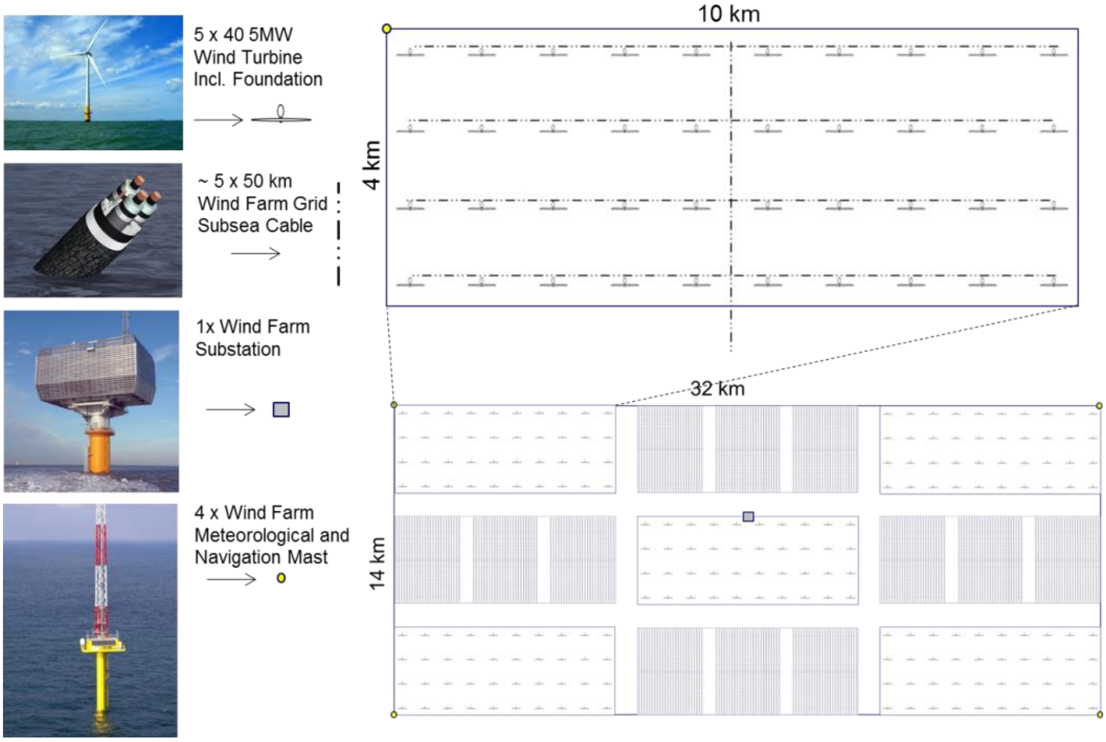


Figure 7-7. Wind farm including auxiliary systems.

Ad 3. Auxiliary systems

The auxiliary systems exist of the internal wind farm grid, the sub-station and the meteo and nautical navigation system. These systems are not further described, because they are considered to be based on proven technology.

Ad 4. Mussel farm clusters

Four mussel farm clusters are located in the virtual Wind & Mussel Farm. As illustrated in Figure 7-8, these mussel farm clusters contain:

- 1,800 mussel long line systems of 100 m and placed in lines of 4 km
- 150 m minimum wide shipping lanes between the long lines
- the long lines will be hold in place by poles or anchors

The expected yield of this configuration would be (Frans Veenstra & Machinefabriek Bakker; pers. comm.):

- 8-15 tons (1,000 kg) production of mussel per system per year
- 12,000-25,000 tons production per cluster per year

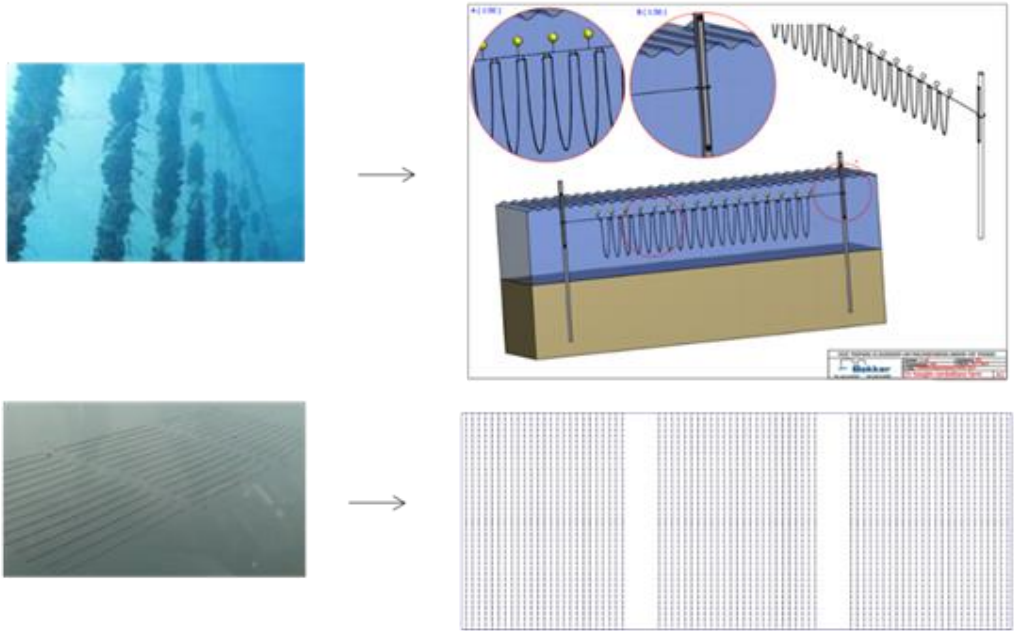


Figure 7-8. Mussel farm cluster outline.

Ad 5. Transport system

The transport system exists of:

- Subsea power cable sub-system
- Offshore wind and fish farming support ships
- Tooling and spares container support system
- Mussel harvest sub-systems

For further details regarding the transport system, refer to Annex E.

Ad 6. Operations & Maintenance management system

Finally, the Operations & Maintenance management system is determined. It is assumed that a farm of this size should be managed and controlled with an integrated information and communication system. For that reason, the newest Asset Management Control (AMC) concept in the field is adopted for this case (Van Leersum et al. 2010). This system is an integrated monitoring & control system over the value chain, called DOWES (Dutch Offshore Wind Energy System). DOWES is designed for managing optimal system performance. Figure 7-9 shows the management aspects it covers and the lay-out of the control room.

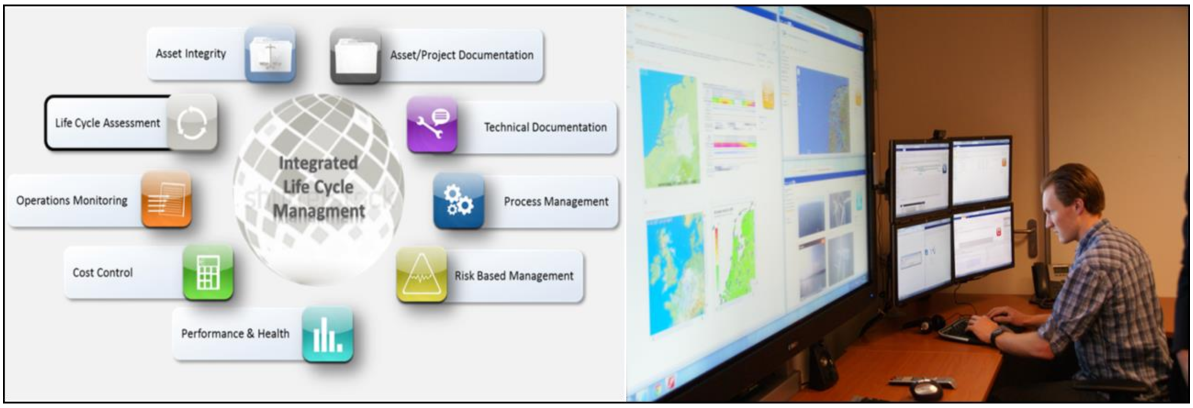


Figure 7-9. The O&M management system, based on DOWES (www.dowes.nl).

Based on the physical representation of the virtual Wind & Mussel Farm case, system configuration figures are determined (see Annex D). These figures are used as starting values for a first simulation run of an O&M period of twenty years, as described in section 7.3.1.

7.4 Asset Management Control (AMC) model

In this study an existing Asset Management Control (AMC) model (Stavenuiter 2002) is expanded/ elaborated, including the entities physical components, process activities and time periods (years). In order to perform the simulation runs the model has to meet the following requirements:

- the whole W&MF can be adapted by parameter settings (for long-term maintenance)
- benefits can be viewed by different parameters/key performance indicators
- different settings in O&M plans (maintenance strategies) are possible
- ups and downs in business, technical as well as economic, can be taken into account
- financial and technical balance sheets should be available per year
- price elasticity, or price changes in general, can be analyzed
- main results, such as revenues, system cost-effectiveness, market value, return on investment, over the exploitation phase, can be presented in charts

A synergy factor is introduced to model the synergy effects of combining wind and mussel farming. It is expressed as a percentage which indicates the extent to which the O&M cost of the wind farm can be reduced by more efficient use of labour, transport and equipment. For example: if the O&M cost of a wind farm is set at 100%, and it will be 95% if it is combined with a mussel farm, then the synergy factor, as defined, is 5%.

As already stated in section 4.3, and in particular in subsection 4.3.1, for offshore-aquaculture the location is the most important criterion for a successful combination with offshore wind. Previous studies have shown that the North Sea is a good habitat for mussels (section 4.2.2). Promising locations for a 1,000 MW wind farm in the North Sea seem to be Borssele, IImuiden-Ver and Schiermonnikoog. The model is based on average parameter settings, but can be tuned for specific locations.
The backbone of the AMC model used for our case, is a system model, called AMICO (Stavenuiter 2002), that is capable of modelling the physical system over the lifecycle, including a logistic process model per year period. A simplified representation of this LCA model is given in Annex D.

The AMC Blauwdruk model is based on these concepts, simulating and calculating the cost/performance parameters per year period. Within this model the following adjustments are possible per (sub)system:

1. total installed capacity
2. installed capacity per cluster
3. number of clusters
4. number of (critical) installations per system
5. initial realization investment
6. interest rate
7. inflation rate
8. farm yield coefficient
9. baseline ROI discount factor (average interest (%) on investment over the years)
10. O&M cost as % CAPEX
11. starting sales prices (in MWh for wind and kg for mussels)
12. sales price increasing rate (if calculations are 'fixed')
13. mussel farming cycles (1 to 4 year)

In this study, two O&M plans were developed: the Base O&M plan and the related retrofit & overhaul plan, which can be budgeted by a multiply factor, called the retrofit & overhaul factor. Settings that can be entered in the LCA model by the control panel (Figure 7-10), are:

- mussel farming & wind synergy factor active? (y/n)
- fixed calculations (y/n). If yes, no uncertainty simulations will be executed.
- multiyear maintenance (MYM) period (1 to 10 year)
- aquaculture & wind synergy factor, expressed as % of the wind farm O&M cost

Control Panel	
☐ Aqua & Wind Farm Synergy	
☑ Fixed Calculations	
7	Select Multi Year Maint. Period
0%	Synergy Factor
5	Retrofit & Overhaul Factor
Color Legend	
	Simulation Settings - Adjustable
	Asset Settings - Adjustable
	Game Settings - NON Adjustable

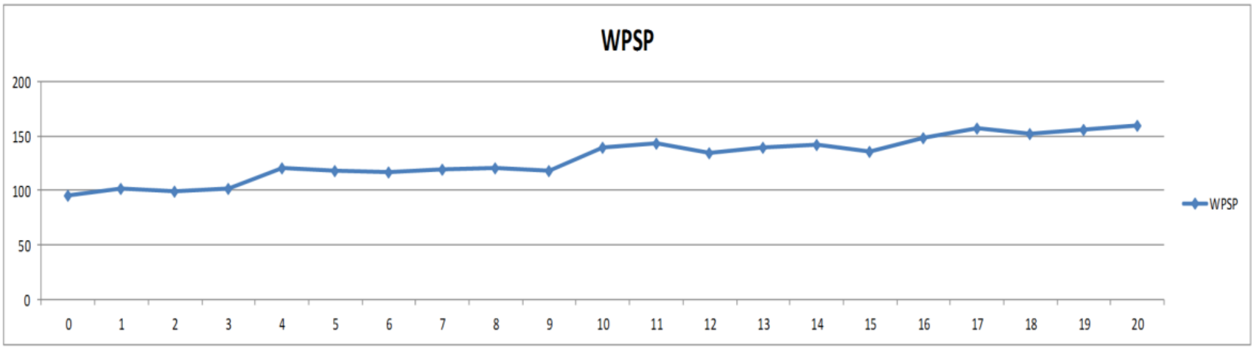
Life Cycle Data:	Wind Farm	Mussel	
Initial Realization Investment [k€]	2425000	200000	k€
Farm Yield Coefficient	40%	90%	%
ROI Discount Factor *Baseline*	8%	8%	%
Interest Rate	3%	3%	%
Inflation Rate	1%	1%	%
Starting Sales Price SP	95	0,6	€
Sales Price Fixed Increasing Rate	3%	3%	%
Number of Installations per Cluster	40	1800	
O&M Cost / (MW-kg)	0,25	0,1	€/(MW/kg)
Installed Capacity per Cluster	200	24000	MW/Tonne
Number of Clusters	5	4	.
Selected MYM Period	7		Yr
Mussel Farming Cycles	2		Yr
Fixed Calculations	Yes		.
Total Installed Capacity	1000	96000	

Figure 7-10. Cost/performance parameters to be adjusted.

In addition, several simulation parameters are included which may vary over the years and can be adjusted by the trend diagram parameters (e.g. fig. 7-11):

- wind power sales price developments
- mussel sales price developments
- operational excellence factor (simulates windfalls and setbacks in business)
- maintenance management control factor (simulates windfalls and setbacks in system failures, based on Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR).

To simulate price changes for the wind power sales price and mussel sales price, the prices can be adjusted by parameter setting of the trend diagram as shown in Figure 7-11. For the underlying formula please refer to Annex D-3.



Life Cycle	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
WPSP	95	101,52	99,42	101,78	120,76	118,66	117,58	119,27	120,96	118,39	139,26	143,42	134,48	139,32	141,58	136,39	148,10	156,94	151,87	155,90	159,76

Figure 7-11. Trend diagram of the 'simulated' wind power sales price developments.

The Operational Excellence Factor and the maintenance Management Control Factor are added to simulate windfalls and setbacks in O&M cost. The effect of these factors depends on aspects/variables such as the system effectiveness (farm condition), type of maintenance plan, but also the upper and lower limit, as set by the researcher, based on expert judgement and/or input from others. For this study, it is based on the research results of Miedema (2012).

For comparison purposes, a '**reference model**' is defined based on the following settings of the adjustable parameters/variables:

- interest rate: fixed on 4% (average based on economic development of the last 20 years)
- inflation rate: fixed on 3% (average based on economic development of the last 20 years)
- wind farm yield coefficient: fixed on 40% (average % of the theoretical maximum production, for offshore wind farms, taking in account; wind speed variation, planned and unplanned stops)
- baseline ROI discount factor: fixed on 8% (as average for investors, e.g. for low risk investments, like mortgage on houses, this is 4% (2014) and for high risk, like product development this could be 12% or more)

- O&M cost as % CAPEX (fixed per installation, between 0,5-15 %, see Annex D) starting wind power sales price: € 95,-/MWh (in year 2014, assumed to be a realistic figure derived from the current subsidy policy)
- starting mussel sales price: € 0,95/kg (in year 2014, assumed to be a realistic figure)
- sales price increasing rate: 3% (in line with the average inflation rate)
  from 2014 to 2033: wind power: 95,- to 172,- €/MWh; mussels: 0,95 to 1,1,72 €/kg
- mussel farming cycle: 2 years (based on figures as described in section 4.2.6 and Annex C)
- aquaculture & wind synergy factor active: no
- fixed calculations: yes (this means no random simulation effects, such as windfalls and setbacks in business, are taken into account)
- multiyear maintenance (MYM) period: 7 year
- operational excellence factor: fixed at 1 (this means no random simulation effects are taken into account)
- maintenance management control factor: fixed at 1 (this means no random simulation effects are taken into account)
- retrofit & overhaul factor: set at 5 times the cost of Base O&M (this means that the retrofit & overhaul (each 7 year) is estimated as 5 times more than the average yearly maintenance program

7.5 Results of the scenario analyses

According to the previously mentioned settings, first a 'reference' simulation run for the wind and mussel farm is performed. The results on ROI are shown in Figure 7-12.

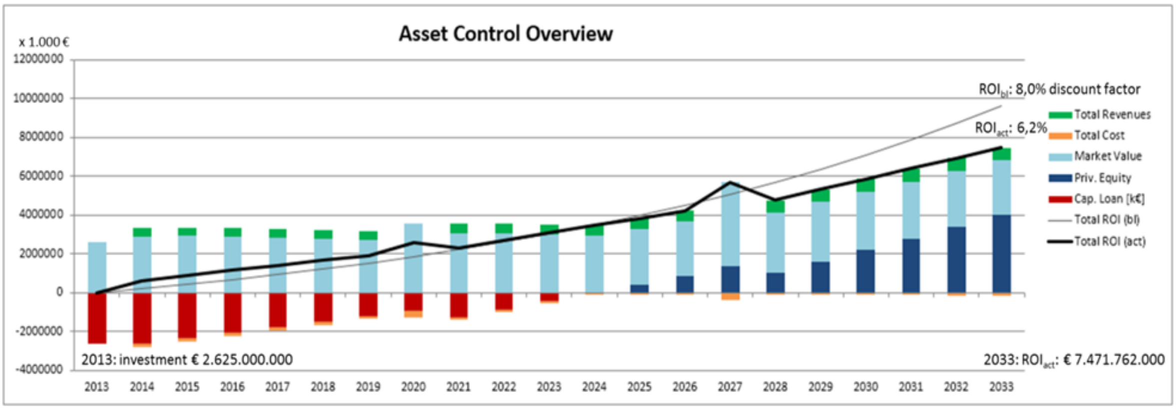


Figure 7-12. Expected ROI over 20 years O&M for the wind and mussel farm with reference settings.

The reference simulation run shows a ROI discount factor of 6.2%. This means that with these initial parameter settings, without windfalls and setbacks, the wind mussel farm investment will have an average interest of 6.2% over the years, which gives an actual ROI of € 7,47 billion over 20 years. Although 6.2% is lower than the 8% aimed for, it is decided to keep the initial (conservative) parameter settings in the next simulation runs.

Based on these results, four simulation runs are selected to demonstrate the possibilities of this dynamic AMC model and to show the synergy effect on wind farm O&M costs when the synergy factor (for cost reduction on O&M) is estimated at 10% (Paragraph 7.2). The type of simulations that have been performed, are visualized in Figure 7-13.

	Prosperous economic developments and windfalls in business	Disappointed economic developments and setbacks in business
No Synergy	Nr 1 LCA	Nr 3 LCA
10% Synergy	Nr 2 LCA	Nr 4 LCA

Figure 7-13. Situational context of the four simulations.

The 'key factor' results of each simulation are presented in Tabel 7-3.

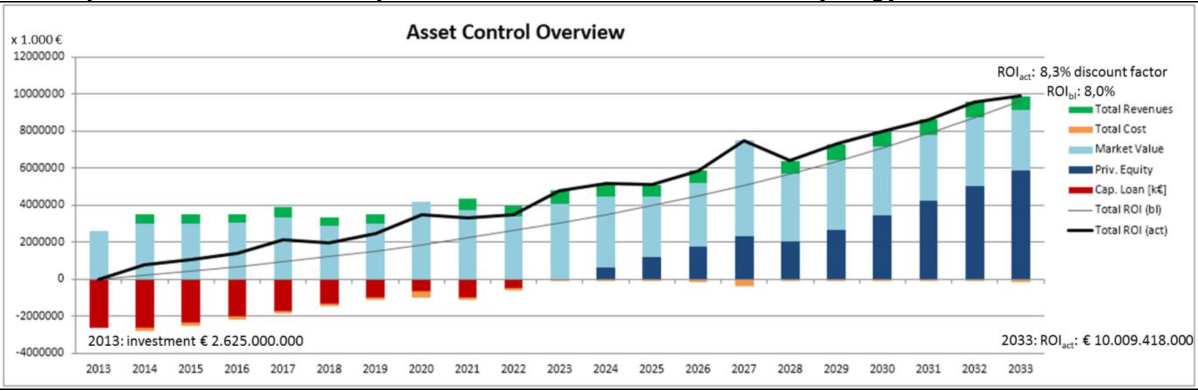
Table 7-3. Key factor results of the four simulation runs, compared to the reference model.

Key factor	**Reference**	**LCA – 1**	**LCA – 2**	**LCA - 3**	**LCA – 4**
ROI_{act} discount factor (baseline target: 8%)	5.7%	8.3%	9.6 %	4.9 %	5.5%
Wind power sales prices €/MWh	95->172	95->232	95->226	95->155	95->152
Mussel sales prices €/kg	0.95->1.72	0.95->1.96	0.95->1.91	0.95->1.53	0.95->1.55

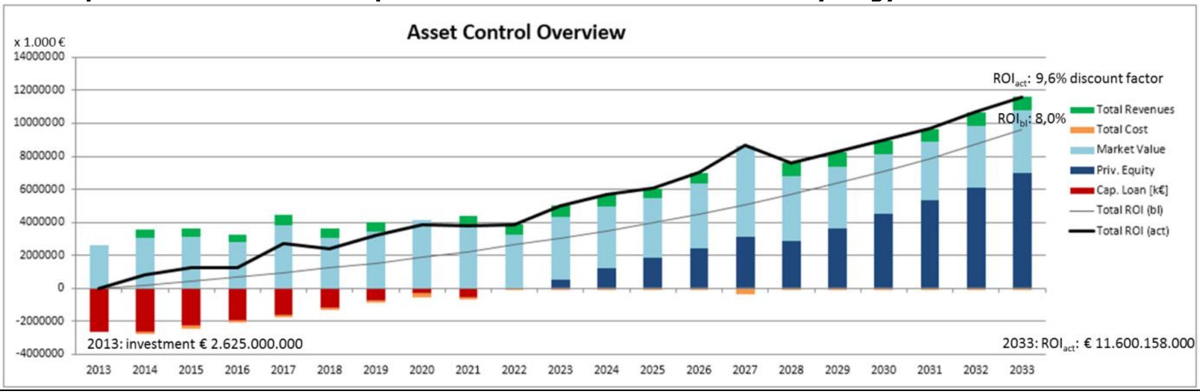
The results of the four simulations are visually presented in Figure 7-14.4. In all runs the external factors, related to the economic and geographical situation, were fixed at:

- interest rate: 4%
- inflation rate: 3%
- wind farm yield coefficient: 40%

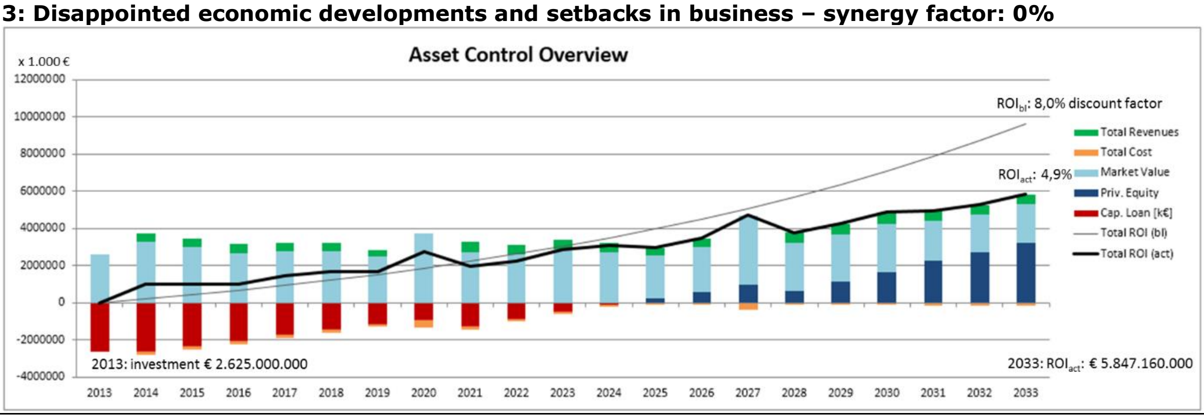
1: Prosperous economic developments and windfalls in business – synergy factor: 0%



2: Prosperous economic developments and windfalls in business – synergy factor: 10%



3: Disappointed economic developments and setbacks in business – synergy factor: 0%



4: Disappointed economic developments and setbacks in business – synergy factor: 10%

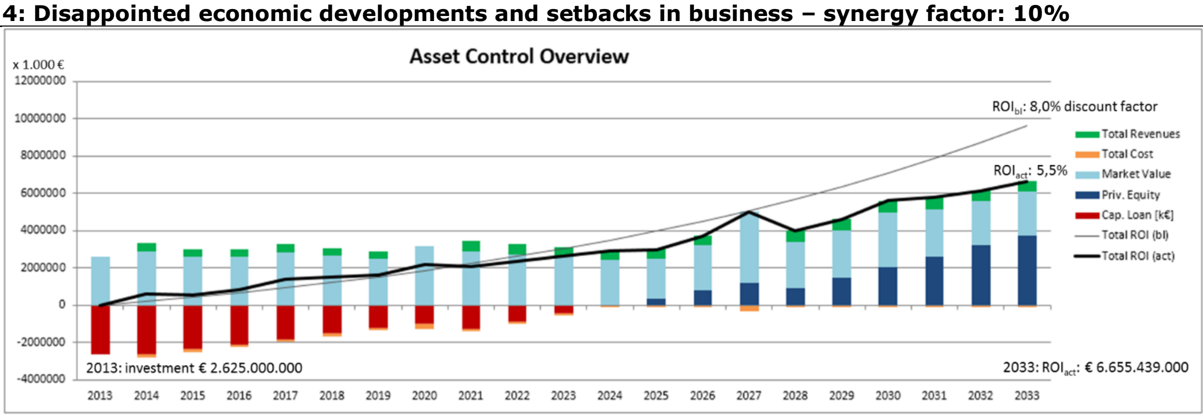


Figure 7-14. Results of the four AMC model simulations and assumed synergy factor (%).

Figure 7-14. shows the positive effect, when assuming a synergy effect of 10% reduction on the wind farm O&M cost, as expected. The interesting thing about this way of modeling is that the influence of synergy can be analyzed in more detail by modeling uncertainties (displayed as windfalls and setbacks). This can be based on situations such as:

- Mussel prices go up
- Wind power prices go down
- Technical setbacks cause higher mussel farm investments than anticipated
- Degradation of wind turbine performance is faster than expected

In the simulation runs above the potential improvement on ROI is demonstrated. They show an improvement of 12 to 16% on the ROI discount factor in disappointing and prosperous economic developments respectively.

With the dynamic AMC model it is possible to run an infinite amount of simulations. Screenshots, given in Annex D, show all the tables with data input and resulting charts, allowing for more in-depth-analyses.

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8 Conclusions, recommendations, perspectives and outlook

8.1 Conclusions

The main objective of the Blauwdruk project was to study the feasibility of the combination of offshore aquaculture with offshore wind energy production on the Dutch Continental Shelf. The focus was on installing large-scale mussel farming in the corridors within a (virtual) offshore wind farm that is arranged in several clusters.

First, the situation and perspectives of the relevant actors was investigated, and the following conclusions were drawn, based on the review of (scientific) publications and government documents:

- The Dutch marine spatial policy stresses two main principles: (1) the need for space-efficient use, such as multiple use of offshore platforms (e.g. offshore wind farms), and (2) the need to follow an ecosystem approach (cf. section 2.1).
- The wind energy sector committed itself to a substantial cost reduction of 40% of the total costs per MWh (cf. section 3.2.1). To achieve this, every discipline involved in offshore energy production is kept under constant review.
- The Dutch mussel sector sees market opportunities for a total yearly production of 100,000 tons of mussels; this is almost twice as much as the current production and can only be achieved if new areas for mussel production become available (cf. section 4).
- There are opportunities to achieve the different objectives of all actors (the government, the wind sector, and the mussel sector) by combining offshore wind energy production with offshore aquaculture.

Up to date, there is no offshore aquaculture in the North Sea. Based on desk research and experiences from other seas/oceans, the current ranking of the suitability of the different types of aquaculture in the North Sea is as follows (cf. chapter 4):

- Most promising are mussel culture and seed mussel culture. The production of mussels for consumption is especially promising in areas with low or absent spat fall.
- The Dutch Continental Shelf is too shallow for the fish cages currently used in fish cultures; therefore, commercial fish culture seems unviable at this moment. This takes away the principle basis for Integrated Multi Trophic Aquaculture (IMTA).
- It is currently not possible to assess the situation for seaweed culture due to unclear market conditions in terms of market value and market demand.

Undoubtedly, multi-use activities offshore do have an effect on (the assessment of) risks arising from (multiple) combined operational processes. The exact details of these operational processes are still unknown and thus cannot be taken into account yet. Looking purely at the risks of damage due to physical and chemical processes, it can be concluded from chapter 5 that risks are assessable and can be mitigated by taking appropriate measures:

- In a combined offshore-wind/aquaculture infrastructure the preferred foundation structure should be monopile or gravity based rather than a jacket type, because for monopile and gravity based foundations, the risk of high drag force (and hence of a potential collapse of the wind turbines) in case of a stuck aquaculture construction is much smaller than for a jacket foundation.
- Whenever aquaculture structures are physically attached to offshore wind foundations, the use of safety wires is highly recommended.

- Maintenance aspects of materials for both offshore wind and aquaculture constructions should be taken into account already in the design phase.
- Appropriate measures should be taken to protect aquaculture and offshore wind constructions from corrosion attack either by selection of corrosion resistant materials or by application of suitable protective coatings.
- Type and size of aquaculture activities determine the extent of effects on water and sediment quality. In turn, water and sediment quality determine effects on corrosion resistance of the materials used. This aspect should be dealt with in a dedicated risk assessment for the specific location.

Ecological effects and impacts of a W&MF can pose potential risks but also benefits to the marine ecosystem. It is difficult to summarize and weigh effects, because the different marine ecosystem components (plankton, seabed organisms, fish, marine mammals, seabirds and bats, and the entire ecosystem) may be affected differently by different pressures, and there is almost no scientific knowledge available on potential ecological impacts of the subject of our study: neither of wind farms in deeper offshore waters nor of large-scale offshore mussel farms, let alone the combination of both. Furthermore, potential effects in the construction phase of an offshore wind (and mussel) farm can differ from those in the operational phase. Below we highlight a few main points that are elaborated on in chapter 6.

Potential negative effects:

- During the construction phase, the sound produced by preparatory subsea works, and construction activities such as pile driving (wind farm) and vessel traffic (wind and/or mussel farm), can harm the marine environment. This refers particularly to underwater-noise disturbance of marine mammals. In general, the ecological impact of placing and anchoring longlines is minor as compared to the impact of founding wind turbines.
- During the operational phase, negative impacts can arise from the physical presence of the wind (and mussel) farm and increased shipping activities, potentially resulting in displacement of marine mammals and seabirds, continued disturbance of the seabed sediments and seabed communities underwater, and collision risks to birds and bats above water. Furthermore, operating wind turbines generate noise, create electromagnetic fields and introduce energy in the seafloor by the tower and via the subsea cables. These electromagnetic fields can have negative impacts on fish, fish eggs or larvae.
- Regarding offshore mussel farming on suspended longlines, the mechanical farming construction and the pure presence of the mussels can lead to a physical alteration of the marine environment, and of the hydro-sedimentary processes, in particular.
- Since constructions in general provide a good, sheltered habitat/substrate for invasive epibenthic species, there is an increased risk of introduction and settlement of unwanted invasive species and an additional increased potential barrier effect due to the more 'closed' construction when aquaculture and offshore wind are combined.

Potential beneficial effects:

- Offshore constructions represent new 'hard substrate' habitat under water, offering food and shelter, thus attracting sessile flora and fauna, thereby enhancing biological diversity, production, and creating (micro-)habitats where organisms may find shelter in addition to food. This new community may attract additional mobile species (small and large piscivores, seabirds, marine mammals).

- Potential beneficial ecological effects that could arise from the combination of an offshore wind and mussel farm (W&MF) are increased shelter. A W&MF potentially protects a greater range of marine species: those that use the wind farm as shelter and habitat (more or less by chance and not caught thanks to the absence of fisheries) and those attracted by the increased biomass/food availability and the type of environment.

In chapter 7, possibilities are identified to reduce operation and maintenance costs in a combined wind and mussel farm. It seems likely that an overall cost reduction of at least 10% is feasible.

Furthermore, running the Asset Management Control Model the return of investment (ROI) for four different scenarios was simulated. Based on the chosen economic parameter values and sales prices estimates, the model simulations show that a ROI of 4.9% should be possible in unfavourable economic conditions when synergy is absent. When 10% synergy can be achieved, a ROI of 5.5% seems possible. The ROI is significantly higher when economic conditions are favourable. Even when there is no synergy, a ROI of 8.3% should be feasible, and in case of 10% synergy the ROI is likely to reach 9.6%.

8.2 Perspectives and outlook

8.2.1 *Roadmap for implementation of offshore mussel culture*

The Blauwdruk project investigated the feasibility for successful development of offshore mussel production co-located with wind farm concessions on the Dutch Continental Shelf. To estimate the economic feasibility large-scale developments were simulated in prediction models. This scale was necessary in order to provide reliable estimates. Development and implementation will of course not be executed at this scale from the start, but rather a step-wise approach will be followed.

1) Design of a test site, and development of technology to support offshore aquaculture (technical design, characteristics of materials, technical test model)
2) Pilot projects should initially test technical feasibility of different systems preferably at multiple locations, both for mussel seed collection devices as well as for grow-out systems.
3) Carrying capacity determination, optimization of large scale farm layout, and development of an optimized production system should be addressed.
4) Stepwise upscaling of mussel production in accordance to a sustainable development (economic, environmental and technical).

Based on previous experiences we estimate that the development from pilot studies to full-scale commercial cultures will take approximately 8-10 years, under the condition that pilot studies result in positive perspectives for further development. The development may co-occur with seaweed production.

8.2.2 *The potential for seaweed*

Although the Blauwdruk project identified the highest potential for mussel culture in offshore areas on the Dutch Continental Shelf for the near future, there are high expectations for the use and production of seaweed. Worldwide seaweed is already used in many different food and health care products, but the quantity needed for those products is limited. In contrast, for plastic products or biofuel material, the quantity of seaweed needed is large and will most probably always be much higher than for food and health products. Hence, efficient large-scale grow and harvest methods need to be developed.

Selection of the right kind of seaweed species and processing techniques, and understanding the potential environmental impact of seaweed culture are the subjects of ongoing studies. The economic feasibility of using seaweed as raw materials for oil production in the Netherlands is lively debated. In short, there is consensus that seaweed will play a major role in a future bio-based economy.

The North Sea has a good potential for growing seaweed: enough space and sufficient nutrients. Potential local effects and potential effects on the entire system, however, are as yet unknown. Chapter 4 outlined that current predictions for technical cultivation, processing and market conditions are uncertain, having a large spread in their estimates, making it impossible to calculate reliable projections for the economic feasibility of large scale seaweed production. Research on seaweed cultivation and processing are however progressing quickly. In the near future it should be possible to clarify profitable business cases, following a similar procedure as applied for mussel cultivation presented in the current report. Hence, development and implementation of commercially viable offshore seaweed cultivation is expected to be a longer term development.

8.2.3 *Alternative small-scale aquaculture production approaches*

The Blauwdruk approach focused on (semi-)intensive offshore aquaculture production. Note, however, that initiatives for sea-ranging and small scale fisheries are recently being investigated in order to optimize spatial use within (the vicinity of) wind farms, such as:

- Integration of 'Building with Nature' approaches with wind farms, e.g. by growing oysters ("oyster skirt") around foundations to prevent scour
- Development of oyster beds for nature and production purposes
- Introduction of fisheries with "passive" fishing gear (such as rod, pots or longlines) within wind farm areas, as their risk impact on turbines is expected to be much lower
- Development of new fishing techniques aiming to establish sustainable fisheries within wind farm areas, with low risk for wind farm operations
- Sea-ranging and stock enhancement of lobsters, as the rocky section of turbine foundations make a good habitat for lobster settlement. Sea ranging of flat fish with or without additional feed sources
- Stock enhancement of fish (e.g. cod) by recruitment/ refugee structures and additional feed sources (sea ranging)

Natural habitat for ecological functions (refuge, nature development and spawning grounds). However, most of these initiatives are merely a theoretical idea or limited data is available. Neither economic predictions nor technical feasibility of these activities can therefore be projected yet. For an overview of existing practices, refer to Verhaeghe et al. (2011).

8.3 Recommendations

- Diversification of aquaculture species should eventually be pursued in order to optimize economic output. The market potential of seaweed should be further explored.
- The mitigation of physical and chemical processes that pose a risk to the constructions should be investigated.
- Monitoring research in a W&MF should be carried out to investigate the processes on ecosystem level and to assess whether potential negative ecological effects actually occur and in how far the risk of invasive species settlement is increased.

- In collaboration with all sectors involved, it should be investigated in more detail how operational processes in a multi-use setting can look like, thus enabling us to accurately quantify potential synergy benefits. Only then will we be able to assess the reliability of our input values and the robustness of the model results.
- Because of the uncertainties regarding the possibilities, risks and benefits, we recommend a stepwise learning-by-doing approach with small-scale pilot projects, instead of a large-scale implementation from the start.

8.4 References

Verhaeghe, D, Delbare, D & Polet, H 2011. Haalbaarheidsstudie: passieve visserij en maricultuur binnen de Vlaamse windmolenparken ?. ILVO-mededeling, no. 99, Instituut voor Landbouw- en Visserijonderzoek – ILVO.

9 Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

Justification

Report Number: C056/14
Project Number: 4305106902

The scientific quality of this report has been peer reviewed by a colleague scientist and the head of the department of IMARES.

Approved: Prof. Dr. H.J. Lindeboom (Marine Ecologist)
Science Director

Signature:

Date: 28 August 2014

Approved: Drs. F.C. Groenendijk
Head of Maritime Department

Signature:

Date: 28 August 2014

Blauwdruk final report – List of Annexes

Annex A – Additional electronic links

Annex B – Mussel culture parameter overview

Annex C – Economic simulation aquaculture offshore

Annex D – Business case simulation parameter overview

Annex E – Transport system details

Annex F – Life Cycle Assessment Model – simplified

Annex A – Additional electronic links

Further reading/ links related to offshore wind energy production:

http://chriswestraconsulting.nl/expertise/offshore/ ontwikkling, expertise en onderhoud,ecologie

http://www.we-at-sea.org/ Het doel van de activiteiten van We@Sea is vanuit een onafhankelijke positie informatie te geven over schone energie van zee, met een sterke focus op offshore windenergie.

http://www.nwea.nl/de-nederlandse-offshore-windsector De offshore windindustrie beslaat de totale keten van het ontwerpen, bouwen en exploiteren van offshore windparken. Zo heeft Nederland binnen haar landsgrenzen internationaal leidende bedrijven, van energieproducent tot mariene aannemer, van fundatiebouwer tot kabellegger en van onderzoeksinstituut tot onderhoudsspecialist.

http://www.nwea.nl/greendeal Doel van de Green Deal Offshore Windenergie is tussen nu en 2020 de kostprijs van offshore wind met minimaal 40% omlaag te brengen

http://www.4coffshore.com/ the leading source of independent, accurate global windfarms and grid installations

http://flow-offshore.nl/ innovatie voor concurrerende Nederlandse offshore windindustrie

http://www.dowes.nl/?id=7 Het Dutch Offshore Wind Energy Services (D OWES) project is gericht op de ontwikkeling van een innovatief ICT systeem waarmee offshore windparken optimaal beheerd kunnen worden.

http://sciencecentre.amccentre.nl/pagina.aspx?site=3&lang=nl&pagina=25&type=p the Simulation Portal (DGAME) uses O&M Year Scenarios to let the user determine the Operation & Maintenance approach of the Wind Farm for the selected years. The ultimate goal of this research is to generate a more realistic simulation. For this reason the O&M Year Scenarios has to be validated.

http://www.renewableenergyworld.com/rea/news/article/2011/09/offshore-wind-targets-cheaper-o-m Several companies are seeking ways to trim the hefty slice of offshore wind farms' electricity costs contributed by operation and maintenance (O&M

http://www.ato.nl/db/WAS50c1f0ccc5a87/Ecofys_6_dec_2012.pdf Reducing the Cost of Offshore O&M (ATO, Ecofys)

http://www.ecn.nl/docs/library/report/2007/m07045.pdf ECN estimating costs of operation and maintenance of offshore windfaerms

TNO rapport, 2008-D-R1048/A aquacultuur op open zee, 28 oktober 2008;drs th.a.M.Reijs, M.Poelman, MsC,IMARES, e.o.

http://www.aqua.dtu.dk/English/Research/Aquaculture.aspx research that covers a wide range of biological and technological aspects of aquaculture.

http://www.awi.de/de/forschung/neue_technologien/marine_aquaculture_maritime_technologies_and_iczm/research_themes/marine_aquaculture/offshore_aquaculture/ Caused by the strong natural fluctuation of recruitment of mussels (Mytilus edulis) during the last years, research commenced in 2000 to assess whether suspended culture technique could be deployed to collect and culture seed mussels on a commercially stable basis under the exposed conditions of the North Sea

Annex B – Mussel culture parameter overview

Table Annex B-1. Characteristics of a fictional mussel production farm (40.000 ton) in the Dutch North Sea, integrated in a wind farm.

Principles/ Baseline assumptions		
Production ambition (tons per year)	50,000	Tons per year
Production ambition (kg)	50,000,000	kg
Clusters of mussel farms in wind farms	4	pieces
Dimension cluster	4000	Ha per cluster
Productivity of mussel system	3-10	kg m^{-1} rope
System density	5	systems ha^{-1}
Estimated cost price systems	15000	euro $system^{-1}$
Production $system^{-1}$ – Singel lines	30	ton $system^{-1}$
Production $system^{-1}$ – Double lines	60	ton $system^{-1}$
Production $system^{-1}$	17	ton $system^{-1}$
Production $system^{-1}$	16	ton $system^{-1}$
Number systems	2388	calculated
Required surface area per system	20x100	m
Dimension system	2x100	m
System density	5	minimum pieces ha^{-1}
Required hectares	478	minimum # ha
Growth period spat	4-6	months
Growth period ‘grow out mussels’	10-12	months
Growth period consumption mussels	18-24	months
Maximum cost price spat	0.3	Euro
Maximum cost price ‘grow out mussels’	0.55	Euro
Maximum cost price consumption mussels	0.7	Euro

Table Annex B-2. Overview of the characteristics of Seed Mussel Capture devices in the Wadden Sea. Data used is only for longline systems, which were deployed in the Wadden Sea in 2012 (Data sourced from Van Stralen, 2013)

Data SMC WaddenSea 2012	
427.0	systems
95.0	ha used
4.5	systems ha^{-1}
2432.0	km longlines
5.7	km $system^{-1}$
25.6	km longlines ha^{-1}
2.8	kg m^{-1}
71.7	ton ha^{-1}
15.9	ton $system^{-1}$

NOTE:

*To harvest 50.000 ton mussels per year in 50 weeks of 5 working days with a working window of 95% requires an average day production of 50.000/(50*5*0,95)= 210 ton. This is 210/24= 8,7 ton/hr. Based on this approximation, it is assumed that 2 modified mussel harvest systems, as described below, with a capacity of 5 tons/hr each (ref.: Bakker Yerseke) are sufficient. This means that a minimum of 2 ships are needed. In that case also the cargo holds of 600 ton per ship will be sufficient to keep the average week production of 1.050 ton.*

Annex C - Economic simulation aquaculture offshore

This annex contributes to the economic feasibility study. The study examines how the vacant space in an offshore wind park is best used, taking different production options into account. Emphasis is on the spatial distribution. We examine how to allocate space, aimed at optimal profit. Also, several sensitivity analyses were done to examine the effects on changes in input parameters.

i. Model description

We used a simple linear optimization model, maximizing total net profit of the use of vacant space. We study three possible activities:

- do nothing
- grow mussels
- grow seaweed

The total net profit of activity j is defined as the revenue minus the total cost.

$$\max \sum_j profit_j = \sum_j \left(revenue_j - TotCost_j\right)$$

Both the cost and the revenue are assumed to be linearly related to the assigned space for the activity. Thus if double the space is assigned to a certain activity, both the costs and the revenue are doubled. The revenue is determined as the price (p) times the production (q) in tons per ha times the amount of ha that is assigned to the activity (space).

$$Revenue_j = p_j * q_j * space_j$$

The total cost of activity j is defined as the assigned space for the activity times the sum of all fixed and variable costs, i.e. fixed cost per ha (cs_{fixed}), repair costs per ha (cs_{repair}), transport costs per ha (CS_{trans}), labour cost per ha (CS_{lab}), material cost per ha (CS_{mat}), all other variable costs per ha (CS_{other}).

$$TotCost_j = \left(cs_{fixed} + cs_{repair} + cs_{trans} + cs_{lab} + cs_{mat} + cs_{other}\right) * space_j$$

The total space used by the activities cannot exceed the total available vacant space (TotalSpace).

$$\sum_j space_j \leq TotalSpace$$

Mussel and seaweed prices are based on the prices of the baseline year (p_{base}) adjusted with a price elasticity (elas). For simplicity, we exclude external price variations during the year (1 and the same price for the entire year), assuming that the aquaculture production of the activity in question outside of the windmill farms stays constant at level q_{base}.

$$p_j = p_{base} * \left[\frac{q_j + q_{base}}{q_{base}}\right]^{-elas_j}$$

One of the possible activities studied is the option of doing nothing with the vacant space. This option is included because if both mussels and seaweed provide a loss it would be less costly to do nothing then to start aquaculture within the vacant space. However it is plausible to assume that there are some synergies between aquaculture and wind farms, especially in transport costs and labour cost. This means that labour cost and transport cost for wind farms will be lower if aquaculture is implemented in the vacant space. This is because such costs can be partly shared with the aquaculture activity. Therefor it is important to note that doing nothing will not mean making zero profit. By choosing to not include an aquaculture activity in the vacant space, the transport cost and the labour costs can no longer be shared with the aquaculture activity. Therefore, without any combined use, a wind farm will not synergy with another sector, and hence, these costs will just remain the same. With a multi-use combination, such costs are assumed to be reduced for the wind farm operator. Thus, doing nothing (no multi-use) means higher O&M cost for the wind farm operators, and lower profit.

ii. Model input parameters

Basic assumptions

In developing the optimization model, we have used the following assumptions:

- Construction of the wind park is a given; this is not part of the optimisation. Instead, we analyse what kind of co-production is most feasible, in three scenarios.
- As point of departure, we assume that both wind farm and aquaculture are of the same owner. There are no transaction costs assumed for between the two activities.
- When looking for synergy between the different functions, we now assume that the construction are not co-used. Although this is described in some researches, we believe that at this stage, there is insufficient knowledge about the risk and opportunities of this.
- Synergy is expected in the labour, harvesting and transport. We do not describe how synergy between offshore wind energy and marine production can be realized in detail (see chapter 7.2).

Mussels

In Dutch aquaculture, mussel production is the dominant activity with highest revenues and profits. Mussel culture is concentrated in Zeeland and the Wadden area. Around 50 companies are actively involved, producing around 50 million kg of mussels annually during the last years. In 2011, turnover of the sector was €56M, employing 170 FTE. EBIT was ca. €19M (STECF, 2013). Market expansion is difficult, although there is a reported additional market demand of 50,000 tons.

The production of mussels (in tons) has declined quite a lot since 1996. In 1996 92,000 tons of mussels were produced. In 2009 the production was only 46,000 tons, a decline of almost 50%. One of the reasons is a shortage of spat due to environmental restrictions on the catch of wild spat and a natural shortage of spat in the areas where catches are still allowed. The current dominant production practice for mussels is under pressure. Mussel spat is collected in the Wadden Sea by bottom trawling. The collected spat is attached to longlines in sheltered waters (Eastern Scheldt, Wadden Sea) where it grows into consumption mussels. If proper size is reached, the mussels are harvested and, dependent on market demand sold or “stored” in the Eastern Scheldt. Concerns about the ecological effects of bottom trawling have led to increased uncertainty about the availability of mussel spat.

In recent years, the mussel sector has experimented with alternative collection methods. So called Seed Mussel Collectors (SMC[52]), using long lines that float in the Wadden Sea, have proven successful. Experiences with on-sea mussel spat collection in the Wadden Sea have shown the technical and economic feasibility (Van Stralen, 2012, 2013).To increase mussel spat collection, the sector has to look for ways to collect mussel spat and produce consumption mussels outside the Wadden Sea. Offshore production can directly fulfil a market need, with an estimated annual value of 50M€.

Experiences with MZI can be used to gather data on the potential of offshore mussel production and estimation of costs. Drawing on information from Buck et al (2010), Van Stralen 2013 and Machinefabriek Bakker (2013), we came to the data on costs and benefits of mussel production. The envisioned production system consists of long lines systems. Each hectare contains 5 systems. The lifespan of the system is set at 4 years.

Seaweed

Currently, seaweed is not farmed at a significant scale in the North Sea. Tropical experiences with marine and brackish water seaweed cultivation are not comparable to seaweed farming in marine temperate waters like the North Sea. Various research projects investigate if and how seaweed farming is possible in marine temperate waters including the North Sea. Little is known about the costs of seaweed production. Some recent publications give indications of total expected costs but do not break-down expenses (Reith et al, 2005, Florentinus et al, 2008). Our analysis uses various publications to construct a breakdown of the total production costs for offshore seaweed.

In the Netherlands there are two on-going research projects experimenting with offshore seaweed cultivation, using either net cultivation or long-line systems. Information about costs and yields are unavailable. However, we do know that the system is labour-intensive as the seedlings need to be attached to the rope manually and capital-intensive). A third Dutch research project (Wierderij) makes use of a similar production method but applies this method near-shore. Based on the experiences within this project the required technology and expected costs can be estimated. The estimated total investments are in the order of € 25,000 to € 75,000 per ha. This includes 10 km of long-lines, (€ 1/m), buoys, mooring and employment. The expected lifespan is 10 years (pers. Comm. Brandenburg). For offshore application, we choose to double expected investment costs. Additionally, new ropes with seaweed seedlings have to be added each growth cycle (year) with an expected costs of € 1/m (1 meters rope + 1 seedling). Estimates for labour costs are unavailable.

Estimation of the labour costs is difficult since the procedures for production, monitoring and harvesting are not yet established. It can be argued that labour cost during operation and maintenance are relatively small. We assume that operation and maintenance of a 1,000 ha sea farm requires four man years of work (4*261 days*8h = 8,351 hours). This would require production process mechanisation and usage of distance, online monitoring. At labour costs of € 35/hr. total labour costs are set at € 292,320.This equals approximately € 300 per hectare per year.

Based on Lenstra et al (2011), we assume harvesting costs of €104 per ton DM. Reith et al (2005) draw upon Suurs (2002) and Hamelinck et al (2008) to calculate costs for transport of seaweed.

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52 In Dutch: MZI = mosselzaad invanginstallatie)

Assuming that the harvesting and transport involves 200km of transport movements, total costs for transport are expected to equal ca . €4 per ton fresh seaweed. Of this, €3.2 are spent on loading and unloading and ca €0.8 for actual transport. This equal €33 per ton dry matter.

The expected yield of seaweed cultivation in 20 ton DM per hectare. When it comes to the expected revenues, there is discussion on potential applications of seaweed and market prices. There are various promising high value applications of seaweed, such as direct consumption and production of pharmaceuticals but there are not established markets for these products from North Sea seaweeds yet. The most common application of seaweed is the production of alginates and thickeners which offers lower value. Dependent on the foreseen use of seaweeds, market values range between €210 and €5,000 per ton DM (van den Burg et al, 2013). In modelling, we are cautious to include high value but not yet proven applications and thus set the expected price at €210 per ton DM (€0.21 per kg).

Overview of input parameters

Based on the discussion above, the following input parameters were formulated:

Variable	Description	Seaweed	Mussels	Wind farm
fxc_share(sector)	Fixed costs (per ha)	10,000	24,671	0
labc_share(sector)	Labour costs (per ha)	1,132	1,489	759
transc_share(sector)	Transport costs (per ha)	2,080	3,306	429
matc_share(sector)	Material costs (per ha)	13,000	0	0
repc_share(sector)	Repair costs (per ha)	18	533	0
otherc_share(sector)	Other costs (per ha)	508	267	-71
price(sector)	Price (per kg)	0.21	0.95	0
prod_share	Yield (kg per ha)	20,000	42,500	0
windfarm	Available area (ha)	4,000	4,000	4000

iii. Model simulation results

The model simulations show that it is most profitable to attribute all the vacant space to mussel production. Given the estimated costs, price and production of the three activities, as presented in the previous paragraph, the overall profit to be made is €38 million for 4000 ha attributed to mussel production. Due to the increased production of mussels the price of mussels is expected to decline slightly to €0.94 per kg. Seaweed is not profitable; based on the input data formulated above, seaweed production would make a loss of €22,000 per ha.

Variable	Unit	Mussels	Seaweed
Total space	Ha	4,000	
Total production	Ton	170,000,000	0
Average price	€/kg	0.94	0.21
Revenue (production * price)	€	159,276,582	0
Total fixed costs	€	98,684,211	0
Total repair and maintenance cost	€	2,132,479	0
Total labour costs	€	5,957,895	0
Total transport costs	€	13,224,015	0
Total other cost	€	1,066,239	0
Total profit	€	38,211,744	0

iv. Sensitivity analysis

The previous results are positive; the data concludes that mussel production is very profitable and that seaweeds have low market value. However, since offshore cultivation of mussels nor seaweed is established practice in the North Sea, there is uncertainty about some of the input parameters. The questions is how sensitive these results are for changes in the base data. Sensitivity analysis is done to shed light on the economic consequences of the following changes:
Changes relevant for mussels

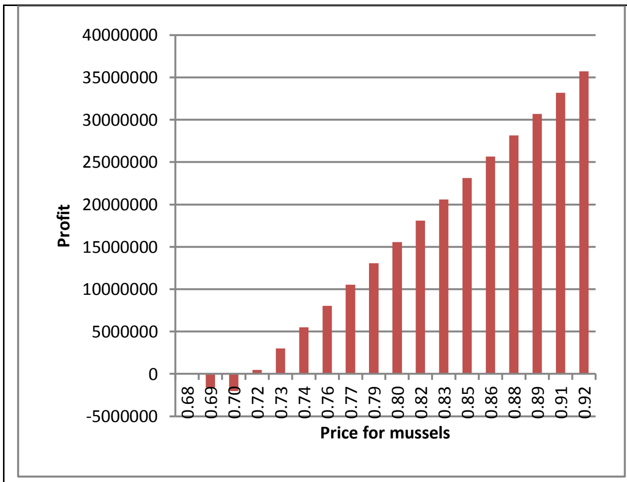
- lower base price mussels
- Lower yield mussels
- Higher cost for mussel production

Changes relevant for seaweed:

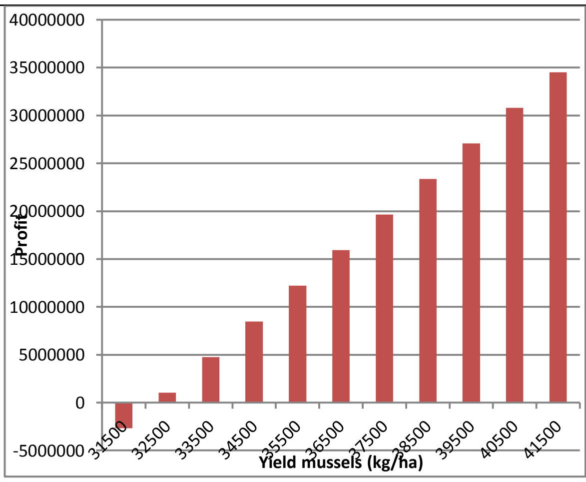
- Higher base price seaweed
- High possible production seaweed

Changes in price, yield and value, related to mussels
Figure Annex C-1 shows the expected profit assuming that the price for mussels is lower than the price assumed in the base data. If the price of mussels drops below €0.70 per kg then growing mussels is no longer profitable. In this case it become optimal to leave the vacant space empty. This means that as long as the baseline price does not drop with more than 25%, growing mussels within the windmill park will be profitable (given that all the othe igure 7-1r variables are estimated correctly).
In the baseline scenario it is assumed that 42.5 tons of mussels can be grown on 1 ha. Figure Annex C-1 shows what would happen with the profit if this figure is optimistic. If the possible production would drop to 30.5 tons per ha, mussel production would no longer be economically viable.

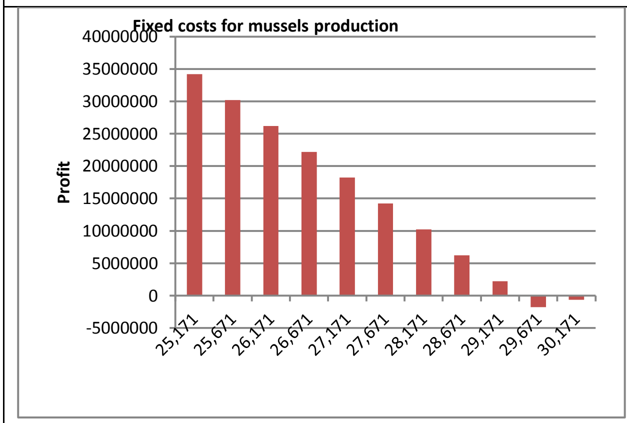
This means that as long as the production is no overestimated by more than 26%, mussel production is profitable on windmill farms.
Figure Annex C-1 also shows the sensitivity of the results for the assumption concerning the 2 most important cost categories: fixed costs and transport costs. Fixed costs could increase from 24,000 to 31,000 before mussel production is no longer profitable, an increase of 22%. The transport cost could increase from 3300 to 14,500 before mussel production is no longer profitable, an increase of 255%.



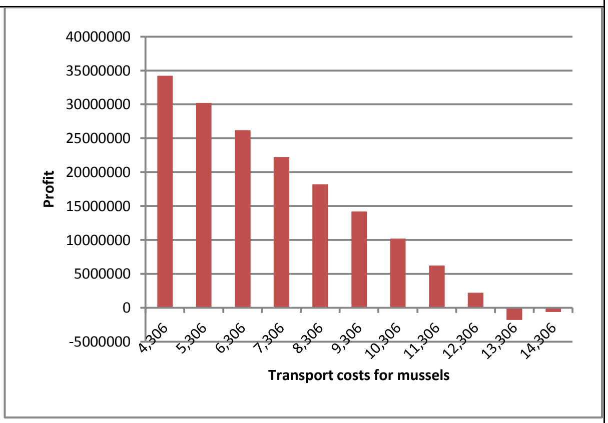
Effect of higher prices for mussels



Effect of lower yield (kg per ha) on profitability



Effect of higher fixed costs for mussels production on profitability

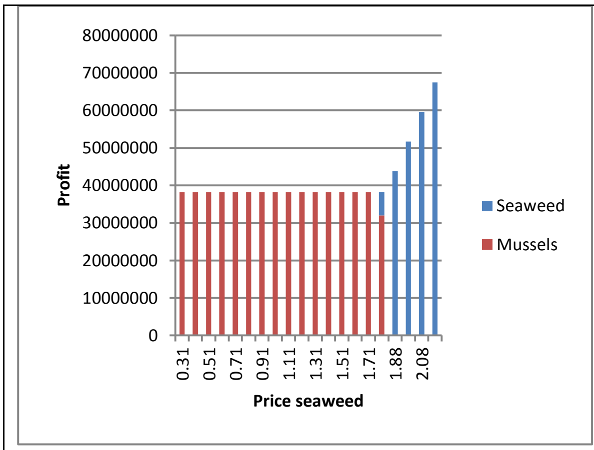


Effect of higher transport cost mussels of profitability

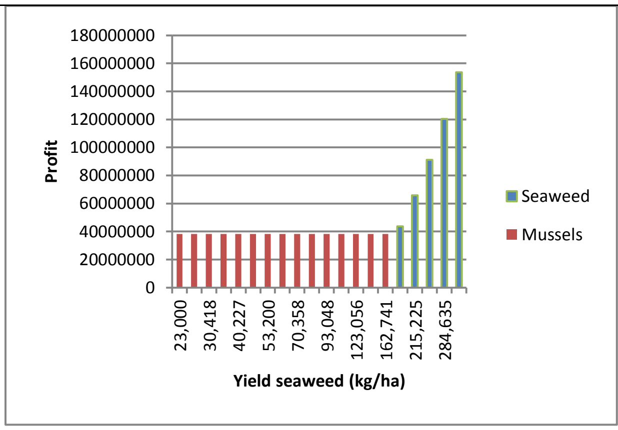
Figure Annex C-1. Sensitivity to changes in price, yield and costs.

Changes in seaweed price and yield
The production of seaweed is not viable in terms of profitability. Figure Annex C-2 shows how much the price of seaweed needs to increase to become more profitable than mussel production. The results show that with a price of €1.88/kg seaweed production is more profitable than mussel production. This means that the price of seaweed needs to increase by at least 790% before seaweed production becomes as profitable as mussel production.

In the base case it is assumed that 20 ton of seaweed can be grown on 1ha. Figure Annex C-2 shows how much the production per ha needs to increase for seaweed to become more profitable than mussels. The production per ha needs to increase from 20 ton to 187 ton per ha to become more profitable then mussels. This is an increase of slightly more than 700%.



Effect of changes in the seaweed price



Effect of changes in the seaweed yield

Figure Annex C-2. Sensitivity to changes in seaweed price and yield.

v. Conclusions

The economic model and sensitivity analysis shows the following results. On the basis of input parameters defined, mussel within wind farms can bring an expected additional profit of ca. €38 million. Seaweed production is not profitable with current seaweed prices. The sensitivity analysis shows that prices and yields of mussel production can be lower quite a bit (both ca. 25%), without making losses. Seaweeds offer low value although there is discussion and research on higher value applications. The total market value for seaweeds would have to rise above €1,88 per kg, (€1.880,- per ton) to be profitable. The economic analysis shows us that mussel production is the most promising co-use within the offshore wind parks.

References to Annex C

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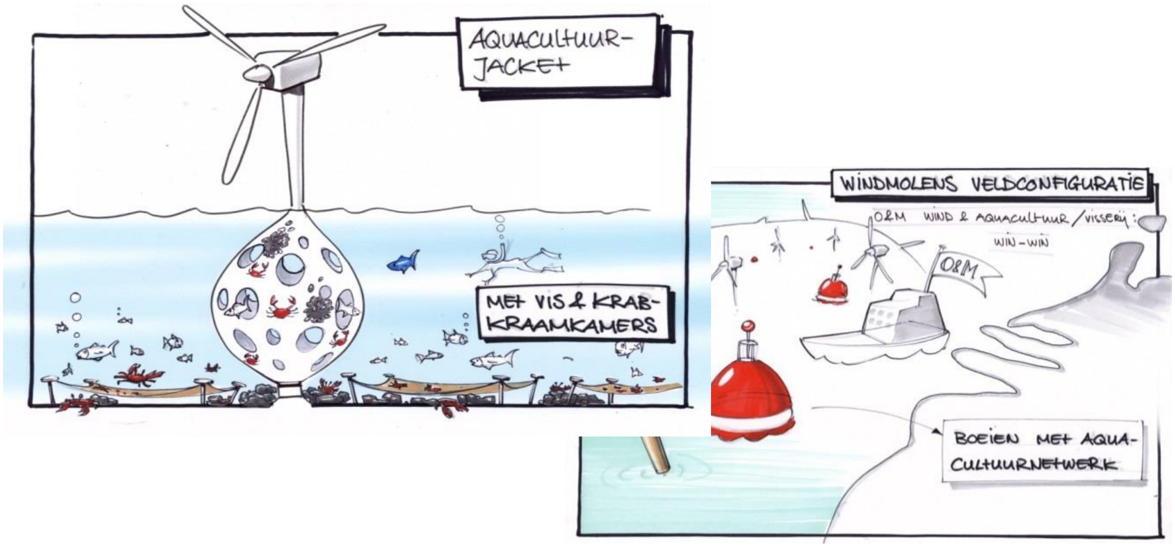
Annex D – Business case simulation parameter overview

D1 – Illustration



D2 - Cost Benefit Analysis model

Table Annex D-1 shows the various model input parameters:

1. Overall system settings
2. O&M management system settings
3. Wind farm system settings
4. Mussel farm system configuration overview
5. Transport system configuration overview
6. Meteo & nautical navigation system configuration overview

Table Annex D-1. Model input parameters

	(Start) Value	Unit
1. Overall System Settings		
Distance to Shore (DtS)	30	NM
Depreciation Period (DP)	20	Year
Interest Rate (ItR)	4	% in average
Inflation Rate (InR)	3	% in average
2. O&M Management System Settings (OPEX)		
Onshore O&M Office	10.000	k€
ERP/AMI IT-system (DOWES)	3.000	k€
SCADA^{+} Control and Protection Subsystem (CPS)	5.000	k€
3. Wind Farm System Settings		
Number of Wind Turbines (WT)	200	turbines
Wind Turbine Power (WTP)	5	MW
Farm Installed Capacity (FIC)	1.000	MW
Farm Yield Coefficient (baseline) FYC(bl)	40	%
Wind Turbine Procurement (WTP)	1.500	k€/MW
Foundation & Installation Procurement (FIP)	1.500	k€/MW
Transmission Station (TS)	30.000	k€
Internal 10-233 MW subsea cable (installed)	175.000	k€
Wind Farm System Operation & Maintenance (O+M)	500	k€/MW
4. Mussel Farm System Configuration Overview		
Number of Long Line Systems (LLS)	1.800	LLS
Procurement Price per LLS	15	k€
Installation & Commissioning Price per LLS	15	k€
Mean Annual Maintenance Cost (MAMC)	5	% CAPEX
Production Capacity	11	ton/LLS/yr
Mussel Seed Price	0,3	k€/ton
Mussel Consumption Price	0,95	k€/ton
Mussel Harvest Capacity per ship	5	ton/hr
Mussel Inspection Capacity per ship	0,2	hr/LLS
Socks Inspection	2,7	hr/LLS
5. Transport System Configuration Overview		
Number of WFF Support Ship	2	ships
CAPEX of a WFF Support Ship	25.000	k€
Ship Mean Annual Maintenance Cost (MAMC)	2,5	% CAPEX
Number of Spare Part Containers	18	amount
CAPEX of a Spare Part 20' Container	20	k€
Containers Mean Annual Maintenance Cost (MAMC)	5	% CAPEX
Number of Mussel Harvest Subsystem(s)	2	subsystems
CAPEX of a Mussel Harvest Subsystem	350	k€
Harvest Sys. Mean Annual Maintenance Cost (MAMC)	5	% CAPEX
Subsea 1031 MW Power cable to Shore (installed)	111.120	k€
Cable Mean Annual Maintenance Cost (MAMC)	0,5	% CAPEX
6. Meteo & Nautical Nav. System Configuration Overview		
Number of Meteorological & Navigation Masts	4	mast incl. foundation
Number of Navigational Marker Buoys	552	buoy incl. line and anchor
Meteorological & Navigation Mast	5.000	k€ per mast
CAPEX Navigational Marker Buoy (installed)	3	k€ per buoy

Table Annex D-2 shows the O&M cost as percentage of the CAPEX (fixed per installation, between 0,5-15%).

Table Annex D-2. O&M costs.

	Procure-ment Cost (PC) k€	MAMC as % of PC	Critical: Y/N, nr
O&M System:			
1 Onshore O&M Mgt Office	10.000	3,0%	Y
2 ERP/AMI IT-system (DOWES)	3.000	15,0%	Y
3 SCADA+ Control and Protection Subsystem (CPS)	5.000	15,0%	Y
Wind Farm System:			
4 Tower Foundation	100.000	1,5%	Y
5 Tower & Nacelle	160.000	3,0%	Y
6 Yaw Gearbox	100.000	3,0%	Y
7 Rotor Installation	430.000	3,0%	Y
8 Blade Adjustment	100.000	3,0%	Y
9 Drive Train	100.000	3,0%	Y
10 Generator Installation	220.000	3,0%	Y
11 Main Power Transformer	40.000	3,0%	Y
12 Auxiliary Power Transformer	80.000	3,0%	Y
13 Auxiliary Power Installation (400-110V)	30.000	3,0%	Y
14 Hydraulic Installation	20.000	3,0%	Y
15 Lubricant Installation	20.000	3,0%	Y
16 Heating, Airco Installation	30.000	3,0%	Y
17 Fire extinguishing Installation	30.000	3,0%	Y
18 Lightning Protection and Grounding Installation	30.000	3,0%	Y
19 Elevator Installation	30.000	3,0%	N
20 Crane and Hoists	30.000	3,0%	N
21 Service Platform	30.000	3,0%	N
22 Boat Landing Facility	20.000	3,0%	N
23 Transmission Station (TS)	30.000	2,0%	Y
24 Internal 10-233 MW subsea power cables (Elec Grid)	175.000	1,5%	Y
Mussel Farm System:			
25 End piles	18.000	5,0%	Y
26 Long Lines	18.000	5,0%	Y
27 Mussel Socks	18.000	5,0%	Y
Transport System:			
28 WFF Support Ship(s)	50.000	2,5%	Y
29 Spare Part Containers	360	5,0%	Y
31 Mussel Harvest Subsystem	700	5,0%	Y
34 Subsea 1031 MW Power cable to Shore	111.120	0,5%	Y
Meteo & Nautical Navigation System:			
35 Meteorological & Navigation Masts	20.000	3,0%	N
36 Navigational Marker Buoys	1.656	5,0%	N

Figure Annex D-1 shows the additional input of the AMC model.

O&M Year Scenario Fact Sheet

1 Average Approach as determined by the OEM-ers
2 Proven Technology and Processing

Difference compared to Base O&M:	**(delete the incorrect characterizations)**			Remarks:
Active Time:	positive	none	negative	
Operation Time:	positive	none	negative	
Reliability	positive	none	negative	
MTBF:	positive	none	negative	
MTTR:	positive	none	negative	
O&M Cost	positive	none	negative	
Asset Management Control:	positive	none	negative	
Operational Excelence:	positive	none	negative	

Related Year Scenarios: Base Refit and Overhaul

General YS Settings:	Base O&M (in general)	THIS YEAR SCENARIO O&M System	Wind Farm System	Mussel Farm System	Harvest & Transport System	Meteo & Nautical Sup. System			
Installation Declining Factor [0,100%]:	5,0%	2,5%	2,5%	5,0%	2,5%	2,5%			
Active Time [0,365]	360	365	360	340	360	365			
Preventive Maintenance Factor [0-100%]:	25%	50%	25%	25%	25%	25%			
Inspective Maintenance Factor [0-100%]:	15%	15%	15%	15%	15%	15%			
Inspective Maintenance Survey(s):	2	50	4	10	50	4			
Mean Time Between Failure (MTBF):	6,5	7	6,5	5	6	7			
Mean Time to Repair (MTTR):	6	4	6	5	5	6			

Cost/Performance Figures: Improvements/Differences compared to the Year Scenario 'Base O&M'

Asset/System Related (ASR):

Scenario Effectiveness Period : 1 — 1 ***SEP= number of year periods from the year of selection.***
Note: if SEP ASR is active then the ASR Cost baselines are related to the Year Scenario involved.

O&M Cost Estimations: **differentiated to the O&M Disciplines**

	Base O&M Maintenance Cost in k€	Percentage of Total O&M Cost	Total Cost this YS	Percentage of Total O&M Cost	O&M System	Wind Farm System	Mussel Farm System	Harvest & Transport System	Meteo & Nautical Sup. System	Retrofit & Overhaul Wind Farm	Retrofit & Overhaul Mussel Farm
Life Cycle Management:											
Annual Cost (Services)	6.500	8,7%	**6.500**	*8,9%*	**800**	**3.500**	**1.000**	**800**	**400**	**700**	**200**
Operations:											
Annual Cost (Services)	10.000	13,4%	**10.000**	*13,7%*	**0**	**4.000**	**4.000**	**2.000**	**0**	**100**	**100**
Improvement O&M (mod./innov./refit):											
Annual Cost (Services & Investments)	0	0,0%	**0**	*0,0%*	**0**	**0**	**0**	**0**	**0**	**1.800**	**600**
Installation/Subsystem Related:											
Inspective Maintenance (total for all inst. & subsyst.):											
Annual Cost (Services)	8.730	11,7%	**8.470**	*11,6%*	**225**	**7.459**	**405**	**279**	**102**	**0**	**0**
Preventive Maintenance:											
Annual Cost (Services)	14.550	19,5%	**14.492**	*19,9%*	**750**	**12.431**	**675**	**465**	**171**	**0**	**0**
Corrective Maintenance:											
Annual Cost (Services)	34.919	46,7%	**33.505**	*45,9%*	**525**	**29.835**	**1.620**	**1.115**	**410**	**0**	**0**
Improvement Maintenance (mod./innov./refit):											
Annual Cost (Services & Investments)			**0**		**0**	**0**	**0**	**0**	**0**	**248.625**	**13.500**
Mean Anual Maintenance Cost (MAMC) in k€:	58.199	*77,9%*	**56.466**	*77,4%*	**2.300**	**57.225**	**7.700**	**4.659**	**1.083**	**251.225**	**14.400**
Annual Total O&M Cost	**74.699**	*100,0%*	**72.966**	*100,0%*							
		delta in €:	-1.733	-2,3%	**+/- Percentage**						

	Base O&M Maintenance Cost in k€ (MAMC)	**THIS O&M YEAR SCENARIO**	+/- Percentage	Base O&M MTBF in Years	**THIS O&M YEAR SCENARIO**	+/- Percentage	Base O&M MTTR in days	**THIS O&M YEAR SCENARIO**	+/- Percentage	**Scenario Effectiveness Period (SEP)**
O&M System:										
1 Onshore O&M Mgt Office	300	300	0%	1	**1**	0%	2	**2**	0%	1
2 ERP/AMI IT-system (DOWES)	450	450	0%	1	**1**	0%	2	**2**	0%	1
3 SCADA+ Control and Protection Subsystem (CPS)	750	750	0%	1	**1**	0%	2	**2**	0%	1
	1.500	*1.500*								
Wind Farm System:										
4 Tower Foundation	1.500	1.500	0%	20	**20**	0%	30	**30**	0%	1
5 Tower & Nacelle	4.800	4.800	0%	20	**20**	0%	30	**30**	0%	1
6 Yaw Gearbox	3.000	3.000	0%	5	**5**	0%	20	**20**	0%	1
7 Rotor Installation	12.900	12.900	0%	5	**5**	0%	20	**20**	0%	1
8 Blade Adjustment	3.000	3.000	0%	5	**5**	0%	10	**10**	0%	1
9 Drive Train	3.000	3.000	0%	5	**5**	0%	10	**10**	0%	1
10 Generator Installation	6.600	6.600	0%	5	**5**	0%	10	**10**	0%	1
11 Main Power Transformer	1.200	1.200	0%	5	**5**	0%	10	**10**	0%	1
12 Auxiliary Power Transformer	2.400	2.400	0%	5	**5**	0%	10	**10**	0%	1
13 Auxiliary Power Installation (400-110V)	900	900	0%	5	**5**	0%	5	**5**	0%	1
14 Hydraulic Installation	600	600	0%	5	**5**	0%	5	**5**	0%	1
15 Lubricant Installation	600	600	0%	5	**5**	0%	5	**5**	0%	1
16 Heating, Airco Installation	900	900	0%	5	**5**	0%	5	**5**	0%	1
17 Fire extinguishing Installation	900	900	0%	10	**10**	0%	5	**5**	0%	1
18 Lightning Protection and Grounding Installation	900	900	0%	10	**10**	0%	5	**5**	0%	1
19 Elevator Installation	900	900	0%	10	**10**	0%	5	**5**	0%	1
20 Crane and Hoists	900	900	0%	10	**10**	0%	5	**5**	0%	1
21 Service Platform	900	900	0%	10	**10**	0%	5	**5**	0%	1
22 Boat Landing Facility	600	600	0%	10	**10**	0%	5	**5**	0%	1
23 Transmission Station (TS)	600	600	0%	10	**10**	0%	10	**10**	0%	1
24 Internal 10-233 MW subsea power cables (Elec Grid)	2.625	2.625	0%	10	**10**	0%	10	**10**	0%	1
	49.725	*49.725*								
Mussel Farm System:										
25 End piles	900	900	0%	10	**10**	0%	5	**5**	0%	1
26 Long Lines	900	900	0%	10	**10**	0%	5	**5**	0%	1
27 Mussel Socks	900	900	0%	10	**10**	0%	5	**5**	0%	1
	2.700	*2.700*								
Transport System:										
28 WFF Support Ship(s)	1.250	1.250	0%	0,5	**0,5**	0%	3	**3**	0%	1
29 Spare Part Containers	18	18	0%	0,5	**0,5**	0%	3	**3**	0%	1
31 Mussel Harvest Subsystem	35	35	0%	0,5	**0,5**	0%	3	**3**	0%	1
34 Subsea 1031 MW Power cable to Shore	556	556	0%	10	**10**	0%	20	**20**	0%	1
	1.859	*1.859*								
Meteo & Nautical Navigation System:										
35 Meteorological & Navigation Masts	600	600	0%	10	**10**		10	**10**		1
36 Navigational Marker Buoys	83	83	0%	5	**5**		5	**5**		1
	683	*683*								
Total Installation & Subsystem Maintenance Cost:	**56.466**	**56.466**								

Figure Annex D-1. Additional input AMC model.

Figures Annex D 2- show the various output parameters during the lifecycle of 20 years for the ‘reference’ simulation run (Figure 7-12).

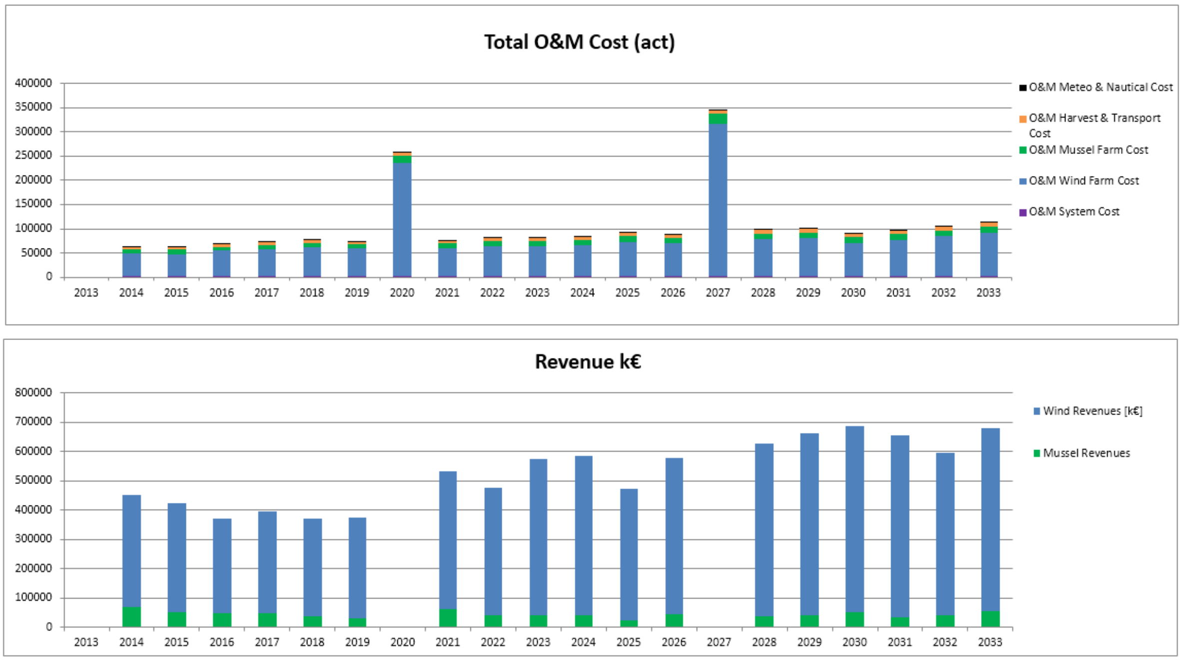


Figure Annex D-2. Costs and revenues.

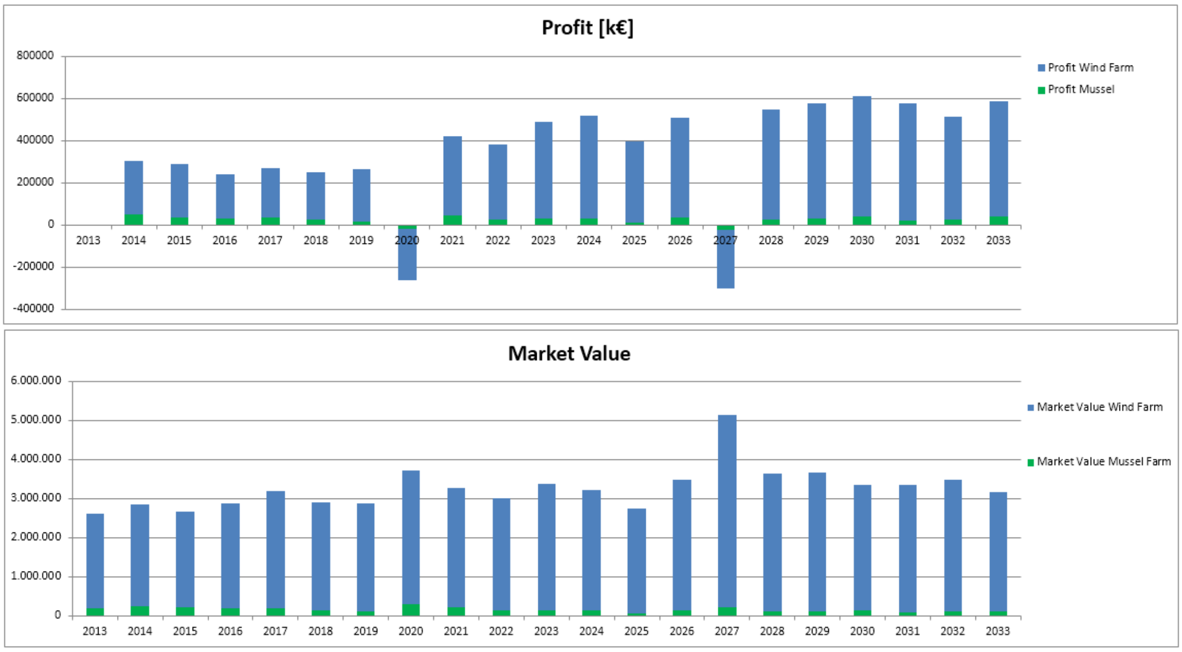


Figure Annex D-3. Profit and market value.

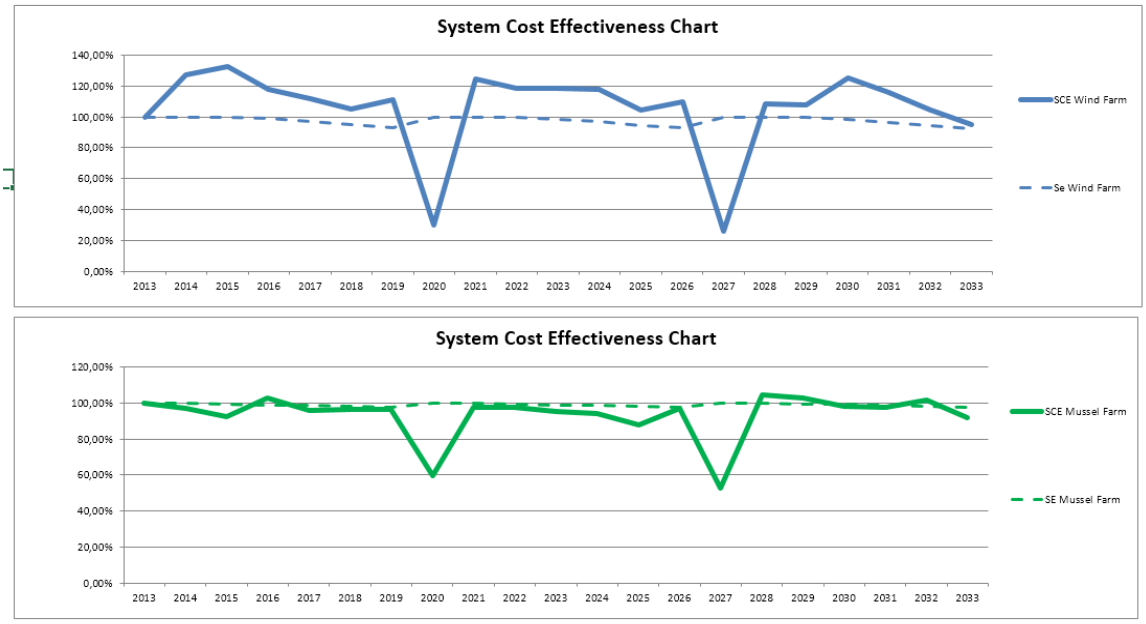


Figure Annex D-4. System cost effectiveness charts Wind and Mussel Farm.

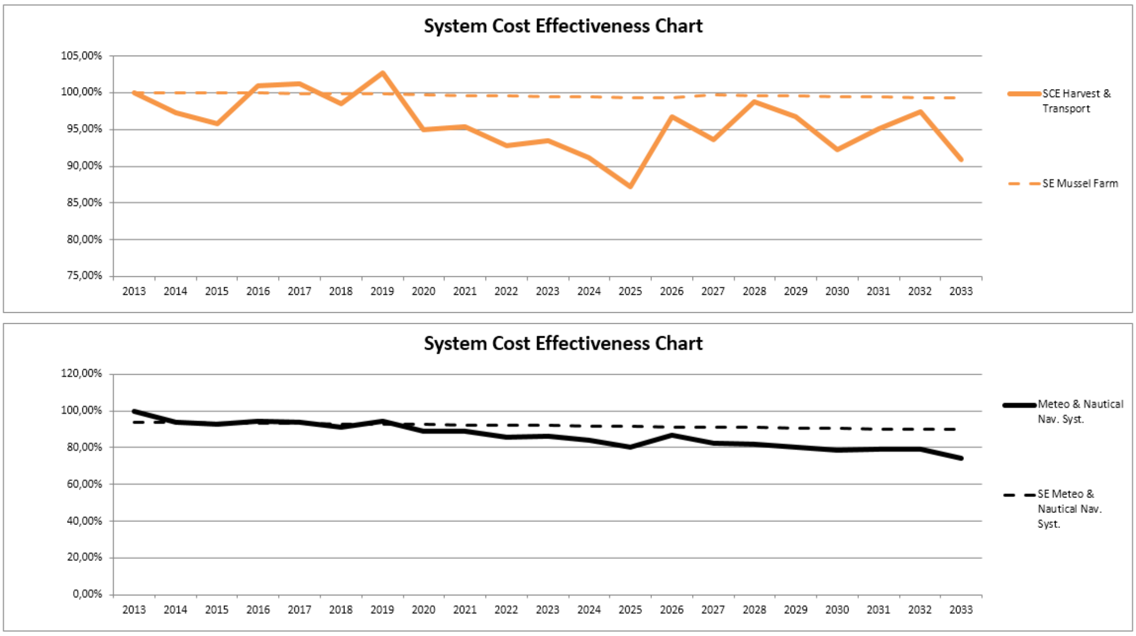


Figure Annex D-5. System cost effectiveness charts SCE Harvest & Transport and Meteo & Nautical Navigation System.

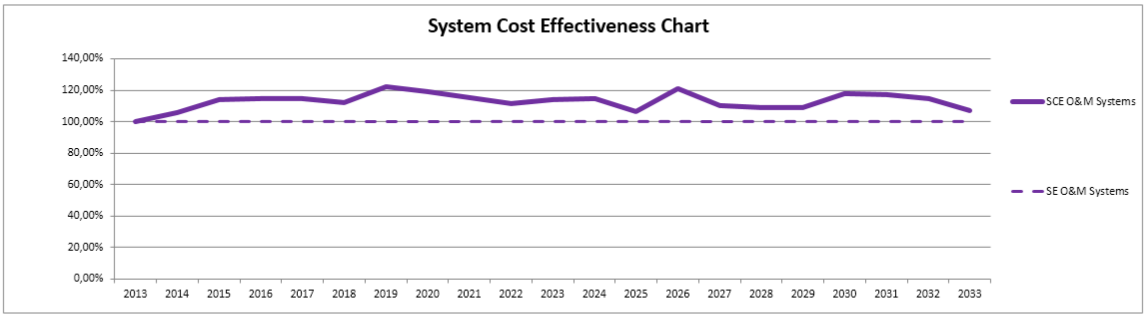
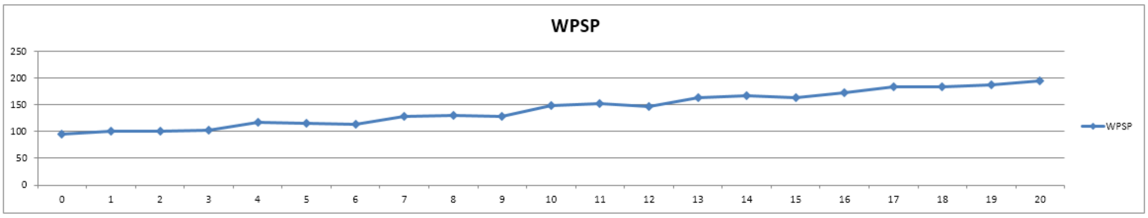
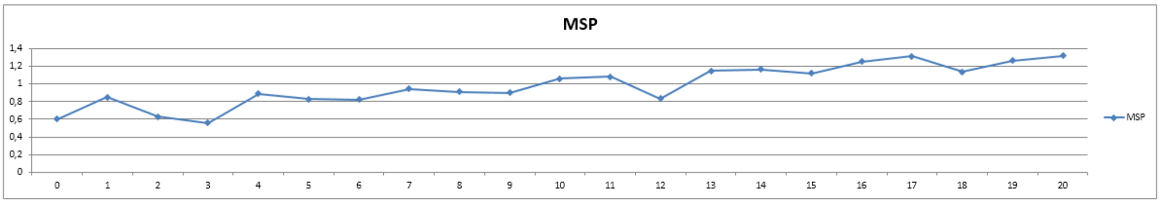


Figure Annex D-6: System cost effectiveness chart SCE O&M Systems

The 'Trend Diagrams' in figure Annex D-7 show the simulated sales price development of respectively the Wind Power Sales Price (WPSP) and Mussel Sales Price (MSP).



Life Cycle	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
WPSP	95	101,02	100,08	102,43	116,91	115,63	113,91	129,06	130,68	128,53	149,22	153,33	146,11	163,06	167,41	163,03	173,43	183,77	183,27	187,55	194,83



Life Cycle	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
MSP	0,6	0,85	0,63	0,56	0,89	0,83	0,82	0,95	0,91	0,90	1,06	1,08	0,83	1,15	1,16	1,12	1,25	1,31	1,14	1,26	1,32

Figure Annex D-7: Simulated wind power sales price (WPSP) and mussel sales price (MSP).

D3 – Basic formula for simulating price developments

The simulated Sales Price Developments are based on the following formula:
Trend Progression: Yr(A+1)=A+(a*sin(qx) + b*x + c)*(1-d(ASELECT-0,5)) which can be adjusted according to the following variables:

- a= 10 degree of the sine movement
- b= 0 progressive change (+/-) of the trend
- c= 4 linear change (+/-) of the trend
- d= 2 degree of uncertainty in the trend (10 = totally unpredictable)
- q= 2 sine wavelength in pi rad. [0-3,14].

By adjusting the parameter values, different Cost/Benefit Analysis 'runs' can be made, e.g. to analyse the influence of (extreme) sales price developments.

Annex E –Transport system details

Subsea Power Cable Subsystem

The Subsea Power Cable Subsystem provides the electrical power transport from the transmission station to shore. For this case the total length of this cable is estimated at 30 NM (55 km).

The technical specifications and cost figures used in this case are extracted from the information as shown in the figure below.

HVDC Extruded Subsea Cables

Date: 2009

DESCRIPTION

Subsea cross-linked polyethylene (XLPE) cables are segmented copper conductors insulated by extruded XLPE layers. As there are no magnetic losses with DC cables, galvanised steel wire can be used for the armour. Galvanised steel wire has better tensile properties than copper or aluminium and as HVDC cables are lighter than HVAC cables for the same amount of transmitted power, there is less tensile force during laying, reducing the stress on the cable. To reduce installation costs, the two single cores of the bipole can be bundled with a fibre optic and laid as one cable.

Image courtesy of Prysmian

CAPABILITIES

	±150kV cable bipole				±300kV cable bipole			
Conductor Area mm^2	Capacity MW	Weight kg/m	Diameter mm	Installed Cost £/m	Capacity MW	Weight kg/m	Diameter mm	Installed Cost £/m
500	233	36	156	820	466	52	216	845
1000	352	54	192	1040	704	74	244	1090
1400	421	62	206	1216	841	86	260	1286
2000	516	82	226	1480	1031	106	280	1580
2400	573	96	242	1656	1146	122	296	1776
3000	653	114	256	1920	1306	140	310	2070

Figure Annex E-1. Subsea Power Cable Subsystem.

References.[http://www.nationalgrid.com/NR/rdonlyres/62196427-C4E4-483E-A43E-85ED4E9C0F65/39230/ODISAppendicesFinal_0110.pdf]

Offshore Wind and Fish Farming Support Ships

The Offshore Wind and Fish Farming Support Ships are important to attain the 10% savings on O&M costs. The design requirements of these ships include:

- capable to transport and accommodate 40 persons, working in 3 shifts for one week
- wind farm spares transport and repair capability
- mussel harvest & transport capability

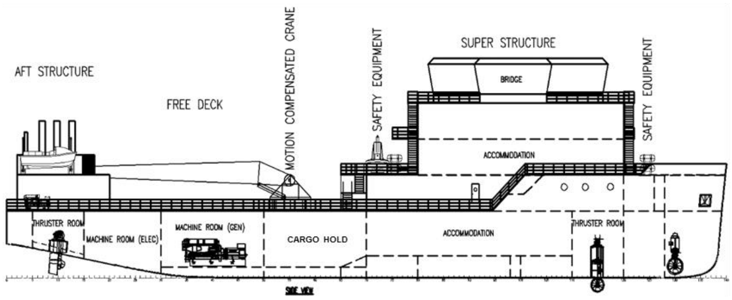
In addition this ship must be also be capable to navigate and work in harsh weather conditions. The following equipment is considered to make this possible:

- a dynamic position system (DP-2)
- a motion compensated crane
- a wide working deck

The size, shape, weight contribution and propulsion should be tuned on such a way that this ship will be a comfortable platform to live on for one week and to work on 24/7 hour with a significant wave height up to 3 meter (North Sea conditions). The illustration in figure Annex E-2 is based on a new preliminary design of a ship which could meet these specifications.

Main Dimensions	Symbol	Value	Unit
Length	Lpp	66.69	m
Length over all	LOA	70.00	m
Molded breadth	B	13.20	m
Least molded depth	D	6.00	m
Mean operating draught	T	3.44	m
Displacement	Δ	2365	m3
Block coefficient	Cb	0.78	-

Motion Compensated Crane	
Boom length	26.0m
Operating luff angle	60°
Max motion compensated lift	3 t @ all
Max non-motion compensated lift	13t @ 13m
Overall Mass	22 t
Installed Power pack	2*200 kW
Construction	Aluminum/Steel



Deck load: 12x20 ft. containers (Tools & Spares)

Accommodation: 50 persons.
The accommodation is applied with as much as possible double cabins to improve the comfort when the accommodation is not completely filled. Dimensioning of the accommodation is guided by the SBM accommodation standard and the NMD and ILO C133 code. At least it should comply with SOLAS.
Cargo Hold: 600 ton (fish/mussel)
Estimations: CAPEX: 20-30 M€, OPEX: 2,5 M€

Figure Annex E-2. Wind & Mussel Farming Support Ship.

The optimization of; size, shape and displacement, makes these ships stable platforms to operate in a working window up to 95% over the year. Besides this the dynamic position system (DP2) and motion compensated crane, make it possible to access wind turbines, with personnel, by man riding with a crew basket (see figure Annex E-3), but also with spare parts and tooling, up to 3.000 kg.

Figure Annex E-3. 'man riding' crew basket 'the FROG' [www.reflexmarine.com]

As support ship for Mussel Farming it is assumed that these ships will be equipped with a cargo hold for 600 ton mussels. For inspecting and harvesting the mussels the dynamic position system and motion compensated crane, are also considered essential. The idea is that already proven mussel harvest systems could be mounted on the motion compensated crane. With this system it should be possible to harvest approximately 5 tons/h.

Tooling and Spars Container Support System

It is supposed that the Support Ships will be designed and build in a multi-functional concept. For that reason a configuration with a wide deck and containers is chosen. In this case it is assumed that for tooling, equipment and spare parts (mainly for Wind Farm Maintenance), 18 specially prepared containers will be sufficient for serving 2 ships (Figure Annex E-4).

		20′ container	
		imperial	metric
external dimensions	length	20′ 0″	6.096 m
	Width	8′ 0″	2.438 m
	height	8′ 6″	2.591 m
interior dimensions	length	18′ 10 5/16″	5.758 m
	Width	7′ 8 19/32″	2.352 m
	height	7′ 9 57/64″	2.385 m
door aperture	Width	7′ 8 [″	2.343 m
	height	7′ 5 ¾″	2.280 m
volume		1,169 ft³	33.1 m³
maximum gross mass		66,139 lb	30,400 kg
empty weight		4,850 lb	2,200 kg
net load		61,289 lb	28,200 kg

Figure Annex E-4. Tooling and Spare Parts Container Support System 18x20 ft.

Mussel Harvest Subsystems

The assumption is made that the existing mussel harvest systems for near shore can be modified in such a way that they can be used for offshore, up to 3 meters significant wave height, when combined with the motion compensated crane as one system. Examples of existing mussel harvest systems are shown in figure Annex E-5.

Annex E-5. Mussel harvest systems.

Annex F – Life Cycle Assessment Model - simplified

Figure Annex F-1 shows a simplified representation of the LCA model.

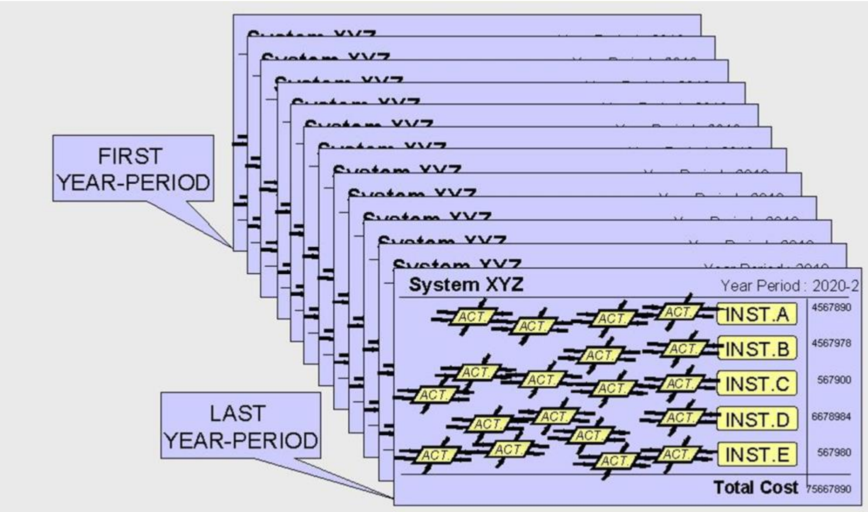


Figure Annex F-1. The Asset System Lifecycle Program (Stavenuiter 2002).