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Socio-economic Analysis of a Selected Multi-use Offshore Site in the North Sea

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Abstract A 600 MW offshore wind farm is under construction in the Netherlands Exclusive Economic Zone at a site called Gemini situated 55 km north of the Wadden Sea island of Schiermonnikoog and 85 km from the nearest Dutch port of Eemshaven. This chapter investigates the option of introducing a multi-use design for the Gemini site by adding mussel cultivation (48 kt wet weight per year) and seaweed cultivation (480 kt wet weight per year) to the wind farm. An institutional analysis indicates a political will in the Netherlands to support the development of adding uses to offshore wind farms, but a number of implementation obstacles are also identified. Those obstacles include an absence of licences for multi-use production and legal restrictions against third-party access to wind farms. There is therefore a need for a regulatory framework for multi-use and trust-building among actors involved in multi-use installations. A financial and economic assessment,

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and a cost-benefit analysis also taking into account monetized changes in CO_2 emissions, indicate that adding mussel cultivation to the wind farm is likely to be both financially and socio-economically viable. Including a seaweed cultivation function is probably not financially and socio-economically viable under current technical and economic conditions. Knowledge gaps and uncertainties in these assessments with respect to, for example, missing site-specific data and non-monetized externalities suggest further research, also including pilot cultivations of mussels and seaweed in planned single-use or multi-use installations.

Keywords Multi-use offshore platforms • Marine infrastructure • Socio-economic analysis • Environmental analysis • Marine Spatial Planning • North Sea

4.1 Introduction

The North Sea is characterized by relatively shallow waters and excellent wind conditions that are ideal for offshore wind development. Therefore, the largest installed capacity of offshore wind in the world is found in this area. Even larger offshore wind farm developments are proposed for the coming decades, significantly increasing spatial claims of already one of the busiest seas in the world. Furthermore, the Dutch North Sea waters contain relatively high concentrations of nutrients, calling for the combination of different types of aquaculture with offshore wind farms as a promising multi-use concept.

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Table 4.1 Basic facts about the North Sea site

Characteristic	North Sea site (Gemini site)
Geographical location	The Netherlands Exclusive Economic Zone
Offshore distance	55 km
Depth	29.5–33.4 m
Substrate	Mainly sand (some thin clay layers)
Water temperature	2–20 °C
Salinity	32.5–35.0 psu
Current magnitude	0–0.6 m/s
Mean tidal range	Approximately 2 m
Significant wave height	Generally lower than 2.1 m
Extreme wave height	10–11 m (1/50 yrs.)
Average wind speed	10 m/s

Source: http://www.vliz.be/projects/mermaidproject/docmanager/public/index.php?dir=Outreach_Material%2F&download=MERMAID_Booklet.pdf

The MERMAID project focused specifically on a case study area located in the Netherlands Exclusive Economic Zone, 55 km north of the Wadden Sea island of Schiermonnikoog and 85 km from the nearest Dutch port of Eemshaven. At this location, an offshore wind energy farm called Gemini is at present under construction and is planned to be fully operational by 2017 (www.geminiwindpark.nl). Table 4.1 presents some basic facts about the Gemini site and Fig. 4.1 shows the location of the site. As indicated in Fig. 4.1, the Gemini site consists of two areas with a total capacity of 600 MW. An annual production of 2600 GWh is expected from a total of 150 4-MW turbines. The seabed conditions are excellent and monopiles have been selected as foundations. In addition to the turbines, an offshore hotel and support centre, two 220 kV substations and two required submarine cables to the onshore connection at Eemshaven are to be developed.

Although an offshore wind farm such as Gemini only has licenses for single use, more stakeholders in the Netherlands – as well as in other countries developing offshore wind – are starting to discuss multi-use possibilities, such as regional fishermen and entrepreneurs for aquaculture and tourism. Through the participatory approach applied in MERMAID (for details, see van den Burg et al. 2016), stakeholders and the MERMAID project team identified mussel and seaweed aquaculture as the most promising uses to be combined with the Gemini offshore wind farm. The conceptual design is shown in Fig. 4.2.[1]

As will be further investigated in this chapter, a multi-use design has the potential of creating synergies related to operation and maintenance, logistics and design. For example, the presence of seaweed causes wave attenuation, which in turn can result in less harsh offshore (wave) conditions for the wind farm through reduced fatigue loads and subsequently also improving the longevity of the applied material. Furthermore, less wave energy inside the wind farm extends the weather windows

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[1] See Table 4.2 for basic facts of the production capacity of this design and MERMAID project (2016) for further design details.

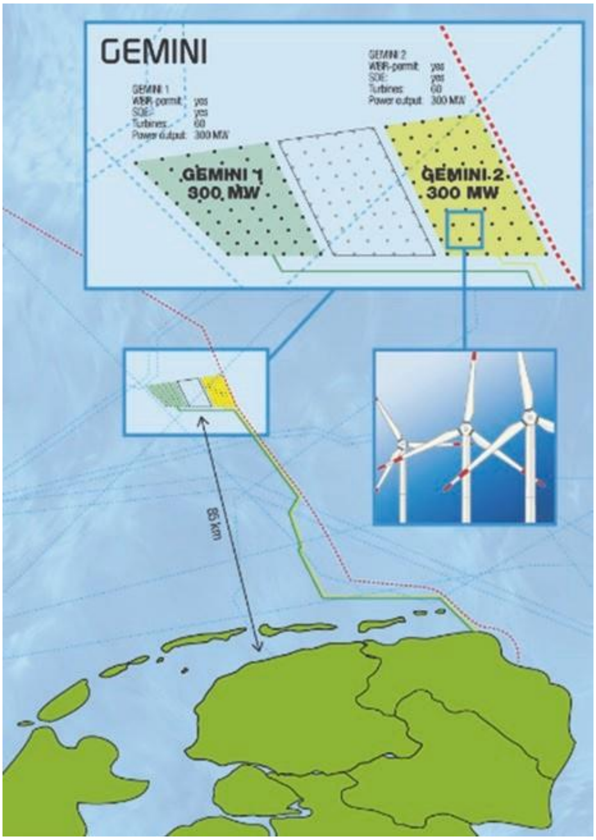

Fig. 4.1 Location of the North Sea site (Gemini site)
Note: The *arrow* shows the shortest distance to the Dutch coast and “85 km” refers to the shortest distance of navigation between the site and the nearest Dutch port of Eemshaven

for operation and maintenance activities. See Hadadpour et al. (2016) for experimental results on wave attenuation by seaweed.

Driving forces for such a potential multi-use design include the fact that the Dutch offshore aquaculture sector is at the beginning of a new development (Stuiver et al. 2016). While the Dutch blue mussel cultivation is to a large extent likely to remain inshore in the Wadden Sea and Eastern Scheldt because mussel farmers are hesitant to go offshore (Verhaeghe et al. 2011), a transition phase to more offshore cultures has started (MERMAID Project 2013). This shift is probably triggered by indications that the market potential for mussels might be twice the current market (van den Burg et al. 2013; Klijnstra et al. 2016). Regarding the potential for seaweed cultivation, the most immediate opportunity is to offer wet seaweed on the local market. However, the use of seaweed not only for food but as a raw material for health care and plastic products indicates an increasing need for larger quantities (Klijnstra et al. 2016).

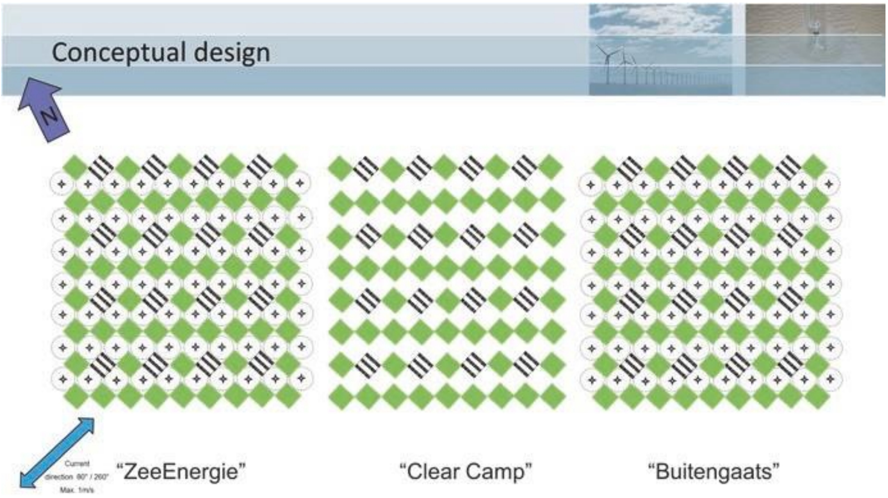

Fig. 4.2 Conceptual multi-use design for the North Sea site. *Green* diamonds illustrates seaweed, *round circles* are the offshore wind turbines in the two wind farm areas of ZeeEnergie and Buitengaats included in the Gemini site, and *black* and *white* diamonds are the areas with mussel aquaculture

Table 4.2 Estimated production for the conceptual multi-use design

Function	Capacity	Annual total production
Wind energy	600 MW	2600 GWh
Mussel cultivation	3 kg WW/m^2	48 kt WW
Seaweed cultivation	10 kg WW/m^2	480 kt WW

Source: MERMAID project (2016)

In an early stage of the design process, fish aquaculture and wave energy were also considered as potential multi-use components at the site. However, fish farming was excluded from the design due to relatively high water temperature peaks exceeding 18 °C during the summer. Currently, no native species are expected to have an adequate economic return on investment under the conditions present at the current location in the North Sea. Wave energy convertors were also judged to not be feasible because of the low efficiency in combination with limited availability of wave energy in the North Sea (MERMAID Project 2015).

The focus of the analysis summarized in this chapter is to evaluate the consequences of changing the single-use of wind energy at the Gemini site to a multi-use site including also mussel cultivation and seaweed cultivation. These consequences are evaluated in comparison to a single-use reference alternative where the Gemini site is only used for the already decided wind farm, excluding any other use. It is also assumed that the added functions of mussel cultivation and seaweed cultivation would not replace any other site for mussel cultivation and/or seaweed cultivation. In principle, this means that environmental and socio-economic impacts of the wind farm are held constant in the analysis as long as those impacts are not influenced by adding the new functions of mussel cultivation and seaweed cultivation to the site. Nevertheless, some major impacts of the wind farm are also described in the chapter in order to provide an enriched context for the analysis.

The remainder of the chapter develops as follows: The case study is put into a socio-economic context in Sect. 4.2 through identifying and describing actors, economic sectors and institutions. In Sect. 4.3, the environmental impact of the multi-use is analysed, and the potential of valuing these impacts in monetary terms is assessed. A financial and economic assessment of the multi-use design is found in Sect. 4.4, which is followed by a social cost-benefit analysis in Sect. 4.5. One major difference between the social cost-benefit analysis in Sect. 4.5 and the financial and economic assessment in Sect. 4.4 is that the former also takes externalities into account, i.e. non-market economic impact. The chapter is concluded with a discussion and recommendations in Sect. 4.6.

4.2 The Case Study in a Socio-economic Context

This section aims at contributing to an improved understanding of the effects of the multi-use design by providing a broader context to the case study. Demographic and socio-economic facts are provided, stakeholders are identified, and relevant institutional and policy settings are described. In the last sub-section, some important probable obstacles to implementation of multi-use designs are identified.

4.2.1 Demographics and Economic Activities

With reference to the EU nomenclature of units for territorial statistics (NUTS), the Gemini site is administratively associated with the NUTS 1 region of Noord Nederland, more specifically the two NUTS 2 regions of Groningen and Friesland, and the three NUTS 3 regions of Delfzijl and surroundings (Delfzijl en omgeving), Other Groningen (Overig Groningen) and North Friesland (Noord-Friesland). The socio-economic profile for the case study is therefore described for those NUTS 2 and NUTS 3 regions. As a comparison, socio-economic facts for the Netherlands as a whole are also provided.

The population of the Netherlands in 2012 was about 16.7 million inhabitants, of which residents in Groningen and Friesland account for 3.5 and 3.9%, respectively, see Table 4.3. The table also shows that the population is rather balanced between males and females, and the range of the average household size varies from 2.0 to 2.3 persons per household.

Table 4.3 Demographic data for 2012 at national level, and also for regional and local levels relevant for the case study

	The Netherlands	Groningen (NUTS 2)	Friesland (NUTS 2)	Delfzijl and surroundings (NUTS 3)	Other Groningen (NUTS 3)	North Friesland (NUTS 3)
Population	16,730,348	580,875	647,214	48,724	381,369	332,742
Persons per household	2.2	2.1	2.3	2.2	2.0	2.2
Per cent males	49.5	49.7	50.0	49.8	49.7	50.1
Per cent females	50.5	50.3	50.0	50.2	50.3	49.9

Source: Statistics Netherlands, www.cbs.nl

The population at national level is characterized by a favourable educational attainment level. In particular, 64% of the population has higher education (baccalaureate, graduate and postgraduate studies), while 6% of the population has elementary education only. Total labour in the Netherlands accounts for 7,387,000 persons, while regional employment in Groningen and Friesland amounts to 247,000 persons and 273,000 persons, respectively. Unemployment at national level amounts to 507,000 persons (or 6.4%), of which 54% are males and 46% are females. The Groningen region exhibits the highest unemployment rate (7.5%) of the Netherlands. At the national level, 35% of the employees has attained graduate and postgraduate studies, 43% holds baccalaureate and 22% has elementary and secondary education. The highest percent of employees with graduate and postgraduate studies (43%) is observed in the Other Groningen, while the highest percent of employees with elementary and secondary education is found the Delfzijl and surroundings region.

The national Dutch economy is to a very large extent service-oriented since the tertiary (service) sector accounts for more than 80% of total employment. The health and community services sector, property and business services sector and trade sector are the major sectors offering employment at the national and regional levels. The highest contribution of the secondary (transformation of raw material into goods) sector to total employment takes place in the Delfzijl and surroundings region (26%), while the primary (raw material extraction) sector contributes by only 1% to total employment at the national, regional and local levels. With regards to the value of regional production, the manufacturing and energy sector contribute by 68% and 56% in the Delfzijl and surroundings and Other Groningen regions, respectively, while the service sector contributes by 60% in the Friesland region.

4.2.2 Stakeholders

Main stakeholder groups in wind power production and maritime logistic services include competent authorities, energy companies, construction companies, investment and development companies, consultancies, fisheries, shipping and non-governmental organisations (NGOs). For the case study site, those stakeholders include Ministry of Economic Affairs, Ministry of Infrastructure and Environment, Province of Groningen, Energy Valley (authorities), NUON Vattenfall, ENECO (energy utilities), Van Oord, Siemens (construction and development companies), Typhoon Offshore (investment and development company), Fair Wind (consultancy), Visafslag Lauwersoog, VisNed, Vissersbond (fisheries), Groningen Seaports (shipping), and The North Sea Foundation (NGO). For aquaculture, also aquaculture companies are main stakeholders. For the case study site, they include POMossel, Machinefabriek Bakker and Hortimare. Also individuals and organizations associated with tourism and recreational boating can be identified as stakeholders.

Based on this general identification, stakeholder groups were contacted and invited to participate in the MERMAID participatory design process (see MERMAID Project 2015 for details). Their participation contributed to knowledge about controversies about multi-use of marine areas, which is further described below.

4.2.3 Institutional and Policy Framework

4.2.3.1 Policies Related to Offshore Wind Energy

In the current Dutch energy policy, a clear policy for offshore wind energy is available. In the earlier energy policy, offshore wind energy was identified as a less important sector, required to achieve formulated objectives. At that time, reservation of sufficient space in marine spatial planning was considered the main bottleneck for development of offshore wind energy. Also, offshore wind was considered to require too much subsidies. Until 2010, offshore wind energy was subsidized under the SDE program (Stimulering Duurzame Energie/Encouraging Sustainable Energy Production). The main current subsidy programme that targets the production of renewable energy is the SDE+ programme. From 2012 onwards, offshore wind energy was not eligible under the SDE+ programme, because wind energy was considered to be expensive compared to other production methods.

In September 2013 the Energy Agreement for Sustainable Growth, concluded by the government with employers, trade unions, environmental organisations and others, contains provisions on energy conservation, boosting energy from renewable sources and job creation. The government regards this agreement as a major step towards a fully sustainable energy supply. With regard to offshore wind this agreement aims to speed up and scale up offshore wind to 4450 MW capacity in 2023, under the condition that a cost reduction of 40% per MWh will be achieved until 2024.

Under EU legislation 2009/28/EC, Member States are required to give renewable energy priority on the national grid. This requirement was implemented through an adjustment of the Dutch Electricity Law, but pending a discussion on the allocation of the cost of congestion management, this law is not yet approved. Another discussion issue on grid integration concerns the costs for connection of offshore wind energy parks to the national grid. Under current Dutch law, these costs are to be made by the project developer. However, based on the Energy Agreement for Sustainable Growth, a debate in the House of Representatives further revolved around the costs of the offshore grid which is now intended to be built and operated by the Dutch TSO TenneT. The investment costs for the offshore grid, which will connect the future offshore wind farms to the onshore grid, will be 2.4 billion Euro (excluding maintenance and financing costs).

An offshore wind energy park requires a permit, based on the Water Management Act (Wet Beheer Rijkswaterstaatwerken, WBR). Before such a permit can be granted, project developers have to go through the environmental impact assessment procedure. When applying for a permit, they are obliged to deliver an Environmental Impact Assessment (EIA) report (milieueffectrapportage, MER), which assesses the environmental impact of their envisioned project. If a project developer has gone through the procedures for the MER and permitting successfully, a 20-year concession is granted to build and operate a wind energy farm. The system of concessions stems from the Mining Act and grants the developer the possibility to build permanent structures and extract resources. In the concession, additional requirements can be included.

4.2.3.2 Policies Related to Multi-use of Marine Areas

The objective of the first Dutch National Water Plan (Nationaal Waterplan 2009–2015) for the North Sea area is to “make the North Sea more sustainable” taking into account its first priority, i.e. safety and protection from floods. The National Water Plan (accepted in 2009) integrated all water areas, from offshore and coastal to rivers and inland water. It also described the outline of spatial planning of future water-related developments. The National Water Plan follows an area-oriented approach, while for each water basin, specific objectives are formulated and a spatial plan is made to accommodate developments. One of the ways to make the North Sea more sustainable is to reserve sufficient space for offshore wind energy parks, with a focus on multi-use. Informed by a 4450 MW ambition (Energy Agreement), it was envisioned that three search areas needed to be reserved for wind park development. Future developments (after 2023) might require more space. Other developments, such as Carbon Capture and Storage (CCS) are also envisioned and the need for mutual adjustment between functions is emphasized. In the National Water Plan, the options for multiple uses of space are explicitly mentioned.

North Sea policies are further elaborated in the Policy Document North Sea 2009–2015 (Beleidsnota Noordzee 2009–2015). After a first identification of areas where offshore wind energy could be developed, a second step was to balance the interests of the various users of the North Sea. This exercise resulted in the identification of two areas for offshore wind development and two so-called *zoekgebieden* (search areas) for future developments. In this policy document, it is explicitly mentioned that co-use offshore wind energy parks, for example for recreation, fisheries and aquaculture, should be allowed as much as possible and needs to be discussed with the involved parties as the policy is implemented.

The co-use issue is also considered in the Integrated Management Plan for the North Sea 2015, which mentions aquaculture inside offshore wind energy parks as a potentially smart use of space, providing opportunities for clever entrepreneurship (IDON 2011). However, no space is allocated to offshore aquaculture for the Dutch part of the North Sea in this plan. This means that aquaculture activities in wind energy parks need to be applied for through permits.

As is indicated by these plans and policies, the Dutch government has the ambition to realize multi-use of offshore wind farms. This political will is manifested by recent stakeholder meetings, processes and projects initiated as well as facilitated by the Ministry of Economic Affairs and the Ministry of Infrastructure and the Environment (Stuiver et al. 2016). However, this has not yet resulted in establishing a regulatory framework for multi-use.

4.2.4 Controversies and Implementation Obstacles

Stuiver et al. (2016) identify a number of obstacles to the implementation of multi-use options of marine areas, dividing them into policy, economic, social, technical, environmental and legal obstacles. We give a few examples of these obstacles here and refer to Stuiver et al. (2016) for further details.

Policy Obstacles Already awarded permits for offshore wind farms such as the Gemini site are only for single-use. The absence of licences for multi-use production is a major obstacle. Also, as was mentioned above, there are no areas designated for offshore aquaculture in the Dutch spatial plans for the North Sea.

Economic Obstacles There is scepticism among stakeholders on the existence of a viable business case for combining offshore wind farms with aquaculture (MERMAID Project 2013, 2015) not least because the current practice for offshore wind parks to prohibit other vessels to enter the designated parks in order to avoid issues on risks and responsibilities. As a result, risks associated with third-party access are difficult to assess, which means that the impact on insurance premiums of allowing multi-use is unclear.

Social Obstacles Lack of trust among potential users might be a considerable obstacle. Offshore wind power has earlier been subject to many discussions between fisheries organizations and wind power companies. In general, any new fishing restriction because of offshore installations is a major issue for fishermen. To counterbalance such restrictions, fisheries organizations have argued for the need for compensation fees and/or additional activities for fishing vessels, e.g., fishing with static gears, organizing sightseeing trips to wind farms for tourists, and providing service and maintenance work in wind farms. This illustrates that controversies could also be a source of opportunities on potential synergies across various uses.

Technical Obstacles Adding additional uses to a wind farm give rise to technical challenges such as finding a design which makes wind turbines and cables satisfactorily accessible for maintenance. Also, Dutch offshore aquaculture is generally in its infancy, which means that there is at present very limited experience of what technical design is suitable for aquaculture installations.

Environmental Obstacles One reason for the fact that there is at present no areas designed for offshore aquaculture in Dutch spatial plans for the North Sea is potential negative environmental impacts of offshore fish farming. While those impacts might not at all be present for other types of offshore aquaculture, uncertainties about environmental risks might still be a general obstacle.

Legal Obstacles For Dutch wind energy parks, restrictions for multi-use stem from the concession agreements in which the competent authorities have included "restricted areas" surrounding wind energy constructions where no ships are allowed. For offshore wind energy parks there is a safety zone of 500 meter around static objects such as turbines. This means that no shipping activities can take place within 500 meter of the turbine, which affects the opportunities to combine aquaculture with wind power. However, exemptions on this rule could be made through permit applications.

Stuiver et al. (2016) conclude that the presence of obstacles such as those mentioned above suggests that there is a need for developing a regulatory framework for multi-use that, for example, help establishing a licensing procedure for multi-use. Furthermore, trust-building and close collaboration among actors directly or indirectly involved in multi-use installations are likely to be of great importance. Such trust-building is likely to be facilitated by the Dutch "poldering tradition" of involving stakeholders (MERMAID Project 2015).

4.3 Monetization of Environmental Impact

4.3.1 Impact on Ecosystem Services

Adding the functions of mussel cultivation and seaweed cultivation to the wind farm at the Gemini site might influence a number of the marine ecosystem services supplied by the North Sea:

- Production of food and raw material: Mussels and seaweed are products that can be used as food or as inputs in other types of production. In addition, marine food sources such as mussels and seaweed are generally seen as healthy food, the consumption of which might imply positive externalities in terms of improved public health. However, it is unknown to what extent the mussels and seaweed produced at the Gemini site would contribute to a changed public diet.
- Water quality: Mussel cultivation and seaweed farming might improve water quality through its need for nutrients. However, the relatively low concentration of nutrients at the offshore location of the Gemini site implies that the general impact of this improvement is likely to be negligible.

- Habitats: Locally at the Gemini site, mussels' and seaweed's consumption of nutrients might contribute to increase the transparency in the water column, which could improve light conditions for benthic vegetation. However, the turbidity caused by tidal forces might still override this effect. The increased nutrient consumption could also cause negative ecosystem effects through less nutrients being available for single-cell algae (MERMAID Project 2015). The net effect on biodiversity is therefore difficult to establish.
- Cognitive development: The multi-use might give rise to scientific and educational benefits by being examples of innovative engineering with aquaculture providing food and other products.

There are also environmental impacts of a single-use wind farm that are not likely to be influenced by an addition of new functions. For example, trawling is prohibited in the wind farm, and wind turbine foundations and associated scour protection installations become an artificial reef providing a new habitat for marine life. This generally increases the abundance of fish and other species (Krone et al. 2013; Reubens et al. 2014). On the other hand, a potential problem is that hard structures in an otherwise soft sediment environment might form "stepping stones" for invasive species, which might have negative effects on the ecosystem, such as reduced overall biodiversity (Glasby et al. 2007). Which net effect on biodiversity would prevail is, again, difficult to establish.

None of the potential effects on ecosystem services of adding mussel cultivation and seaweed cultivation to the wind energy park were monetized due to lack of data in combination with the negligible or uncertain nature of potential effects. However, the potentially positive effect on health might be reflected by the demand for mussels and seaweed and would in such a case at least partially be taken into account through the market price of mussels and seaweed. To establish the total economic value of health improvements would require a study of non-market values, which should be an objective of future research.

4.3.2 Impact on CO_2 Emissions

Another environmental effect associated with the Gemini site is emissions of carbon dioxide (CO_2). Those emissions were possible to estimate through applying a life cycle assessment (LCA) for evaluating the Global Warming Potential (GWP) associated with the multi-use for the Gemini site.[2] Resulting quantity of emitted CO_2 equivalents (CO_2eq) for each of the uses, and total amounts of emissions are pre-

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[2] An LCA consists of four stages; (a) objective and scope definition, (b) inventory analysis, (c) impact assessment and (d) interpretation. LCA is a standardized method which follows ISO 1040 series (ISO 2006a, b) and covers life cycle stages of a product or function. During the life cycle inventory stage, after constructing the flow chart of the product/function, for each process or activity inputs and outputs are listed with their quantities. The next step is converting emissions to the related impact categories using several methods like TRACI, CML 2001, etc.

Table 4.4 Unit amount of CO_2 emissions per function and the compared production technologies

Function	Parameter	Amount	Unit
Wind farm electricity production	Amount of CO_2eq production per 1 kWh	10	g CO_2eq
Coal based electricity production	Amount of CO_2eq saved through wind farm electricity production per 1 kWh	810	g CO_2eq
ENTSO-E electricity production	Amount of CO_2eq saved through wind farm electricity production per 1 kWh	452	g CO_2eq
Mussel cultivation	Total amount of CO_2eq production per 1 kg	0.622	kg CO_2eq
Seaweed cultivation	Total amount of CO_2eq production per 1 kg	0.0192	kg CO_2eq

Table 4.5 Total amount of CO_2 emissions per function and the compared production technologies

Function	Parameter	Amount
Wind farm electricity production	Amount of CO_2eq production (assuming 2600 GWh/year)	10 g CO_2eq/kWh * 2600 GWh/year * 20 years =520,000 ton CO_2-eq
Coal based electricity production	Amount of CO_2eq saved (assuming 2600 GWh/year)	810 g CO_2eq/kWh * 2600 GWh/year * 20 years = 42,120,000 ton CO_2-eq
ENTSO-E electricity production	Amount of CO_2eq saved (assuming 2600 GWh/year)	452 g CO_2eq/kWh * 2600 GWh/year * 20 years =23,504,000 ton CO_2-eq
Mussel cultivation	Total amount of CO_2eq production (assuming 48,000 t WW/year)	0.622 ton CO_2eq/ton * 48,000 ton mussel/year * 20 years =597,120 ton CO_2-eq
Seaweed cultivation	Total amount of CO_2eq production (assuming 480,000 t WW/year)	0.0192 ton CO_2eq/ton * 480,000 ton seaweed/year * 20 years =184,320 ton CO_2-eq

sented in Tables 4.4 and 4.5; details about the estimations are found in the paragraphs below.

Wind Farm As mentioned in Sect. 4.1, the wind farm will consist of 150 Siemens SWT 4.0 wind turbines, giving a total capacity of 600 MW.[3] The Environmental Product Declaration (EPD) of Siemens SWT 4.0 declares that for 1 kWh energy produced, the greenhouse gas (GHG) emissions are 10 g CO_2eq. The data represented in the EPD is derived from the full scale LCA which is carried out for a wind farm that consist of SWT 4.0 wind turbines, cables to grid, and substation. Therefore the results in the EPD are substitutable for Gemini wind farm. If the obtained GWP result is compared with GWP potential of coal based electricity production (820 g CO_2eq, Schlömer et al. 2014), and European electricity mix value (ENTSO-E network) (462 g CO_2-eq/kWh, Itten et al. 2014), the difference is 810 g CO_2eq and 452 g CO_2eq/kWh, respectively. The wind farm can thus help reducing CO_2 emis-

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[3] The capacity factor (average generated power divided by its peak power) varies between 25 and 50% roughly for Danish wind farms. For the Gemini wind farm web site this value is given as 2600 GWH/year (capacity factor of 49.5%).

sions, given an assumption that a change towards non-fossil fuel energy sources such as wind power would facilitate a reduced cap in the EU emissions trading system.

Mussel Cultivation An LCA in line with ISO 14040 and 14,044 standards was carried out for mussel production using Ecoinvent integrated GaBi software to determine environmental impacts of a mussel farm for its life cycle (ISO 2006a, b). For the calculation, the CML 2001 method was chosen as the methodology due to being a midpoint approach and a method widely used in LCA studies (Dreyer et al. 2003). The systems studied included production and installation of structure, operation and maintenance activities, disposal of structures as well as transportation of materials during the life cycle stages. The selected functional unit was kg of mussel harvested. With regards to GWP, the information about the mussel farm is limited to capacity and technique (long-line mussel farming) of the proposed farm. There are two studies for calculating the carbon footprint of blue mussel farming using long-line technique. Fry (2012) calculated carbon footprint of Scottish suspended mussels and intertidal oysters. The study includes cradle to farm gate life cycle stages and the inventory data is collected from Scottish farmers. Fry (2012) reported material input and energy consumption data for one ton of cultivated and packed mussels and also compares the inventory data with the data reported by Winther et al. (2009). Winther et al. (2009) calculated carbon footprint and energy use of Norwegian seafood products, taking into account material and energy consumption data for 1 kg of edible mussels as well as transportation to the wholesaler. Both studies were about blue mussels farmed by long-line techniques in North Sea coastal countries and it is therefore assumed the same amount of inputs can be applied to the Gemini site. This results in an estimate of 0.622 kg CO2eq per kg mussels in terms of GWP, assuming that the mussel production at the Gemini site would not replace any other production elsewhere.

Seaweed Cultivation The total capacity of the seaweed farm is 480,000 ton wet weight (WW) per year, and the seaweeds will be grown using textile cable structure with buoys and metal spreader bars. Lack of data precluded the use of LCA of the seaweed farm, but instead the results of Fry et al. (2012) are used as an example of GWP of seaweed production on a cradle-to-gate basis. These results indicate emissions amounting to 0.0192 kg CO2eq per kg harvested seaweed, again assuming that the seaweed production at the Gemini site would not replace any other production elsewhere.

Finally, the emission estimates were monetized by applying the social cost of carbon. This refers to the shadow price of world-wide damage caused by anthropogenic CO_2 emissions (Pearce 2003). According to Arrow et al. (2014), the social cost of carbon is \$19.50 per ton of CO_2 using the random walk model in Newell and Pizer (2003), \$27.00 per ton using the state-space model in Groom et al. (2007), and \$26.10 per ton using the preferred model in Freeman et al. (2013). The monetization was based on the estimate from the state-space model, which correspond to 22.50 Euro per ton.[4]

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[4] Exchange rate 0.83 \$/ €.

4.4 Financial and Economic Assessment

The financial and economic assessment benefited from data available about the ongoing Gemini offshore wind farm project and from some specific research developed for the North Sea, focused on mussels and seaweed (Bartelings et al. 2014; Buck et al. 2010; Burg et al. 2013). Additionally, seaweed farming assessment received valuable contributions from Schipper (2015). Below we go through the financial assessment for each of the functions in the multi-use design. Results are summarized in Table 4.6.

Wind Farm Specific data for the Gemini wind farm, market analysis and literature suggest that 2800 million Euro are invested for the first year, while an additional investment of 1800 million Euro is required to replace the wind turbines that are assumed to have a design life time of 15 years. As to operation and maintenance (O&M) costs, results related to hypothetic or real offshore wind farms indicate a cost interval of 60–140 million Euro per year. Different O&M costs per energy produced yearly in MWh (Bartelings et al. 2014; Næss-Schmidt and Møller 2011; IEA 2013; DECC 2013), or per capacity installed in MW (DECC 2011, 2013) are suggested. The O&M cost interval excludes estimates from the literature that were not considered as representative for the Gemini site, e.g. because they are based on sites located much closer to the coastline than the Gemini site, which is likely to have a strong impact on costs for transports. The O&M cost interval might still be an overestimation, because details of the wind farm investment agreement are not fully known, which means that at least some O&M costs might be included in the investment costs. The costs associated with the offshore hotel and support centre at the Gemini site are assumed to be included in the investment cost and the O&M cost interval mentioned above. With regard to revenues, 442 million Euro per year are estimated for the first 15 years. Later on, the estimated revenues decrease to 112 million Euro per year, as the project is only entitled to subsidies during the first 15 years. This means that subsidies amount to 330 million Euro per year during the first 15 years. These revenues are based on a production of 2600,000 MWh per year and an electricity price of 170 Euro per MWh (including subsidies) or 43 Euro per MWh (excluding subsidies). That is, the subsidy during the first 15 years amount to 127 Euro per MWh.

Mussel Cultivation 7–11 million Euro are assumed to be required to invest every 5 years, which is based on assumptions and on unit costs of components in a mussel plot (Buck et al. 2010) applied to the conceptual multi-use design. The higher value of the range takes into account the eventual need of investing in a new vessel (Buck et al. 2010). A range of 8.5–57 million Euro per year is estimated for O&M costs. This interval is based, respectively, on annual sub-costs per area and on annual sub-costs per area for a specific production installed, as suggested by Bartelings et al. (2014), and is probably an underestimation of the total O&M costs. A mussel production of 48,000 ton WW (wet weight) per year is assumed to result in revenues amounting to 45 million Euro per year, given a price of 940 Euro per ton WW (based on Bartelings et al. 2014).

Table 4.6 Summary of the financial characteristics for the Gemini site

	Wind farm	Mussel cultivation	Seaweed cultivation
Investment costs	2800 (year 1)	7–11 (every 5 years)	21–400 (year 1)
	1800 (year 16)		10 (every 5 years)-400 (every 10 years)
Operation and maintenance costs	60–140 per year	8.5–57 per year	47–68 per year
Revenues	442 per year (first 15 years)	45 per year	17–48 per year
	112 per year (year 16 and following years)		
Financial profitability	Yes, as long as there are subsidies.	Yes, probably.	Very uncertain; depends very much on the development of the market price of seaweed products.

All amounts in million Euro

Seaweed Cultivation Initial investment costs can be estimated to 21–400 million Euro. According to assumptions provided by Schipper (2015), a relatively low investment cost of 21 million Euro for the production capacity installed would be succeeded by reinvestments of around 10 million Euro every 5 years. The considerably higher estimates of 40 million Euro (based on Burg et al. 2013) and of 400 million Euro (based on Burg et al. 2013; and on Bartelings et al. 2014) would apply both for the initial investment and for reinvestments every 10 years. The former estimate is based on unit costs per production capacity installed (Burg et al. 2013), and the latter on unit costs per area for a specific production installed (Burg et al. 2013; Bartelings et al. 2014). Expected O&M costs amount to 47–68 million Euro per year, based on unit costs and sub-costs per area for a specific production capacity (Schipper 2015; Bartelings et al. 2014). Revenues for seaweed farming are very uncertain, but can be expected to be within the range of 17–40 million Euro, depending on estimated prices of 210 Euro per ton DM (Dry Matter) (Bartelings et al. 2014) or of 600 Euro per ton DM (Schipper 2015). A production of 80,000 ton DM of seaweed, corresponding approximately to 480,000 ton WW of seaweed, was used in the calculations (Bridoux 2008).

Table 4.6 provides a summary of the financial characteristics. Note that future revenues and costs are at this stage of the analysis not discounted for the computation of annual figures. Additionally, decommissioning costs can be estimated to 3% of total costs, based on Climate Change Capital (n.d.) and Januário et al. (2007). All values are associated with a considerable uncertainty because some data is missing – either not made available or unknown – and therefore estimations had partly to rely on not site-specific data and expert judgement. The lack of site-specific data also made it difficult to estimate what cost reductions could be expected because of efficiency gains from multi-use synergies. However, based on Bartelings et al. (2014), a 10% efficiency gain can be expected due to savings on operation and maintenance costs. On the other hand, the multi-use design might give rise to increased insurance costs. On the whole, those considerations are not likely to influence the main conclusions about financial profitability in Table 4.6, i.e. that there is probably a business case for adding mussel cultivation to the wind farm, but it is very uncertain whether there is also a business case for adding seaweed cultivation. The wind farm that is already under construction is likely to be financially profitable, at least as long the production is subsidized.

The possibility of a business case for mussel cultivation and/or seaweed cultivation is further illustrated by two extreme scenarios taking into account the rather wide cost and revenue intervals estimated for some of the functions. The first scenario gives a maximum profitability by combining the lowest estimates of investment and O&M costs with the highest estimates of revenues, and the second one gives a minimum profitability by combining the highest estimates of investment and O&M costs with the lowest estimates of revenues, see Tables 4.7 and 4.8 for results. Again, seaweed cultivation shows a negative financial profitability, also in the maximum profitability scenario. However, the future development of the market price of seaweed products is highly uncertain. As an illustration of what market price is required for making offshore seaweed farming to a business case, a break-even price was estimated to approximately 620 euro per ton DM of seaweed for the maximum profitability scenario and to about 1400 Euro per ton DM of seaweed for the minimum profitability scenario.

Finally, some economic considerations in terms of job creation opportunities are added to the financial assessment above. The wind park that is under construction is expected to create around 500 full-time jobs during the construction and installation phase and another 120 full-time jobs during the operational phase (Van Oord n.d.). The local tourist industry might also benefit from sightseeing trips to wind farms. The employment impacts of the maritime logistic services are mainly concentrated on the redesign of fishing vessels towards multipurpose vessels, which may give fishermen the opportunity to carry out maintenance works and logistic activities. Adding the functions of mussel and seaweed cultivation to the wind farm can be expected to produce approximately an additional 60 full-time or seasonal jobs (based on Buck et al. 2010; Burg et al. 2013).

Table 4.7 A maximum profitability scenario for the Gemini site (lowest estimates of investment and O&M costs combined with highest estimates of revenues)

	Wind farm	Mussel cultivation	Seaweed cultivation
Investment costs	2800 (year 1) 1800 (year 16)	7 (every 5 years)	21 (year 1) 10 (every 5 years)
Operation and maintenance costs	60 per year	8.5 per year	47 per year
Revenues	442 per year (first 15 years) 112 per year (year 16 and following years)	45 per year	48 per year
Financial profitability	Yes, as long as there are subsidies.	Yes.	No.

All amounts in million Euro

Table 4.8 A minimum profitability scenario for the Gemini site (highest estimates of investment and O&M costs combined with lowest estimates of revenues)

	Wind farm	Mussel cultivation	Seaweed cultivation
Investment costs	2800 (year 1)	11 (every 5 years)	400 (year 1)
	1800 (year 16)		400 (every 10 years)
Operation and maintenance costs	140 per year	57 per year	68 per year
Revenues	442 per year (first 15 years)	45 per year	17 per year
	112 per year (year 16 and following years)		
Financial profitability	Yes, as long as there are subsidies.	No.	No.

All amounts in million Euro

4.5 Social Cost-Benefit Analysis

As a rule, a project is deemed to be socially profitable if total discounted benefits exceed total discounted costs, i.e. a positive net present value (NPV). Monetized values of externalities are included in the benefits or costs, which is one major feature that distinguishes a SCBA from a financial assessment. Also the internal rate of return (IRR), i.e. the discount rate that makes the NPV equal to zero, can give useful information: The higher a project's IRR, the more desirable is the undertaking of the project. Any project with an IRR greater than the discount rate used for the project is a profitable one.

For the Gemini site the financial costs and revenues reported in Sect. 4.4, together with the benefits (costs) associated with reduced (increased) CO_2 emissions (see Sect. 4.3.2), were included in the SCBA. For the case of wind energy production, both the case of coal based electricity production and the case of European electricity mix value (ENTSO-E) was used in the analysis (see Sect. 4.3.2).

Two alternative values for the social discount rate were used in the SCBA: 3% and 4%, which are values often obtained when applying the Ramsey equation for long-lived projects for example (Arrow et al. 2014). Further, a 20-year time horizon was selected for the SCBA. Given this time horizon, the SCBA has to cope with the fact that the timing of reinvestments in installations because of wear and tear is not synchronized across the three multi-use functions of wind energy, mussel cultivation and seaweed cultivation. This issue was handled by adapting the reinvestment structure for the SCBA in the following way:

- For wind energy, a major re-investment in wind turbines and foundations is planned for year 16, because they are assumed to last for 15 years. However, reinvestments in offshore cables and offshore sub-stations can be expected to be necessary after 20 years, i.e. in year 21. Given the time horizon of 20 years, it was therefore assumed that the wind energy operations stop in year 15. However,

decommissioning is assumed to take place in year 20 in order not to disturb mussel and seaweed operations during years 16–19.
- For mussel cultivation and seaweed cultivation, decommissioning is assumed to take place in year 20, instead of having an otherwise necessary reinvestment in this last year.

Monte Carlo simulations involving 1000 repetitions were performed for taking uncertainty into account. Triangular distributions were applied for the investment costs of mussel cultivation and seaweed cultivation, respectively, for O&M costs of wind energy, mussel cultivation and seaweed cultivation, respectively, and also for the price of seaweed. The triangular distribution was regarded as the best choice because it made it possible to apply the maximum and minimum profitability scenarios described by Tables 4.7 and 4.8. It was assumed that the estimates associated with the maximum and the minimum profitability, respectively, are associated with the lowest probabilities of occurrence in the triangular distribution, and the average of those estimates with the highest probability of occurrence in the triangular distribution.

The normal distribution was used in the simulation for all other variables. Since there was no information about the specific distributions and only a central value for each of the items, a normal distribution with mean equal to the given central value was assumed. The structure of the normal distribution was determined such that the mass included in the interval of ± two standard deviations from the mean has boundaries at a distance of $\pm\gamma$ per cent of the mean. The choice of γ was consistent with the data of the specific case. That is, $\mu \pm 2\sigma = \mu \pm \gamma\mu$.

The SCBA results for the case when the functions of mussel cultivation and seaweed cultivation are added to the single-use of wind energy is shown in Table 4.9. Adding only mussel cultivation entails a positive NPV (117 million Euro as an average for the two discount rate alternatives), but adding both mussel cultivation and seaweed cultivation results in a negative NPV (−474 million Euro as an average for the two discount rate alternatives). This is explained by the considerably negative NPV of seaweed cultivation (−594 million as an average for the two discount rate alternatives). These results are not surprising, given the findings in the financial assessment in Sect. 4.4.

The results in Table 4.9 are valid when having the single-use wind farm at the Gemini site as a reference alternative, which is reasonable because it is under construction. If the reference alternative is instead an unused space at the Gemini site, it would make sense to investigate the NPV of constructing a multi-use site with wind energy and mussel cultivation and/or seaweed cultivation. The NPV for this case is reported in Table 4.10 in a situation where subsidies are not deducted from the price of electricity produced by the wind farm at the Gemini site. All combinations are now associated with a positive NPV. The considerable profitability of the wind farm compensates for the losses entailed with the seaweed cultivation. Not surprisingly, the most profitable design is the combination of wind energy with mussel cultivation only.

Table 4.9 Estimated NPV in million Euro (mean and standard deviation) for making the single-use Gemini wind farm to a multi-use design with either mussel cultivation or seaweed cultivation, or both

	3% discount rate		4% discount rate	
Design	Mean NPV	St. dev. of NPV	Mean NPV	St. dev. of NPV
Adding mussel cultivation only	122.47	32.94	110.95	29.47
Adding seaweed cultivation only	−617.67	113.10	−570.99	104.24
Adding both mussel cultivation and seaweed cultivation	−492.82	118.74	−456.15	106.69

Not deducting the subsidies to wind power in the SCBA can be motivated by an assumption that those subsidies serve as a proxy for positive externalities from wind power other than reduced greenhouse gas emissions. Examples of such possible additional externalities from a renewable energy source such as wind power might be positive network externalities that promote technological improvements and support the transition to a low carbon economy. However, an assumption that there are no such additional externalities would imply that the subsidies should be deducted in the SCBA. In such a case, the NPV of wind energy is reduced substantially, which is illustrated in Table 4.11 for the deterministic maximum profitability scenario. Given this scenario, the NPV ranges from −282 million Euro to 46 million Euro, depending on the choice of discount rate and comparison to type of alternative electricity production. However, this suggests that constructing a multi-use site by adding the profitable mussel cultivation to the wind farm can be crucial for increasing the chances of having a positive NPV also in a case when wind energy is assumed to have no other positive externalities than greenhouse gas reduction. The probability for a positive NPV would be further increased if the potential efficiency gains due to multi-use of about 10% can be realized, cf. Sect 4.4.

4.6 Discussion and Recommendations

A main conclusion that follows from the assessment is that adding mussel cultivation to the single-use wind farm at the Gemini site is likely to be both financially and socio-economically viable. While this supports a multi-use design at the site, this does not mean that the site is an optimal multi-use location. From a mussel farming perspective, sites situated closer to the Dutch shore are likely to provide conditions that entail an improved financial and socio-economic performance. Another main conclusion is that including a seaweed cultivation function is not likely to be financially and socio-economically viable under current technical (investment costs and O&M costs) and economic (market prices) conditions.

There are some limitations in the assessments that should be taken into account when interpreting these conclusions. For example, the monetization of environmental externalities in Sect. 4.3 included CO_2 emissions, but no other potential externalities such as improved public health and water quality became part of the

Table 4.10 Estimated NPV in million Euro (mean and standard deviation) for constructing a Gemini site with wind energy, mussel cultivation and/or seaweed cultivation, given a reference situation with an unused site

	3% discount rate		4% discount rate	
Design	Mean NPV	St. dev. of NPV	Mean NPV	St. dev. of NPV
Wind energy only (coal)	1252.50	98.08	1009.27	90.96
Wind energy only (ENTSO-E)	1020.93	95.92	799.64	91.46
Wind energy (coal) and mussel cultivation	1369.55	105.73	1123.43	96.44
Wind energy (ENTSO-E) and mussel cultivation	1140.58	105.49	904.54	94.57
Wind energy (coal) and seaweed cultivation	630.74	150.25	448.93	143.55
Wind energy (ENTSO-E) and seaweed cultivation	397.88	149.39	225.82	138.95
Wind energy (coal) and mussel cultivation and seaweed cultivation	755.90	153.43	541.05	147.82
Wind energy (ENTSO-E) and mussel cultivation and seaweed cultivation	520.32	153.23	328.12	147.00

coal Wind energy compared to coal energy production
ENTSO-E Wind energy compared to European electricity mix production

Table 4.11 Estimated NPV in million Euro for the Gemini wind farm for the deterministic maximum profitability scenario in a case when subsidies are deducted. (Monetized positive externalities due to CO_2 emission reduction are still included)

Design	NPV (3% discount rate)	NPV (4% discount rate)	IRR (percent)
Wind energy only (coal)	45.76	−68.81	3
Wind energy only (ENTSO-E)	−183.93	−281.52	1

coal Wind energy compared to coal energy production
ENTSO-E Wind energy compared to European electricity mix production

quantitative assessment. This might result in a bias of unknown magnitude and direction, which suggests a need for further research. Further, the financial and economic assessment in Sect. 4.4 was mainly supported by data from a literature review and expert judgments, because site-specific data was available only to a limited extent. There is thus a risk for inconsistencies because of different sources and different assumptions. There are also considerable uncertainties associated with the choice of statistical distributions and some of the estimated values, which is evident from the quite substantial intervals for some costs and revenues. Missing site-specific data on sub-categories of costs made it also difficult to estimate site specific efficiency gains from the multi-use design. These limitations suggest that the SCBA results in Sect. 4.5 should be interpreted as preliminary. If additional information becomes available through, for instance, a wider monetization of externalities or a more precise investigation of synergy opportunities, this could potentially change some of the conclusions. For example, seaweed cultivation as a potentially profitable multi-use function in the future should not be ruled out, because knowledge gaps in the assessment are substantial and the market price development for seaweed products are highly uncertain.

These issues illustrate the difficult choice in a research project between either relying at least partly on data that are relevant though with high uncertainty (e.g., apply not site-specific data), or to only gathering data that is accurate with high certainty (e.g., site-specific data). Aspects such as data availability (lack of data), focus of the research and time availability drove the research in a certain direction, with the presented outcomes. The outcomes could have been different if other or complementary inputs and approaches had been used, such as the following:

- Different design of the site in terms of, for example, capacity installed and size of the site.
- Comparison of the profitability of seaweed cultivation in an offshore single-use site, in an offshore multi-use site, in a coastal site close to the North Sea, or in the conventional markets such as Asia.
- Analysing offshore mussel cultivation in comparison to more near-shore mussel cultivation.
- Assessing differences in externalities associated with an offshore location in comparison to an on-shore location or a location closer to shore, taking into account that coastal areas are already subject to considerable environmental pressures.
- Different economic valuation methods.
- Longer time horizons in the SCBA than 20 years.

A particularly considerable uncertainty is related to the existence of potential synergies when combining uses. As mentioned in Sect 4.4, literature suggests that a 10% cost reduction is possible because of the possibility of efficiency gains in combining different functions in a multi-use site. This potential cost reduction was not taken into account in the financial assessment and in the SCBA. While such a reduction would not change the qualitative conclusions above about the financial and economic viability of adding mussel cultivation and seaweed cultivation to the wind farm, it should be emphasized that the extent of the potential synergies were not investigated with site-specific data. More detailed information could have improved or worsened the case for any of the multi-use options.

It should also be emphasized that realizing multi-use sites in the future hinges crucially on a number of governance issues to be resolved, such as multi-use licensing and the possibility to obtain insurance for multi-use. Further, some additional key challenges that deserve further study include the design of mussel and seaweed cultivation systems within an offshore wind farm (integration of the two types of aquaculture, design of harvesting equipment, etc.), and the ecological challenges linked to aquaculture activities (e.g. risk assessment of environmental impact and the mitigation of diseases). For the Gemini site, there are also considerable operational challenges related to the relatively long distance to the nearest main port (85 km) and the extreme wave heights that occur during storms.

The uncertainties and challenges suggest the need for further research on how multi-use sites should best be realized. For example, complementary research about seaweed cultivation in a multi-use site could be done by incorporating pilot cultivation in planned single-use or multi-use installations. This would increase know-how about such things as biomass production and costs, and therefore decrease uncertainty about this use. For example, this could clarify to what extent the presence of seaweed cultivation could protect wind farm installations and facilitate operation and maintenance activities through wave attenuation. Pilot installations entailing low investment costs might be easily accommodated within already subsidized projects with high investment costs such as wind farming. Introducing subsidies for "start-ups" for offshore mussel and seaweed production would improve its financial viability, although our results indicate that seaweed production would require a substantial subsidization. However, introducing subsidies might introduce a risk that investors are not making maximum efforts for discovering and implementing multi-use synergies, which suggests that a "start-up" subsidy system already from the beginning should entail a clear structure for phasing out the subsidies.

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