Summary

The European Blue Growth strategy aims to expand the new maritime sectors of aquaculture, energy, biotechnology, coastal tourism and mineral mining. Growth of these sectors will increases pressure on the seas, particularly on those areas that are densely used by traditional sectors such as fisheries and transport. This has triggered interest in developing multiuse of space and multiuse platforms at sea. This paper assesses the feasibility of offshore mussel production project in wind farms by design and ex-ante evaluation of a mussel aquaculture system in the North Sea. A system for mussel cultivation in the Dutch Borssele offshore wind farm was designed, producing both mussel seed and consumption-sized mussels with semi-submerged longlines. Based on the economic model and the risk assessment, this paper concludes that mussel aquaculture is an appealing commercial model for increased returns in offshore wind farms. The economic models shows that the internal rate of return and net present value are positive and based on the sensitivity analysis, it can be concluded that these results are robust.

Key words

Aquaculture, mussels, offshore wind, business case, risk assessment

1. Introduction

The European Blue Growth strategy aims to expand the new maritime sectors of aquaculture, energy, biotechnology, coastal tourism and mineral mining (European Commission, 2012, 2014). Some of these sectors are still small and claim little ocean space whilst others are expanding rapidly. The European Wind Energy Association reports growth of offshore wind installations in the EU of 1.6 GW or 110% from 2014 to 2015 and argues it will continue to develop rapidly (EWEA, 2016). This increases pressure on the seas, particularly on those seas that are densely used by traditional sectors such as fisheries and transport. Policy-makers have become interested in developing multiuse of space and multiuse platforms at sea (see for example Ministry of Infrastructure and Environment and Ministry of Economic Affairs, 2015).

Whilst the mussel sector is subject to various challenges, including marine acidification (Clements & Chopin, 2016) and adaptation to climate change (Rosa et al., 2012), the most imminent challenge to the Dutch sector is the development of new production processes with less impact on the Wadden Sea. For a long time, mussel seed was collected in the Wadden Sea area using bottom-trawling methods. Use of this method is now restricted (Smaal, 2002; Floor et al., 2016), forcing the sector to look for new ways to collect mussel seed (Jansen et al., 2016). Together with government authorities and civil society organisations, the mussel sector has set-up a transition programme for mussel seed collection (Ministry of Economic Affairs et al., 2014).

Reduced availability of mussel seed has already limited the total production of the Dutch mussel sector. Total production in the Netherlands decreased from over 90 million kg in the mid-1990s to 56 million kg in 2010 (Guillen & Motova, 2013). The development of offshore wind farms can solve this problem by providing more space for mussel aquaculture away from other marine uses. Still, institutional and legislative restraints as well as economic aspects have been judged important unresolved issues of multiuse of wind farms and mussel aquaculture (Michler-Cieluch et al., 2009).

The combination of mussel aquaculture in offshore wind farms has been studied in earlier research projects in the North Sea (Buck, 2017, Buck et al., 2008, Buck et al., 2010, Röckmann et al., 2015, Jansen et al., 2016). Following a participatory design process with various North Sea stakeholders, it was concluded that the most promising multiuse design for the North Sea basin comprised bottom-fixed offshore wind turbines and mussel aquaculture (van den Burg et al., 2016; Stuiver et al., 2016). This combination was evaluated by performing a social cost benefit analysis (Zanuttigh et al., 2016; Koundouri et al., 2016). A detailed business case for this multiuse combination is however lacking. A financial and risk assessment for such concept is needed to inform decision-makers on whether an attractive profit could be realisable from mussel cultivation in offshore wind farms.

The objective of this paper is to review the feasibility of an integrated facility for offshore mussel production project in wind farms by design and ex-ante evaluation of a mussel aquaculture system in the North Sea. This evaluation includes a technical, financial and risk assessment. The findings are based on review of literature, analysis of market data and consultation with experts. This paper focuses on the wind farm Borssele (see Figure 1), located 12 miles offshore.

<< Figure 1 here >>

The next section summarises available knowledge on multiuse of offshore wind farms. After that, the methodology used is described. The paper continues with a description of the proposed design, a financial and risk assessment. After describing the feedback received from maritime experts, concluding remarks are drawn.

2. Background

2.1 Biological conditions

For successful offshore mussel culture a number of biological conditions need to be satisfied: sufficient availability of starting material (mussel seed), no excessive fouling or predation, parasites and diseases below the regulatory limits, toxic algae and toxic compounds below the regulatory limits, and no significant negative effects on the environment.

Earlier studies showed that mussel growth occurs on the buoys throughout the Dutch Exclusive Economic Zone. Two surveys of shipping lane buoys were carried out in the Dutch part of the North Sea (Steenbergen et al., 2005; Kamermans et al., 2016) and results indicate that seed collection is possible. Growth potential is good as well: in a period of 15 months, mussels can grow to market size (Kamermans et al., 2016). Information on the presence of fouling organisms is available through biodiversity studies on oil and gas rigs and wind farms. Species such as the acidian *Ciona intestinalis*, which causes problems in Canadian mussel longline culture (McKindsey et al., 2007), were not observed (Van der Stap et al., 2016). Thus, fouling may be less of a problem than at near-shore locations. North Sea crabs occur at all depths on the piles, but densities are highest closer to the sea bed (Van der Stap et al., 2016). Oil and gas rigs and turbine foundations have direct contact with the sea bed. This facilitates access for crabs and starfish. For mussel culture on longlines contact with the bottom is via anchor lines. This may reduce the presence of predators.

2.2 Technical requirements

The feasibility of offshore mussel and mussel seed production will depend on what production system is employed in the wind farms. The culture systems need to be able to resist the conditions in the North Sea. Based on available literature the following set of technical challenges for a successful offshore mussel farm were identified:

- The system structure should be fully able to withstand weather and use.
- Loss of mussels falling off the ropes should be avoided.
- It must enable a reliable and robust harvest method.

Kamermans et al. (2011) carried out an inventory of existing offshore mussel culture systems and concluded that semi-submerged longlines anchored with concrete blocks are the most suitable system in the North Sea, with high wave conditions (Langan & Horton 2003). A semi-submerged system has a horizontal longline at 10 m depth (illustrated in Figure 3). Waves move above the longline. The location needs to be deeper than 20 m to assure enough space below the longline for dropper ropes (mussel cultivation rope) and changes in water heights due to tides. These systems have been used in the French Mediterranean (Mille & Blachier, 2009), the South coast of England (personal communication John Holmyard), the Portuguese coast (personal communication Antonio Miguel Cunha), the East coast of the USA (Lindell et al., 2011), the Black Sea in Turkey (Karayucel et al., 2015) and in New Zealand (Cheney et al., 2010). The depth of submergence depends on the combinations of tides, wave heights and the total water depth.

2.3 Synergies between wind and mussel aquaculture

The economic feasibility of offshore mussel cultivation in the North Sea has been studied by - among others - Buck et al. (2010), Lagerveld et al. (2014), Griffin et al., (2015) and Jansen et al. (2016). All these studies discuss the potential synergy between these two sectors. Costs for mussel aquaculture include the deployment, fixation, maintenance and reeling of aquaculture installations and cultured organisms (Michler-Cieluch et al., 2009). Additional costs are made for control and regulation of harvesting operations as well as monitoring of the health of mussels, as part of the management of new farming grounds (Michler-Cieluch et al., 2009). Separate processing and distributing sectors may be involved in cultivators activities, and thus must be paid, for instance to take care of grow-out of seeds until market size, transfer of seeds to licenced nearby cultivation spots, as well as onshore processing or marketing (Michler-Cieluch et al., 2009 p 60).

Wind farms and mussel aquaculture are likely to affect each other in one way or the other in multiuse arrangements - using ocean space for different purposes and activities (Michler-Cieluch et al., 2009 p 60). Both sectors face the same constraints in terms of operation costs, limited accessibility (weather windows), distance to farm site, available working days, and difficult logistics for operation and management (Michler-Cieluch et al., 2009).

In the MERMAID project, it was concluded that shared use of the physical infrastructure - e.g. the turbines' monopiles - is not desirable (Rockmann et al., 2015). The cost category with the greatest potential for reduction is the operation and management cost. Up to 50% of the charged maintenance labour costs are lost as waiting time: waiting for good weather conditions, certified personnel, transport, necessary tools and equipment (He et al., 2015). It is suggested that by combining wind energy and mussel aquaculture, these costs can be reduced. For example, when a multi-purpose vessel sails out to transport a maintenance crew to and from the wind turbines, its crew can inspect the aquafarm installations feed the fish and maybe harvest fish/mussels, while the maintenance crew is busy carrying out the maintenance work. When tasks are finished, the maintenance crew boards the vessel again and the crew and harvest are taken ashore. Based on expert consultation, Lagerveld et al. (2014) expect a 10% reduction in O&M costs can be realised through this multiuse.

3. Methodology

The business case is constructed in a three-step process. In step 1, a design for mussel cultivation project in the Borssele offshore wind farm was made. This design was assessed from a financial and risk perspective in step 2. Step 3 comprised the discussion of preliminary findings at an advisory session with maritime experts.

3.1 Business plan and risk assessment

An economic model was developed to assess the financial feasibility. Projected costs and revenues were calculated for a commercial application with fully developed technologies. The work completion date for the proposed commercial project was assumed to be 2020, with final investment decision (FID) in 2016. The weighted average cost of capital (WACC) or discount value was assumed to be 8.9%, in line with what was used by the UK Government Department of Energy and Climate Change when assessing energy technologies.

Input parameters for financial modelling were drawn from various sources including parameters on the costs of fixed offshore wind (BVG Associates (2015)) and costs of mussel cultivation (Buck et al., 2010; Lagerveld et al., 2014; and Jansen et al., 2016). Input parameters on the biomass growth were derived from van Stralen (2015). Input parameters for the value of products were drawn from a Dutch database on agriculture information (www.agrimatie.nl, last accessed 17-11-2016).

3.2 Risk assessment

A methodology was established to assess the individual and combined risks from offshore wind and aquaculture components of the multiuse combination (IEA. 2011, Renewable UK, 2014). A standard hazard ranking methodology was deployed with a risk matrix comprising the frequency (or likelihood) and consequence (severity of potential outcome) as shown below in Figure 2. Six categories were defined where all the risks would fall under depending on types and nature of the hazards identified, including: a) operational, b) economic and political, c) financial, d) environment, e) socio-economic, and f) health & safety.

<< Figure 2 here >>

By considering and combining consequences and likelihoods a level of magnitude was then obtained (Consequence x Likelihood) for a particular risk hazard. Ranking of hazards was done by expert judgement, consulting researchers and companies involved in the MARIBE project. Risk mitigation measures to reduce exposure to the identified hazards were proposed leading in most cases to a reduction in likelihood or frequency parameters and hence a final score. The full risk assessment is presented as supplementary material to this article. Section 4.3 below identifies and discusses risks that are amplified by combining mussel aquaculture and offshore wind energy.

2.4 Advisory session

The MARIBE project organised an advisory session in June 2016 in which various concepts for multiuse of marine space where presented to, and discussed with, a panel of maritime experts. The advisory session maritime 13-member expert panel represented sectors including banking, financial services, multinational professional services, engineering procurement and construction services, naval architecture, research institutes, ocean energy and aquaculture, among others. Following the presentation, an extensive Q&A session with the panel focused on the strengths and weaknesses of the business plan. After presenting the business case, the panel was asked to comment on the combinations technological feasibility, financial feasibility and risk assessment . Although remarks from the experts are presented below, the experts remain anonymous in this article.

4. Results

4.1 Technological design

<< figure 3 here >>

The aquaculture system in this case study project concerns a culture system using simple structures such as ropes and frames (Christie et al., 2014). This shellfish production consists of semi-submerged longlines as shown in Figure 3. These lines are connected to the sea bottom through a mooring system. Installation time for this option is less than a week (He et al., 2015). Two anchors are used to which a double longline is attached with ropes (Figure 3). The locations of the anchors are marked with buoys. The longline is kept suspended at a certain depth below the surface by cylindrical floats. So called "continuous looped droppers" are attached to the longline, as can be seen in Figure 3. The proposed system is independent of the infrastructure of the wind turbines. The dimensions of the system are presented in Table 1.

<< table 1 here >>

In the analysis presented, it is expected that by 2020, 5.5 million kg of mussel seed is collected annually offshore. To achieve this in a single commercial project, 98 ha of mussel aquaculture units are needed.

Seed can be collected once a year. Assuming a similar yield as in the Wadden Sea (average seed yield of 2.93 kg per m of rope; van Stralen, 2015) a seed yield of 75,008 kg per ha (on 25,600 m longlines per ha) is expected (Table 2). In this case study, it is proposed not to re-sock the mussels but thin them out. By thinning out, a proportion of the mussels remain on the line to grow to the next stage, while the harvested seed mussels and half-grown mussel can be transported to near shore culture areas for further growing. This allows delivery of several products at different times of the year: mussel seed 9 months after deployment, half-grown mussels 15 months after deployment and consumption size mussels 21 months after deployment (Table 2).

<< table 2 here >>

4.2 Economic performance

In the following section the results of the economic modelling are presented. Definitions of CAPEX, OPEX, DECEX and the product output are given in Appendix 1, followed by a list of the main assumptions in Appendix 2. A breakdown of costs is given in Appendix 3.

Based on these input parameters, the economic performance of the modelled wind-mussel combination can be calculated (see Table 3). Results show that the modelled multiuse system has a positive investment return rate (IRR) of 10.8%.

Total investment (CAPEX) in the system equals 1448 € m, of which 1390 € m is for the investment of offshore wind. The levelised costs for electricity generation are calculated to be 136.11 €/MWh while the costs for mussel production are an estimated 909.67 €/tonne. The combination of offshore wind and mussel cultivation on 98 ha is expected to generate 367 full-time jobs when in operation.

<< table 3 here >>

The sensitivity to a 5% and 10% change in CAPEX, OPEX, output, and revenues are presented in Table 4. In all scenarios, IRR and NPV remain positive. The increase/decrease in the revenues has the greatest impact on the economic performance but even a 10% reduction in revenues does not lead to an unattractive IRR. This sensitivity analysis shows that the economic performance of mussel aquaculture in offshore wind farm is robust and capable to withstand increases in costs or reductions in revenues.

<< table 4 here >>

4.3 Risk assessment

A total of 105 hazards were identified under six categories: (a) operational, (b) economic and political (c) financial, (d) environment, (e) socio-economic and (f) health and safety. Hazards were colour coded (risk matrix 1-25), depending on risk magnitude revealing 25 high (red), 62 medium (orange) and 18 low (green) hazards before mitigation. After mitigation strategies were proposed as an academic exercise (i.e. no companies were involved during the risk appraisal) 39 medium and 66 low risks remained. The full risk assessment is available as supplementary material. In the following section, the focus is on the risks that were considered to be amplified in a multiuse setting. Risk are identified, assessed and a mitigation strategy is proposed (see Table 5).

<< table 5 here >>

Operational (all stages)

At the preconstruction phase the main risks are associated with technical challenges (e.g. innovative mooring designs) and insurance (i.e. complexity, unproven nature of technologies combined/co-located, potentially destructive interaction with one another). These may increase the cost and delay the deployment of either of both sectors. Liaising with the insurance industry from an early stage to ensure their requirements are fully understood and investing in demonstration of new technologies and preparation of safety measures and risk based management can mitigated or avoid such risks. .

During construction phase bad weather or no access to specialist installation vessels (i.e. competing with other sectors such as oil and gas) may cause higher installation costs and delays, missing allocated construction/installation time windows. This risk will need to be considered in the project planning stage. The aquaculture farm can be assembled in a shore-based sheltered area located close to the deployment location, which reduces the risk of running into bad weather. Good connectivity and access to an established local supply chain of experienced contractors including specialist vessel operators will mitigate the risk and will enable aquaculture farm components to installation even at harsh conditions.

During operational phase pollution issues may result in ceasing power production, higher costs and delays and implications to potential injured personnel/subcontractors. At extreme circumstances pollution (e.g. from leaked chemicals) from wind turbine components could destroy or contaminate nearby aquaculture or even fisheries industries resulting in liable losses. Aquaculture production may also be affected as a result of operational wind park emitted pollution (i.e. noise/vibration) resulting in reduced yields and consequently less revenue generated. Formulating mitigation measures requires better understanding of the pressures of the wind park, including wind park size and technology used, which may interfere with the physiological status, and thus growth and settlement.

Insurance cover will transfer the aforementioned risks while the insurance sector involvement will ensure that the risk response measures are adequate for the scale of the intended operation. Employing an experienced environmental manager and team and monitoring of aquaculture stock with already established water monitoring techniques/regimes will ensure enough reaction time is available to all industries.

An adaptive monitoring programme will need to be established that in an event of any chemical spill rapid action and elimination of risk will be undertaken. The aquaculture and wind farm will be located relative in a secure distance one to another to minimise any harm to each other. This distance will be agreed by mutual consent to ensure that cost reduction benefits can also be realised.

Regarding issues of accelerated corrosion as a result of exposure to aquaculture activities, standard protection techniques are already in use in the offshore wind sector with sacrificial anode blocks or impressed current cathodic protection becoming standard practice in foundation design for wind turbines. Maintenance and inspection regimes will be revisited to ensure that any adverse effects will be captured early and acted upon.

Economic and Political

The key economic and political risks identified relate to issues around market entry due to intense competition including against established sectors such as fossil fuels and nuclear vs offshore wind and fisheries vs aquaculture shellfish. Competition against other renewables or organic farming would add magnitude to the risk. The "organic farming" brand name could be compromised due to combination of aquaculture-shellfish with a wind park on "industrial" production setting. Mitigation requires support from authorities and certifiers. Climate change is a driver for national policies including renewables in energy mix; opportunity for market entry exists for a large number of competitors but this is not restrictive apart from the competition for grants during early stage technology development. Possibilities to get certified require early cooperation with private and public standard-setting agencies.

Financial

The scalability of aquaculture activities may be severely limited in order to comply with insurance requirements due to the close proximity of the two industries. Due to lack of benchmark data insurance implications need to be studied early on in the design phase and insurance sector requirements to be fully understood. The proximity of the two different sector activities will need to be considered with scalability in mind, and ensure future expansion for either or both sectors.

Environment

The adverse impacts on the environment can be amplified by the combination of activities due to cumulative and in-combination impacts. During construction and installation, operation and maintenance, impacts on the physical environment as a result of offshore projects (and associated activities) is combined with impacts from other marine activities or users if the sea. A detailed environmental impact study, including ecosystem effects, needs to be undertaken to avoid these issues.

Socio-economic

The proposed activity can come with associated alterations to the marine historic environment through the use of manmade vessels, and offshore wind energy platform. The use of only proven technology (or technology with acceptable adverse effects levels) can mitigate these impacts. Knowledge of the surrounding waters – through baselines surveys and monitoring – is needed to ensure enough reaction time is available to industries to respond to environmental changes.

Health & Safety

Multiple Health and Safety risks are identified. Injuries can be caused by incident with geological features, including injuries as a result of vessel interaction during installation, cable lay or access (e.g. vessel grounding or capsizing), caused during foundation installation caused by gas pockets or equipment failure during pile refusal caused by geological features and as as a result of system interaction during installation (e.g. grounding or capsizing). Injury caused conflicting offshore operations and vessel interactions can be caused by vessel collision, by simultaneous operations (e.g. subsea and topsides) and by interference with other sea users. Dependent on the type of risk, mitigation strategies include conducting a full geological survey prior to installation, the development of adequate safety plans, targeting the prevention of simultaneous operations, and creation of a marine vessel exclusion zone in conjunction maritime authorities. Injury to divers during subsea operations include injury caused by entrapment, injury caused by falling objects, injury caused by decompression sickness and injury caused by use of tools underwater. Mitigating these risk requires divers to be fully certified, using a reputable dive company with an accident-free track record and ensuring that this company produces and complies with a high-level safety plan for the work being undertaken.

4.4 Feedback from the advisory session

The discussion in the advisory sessions highlighted the strengths and weaknesses of mussel aquaculture in offshore wind farms and pointed at the difficulties of realising this combination in practice. The combination is generally considered to be technologically feasible; no major objections to the technology or concerns about the safety and reliability of the system were raised, “The project does not seem to involve a lot of technological development” (expert 2), “the technology is all in place” (expert 4). The technological feasibility was rated high (average 8.4 on 1 to 10 scale).

Financial performance is valued lower. Experts are particularly concerned with the unclear, or absent, benefits for the offshore wind farm operator. For safety reasons – and subsequent insurance premiums – they will be reluctant to allow other operators within their wind farms. It is not clear enough if they benefit from co-location: “Is there a direct benefit from co-location?” (expert 5). Potential benefits can include the wave-dampening effect or restricted access to the park by unauthorised vessels but both need to be quantified to be taken into consideration. Lack of real-life experiences impacts on the experts’ assessment of the risks. Potential risks are acknowledged and risk mitigation strategies need to be developed in time. It is questioned “”Whether mussel farming will increase bio-fouling, a potential risk for wind farm operators (expert 11).

The weakness of the combination lies somewhere else: “No real or apparent technology problems – partnership issues and how to best work together need to be resolved for progress” (expert 1). There is no business committed to the development of this combination, despite the positive social benefits and business case. The critical question is which actors can be expected to take the lead in further developing this combination.

According to some experts, the wind sector is key. To initiate this combination one “Needs a wind farm developer on board.” (Expert 3). This will be challenging, given the fact that it is not clear what benefits they gain from the combination. The mussel sector is considered too small, lacking capital and human resources to invest in the development and experimentation with offshore technologies. If this combination is to take off, government intervention might be required. According to the experts, this can take two forms. Governments can stimulate or oblige co-use of the wind farms: “Unless there is an imposition from government, I don’t think it is going to happen” (expert 7). Alternatively, the public benefits of this combination and contribution to food security justify strong government support, either for pilots or direct involvement: “This combination is potentially important and needs to be sold to government” (expert 9).

5. Concluding remarks

Based on the economic model and the risk assessment, this paper concludes that mussel aquaculture is an appealing commercial model for increased returns in offshore wind farms. The economic models shows that the IRR and net present value are positive and from the sensitivity analysis it can be concluded that these results are robust. Synergy between the two sectors is limited with only some shared vessel use and shared Operations and Maintenance activities foreseen.

Earlier studies concluded that new vessels would be required for maintaining and harvesting the offshore mussel systems (Kamermans et al., 2016) and these extra costs are taken into account in the economic model. As for the aquaculture technology, the system is based on proven technologies, tested in other seas. The risks are well understood and expected to have low magnitude subject to well-developed mitigation strategies which are in place and supported by expert consultants, making it more likely that wind farm developers will be willing to accommodate multiuse.

As of now, there is no mussel aquaculture taking place in the offshore wind farms. The critical question behind this business case then is which of the sectors is motivated and capable to realise multiuse in practice. Confirming the conclusion of Röckmann et al. (2015); the wind sector is not likely to take this initiative. The mussel sector is significantly smaller and it is questionable if they have the financial and organisational resources to take this step.

Public involvement in testing and developing offshore mussel cultivation is justified as offshore mussel aquaculture comes with various socio-economic benefits. Next to efficient use of ocean space and a contribution to food security, mussel aquaculture contributes to a clean marine ecosystem. According to Lindahl et al. (2005), mussel aquaculture is a simple, flexible and cost-effective measure to counter marine eutrophication, and thus, the added benefits of mussel aquaculture for society are striking. The commercial mussel aquaculture can reduce societal costs of nutrient damage in sea water, stemming from, among others, organic fertiliser, food and human consumption, for which they are unrewarded.

A full-scale system has not yet been tested in the North Sea conditions. This leads to uncertainty, which can be taken away once a system is deployed and monitored. Public support for a pilot mussel cultivation in offshore wind farms can generate the evidence required to convince a reluctant sector to go offshore and use of the full potential of the marine ecosystem.

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Appendix 1 : Definitions

Type	Parameter	Definition
CAPEX	Project up to FID	Development and consenting work paid for by the developer up to the point of FID. Includes internal and external activities such as environmental and wildlife surveys, met mast (including installation) and engineering (pre FEED) and planning studies. Excludes: any reservation payments to suppliers.
	Project from FID to WCD	Includes: Further site investigations and surveys after FID Engineering (FEED) studies Environmental monitoring during construction Project management (work undertaken or contracted by the developer up to WCD) Other administrative and professional services such as accountancy and legal advice Any reservation payments to suppliers Excludes: Construction phase insurance and suppliers own project management
	Construction phase insurance	Cover from start of construction until operation start. All construction risks & third party
	Turbine	Payment to wind turbine manufacturer for the supply of the nacelle and its subsystems, the blades and hub, and the turbine electrical systems to the point of connection to the array cables. Includes: Delivery to nearest port to supplier, warranty, commissioning costs Excludes: Tower, OMS costs, RD&D costs
	Support structure (including tower)	Includes: Payment to suppliers for the supply of the support structure comprising the foundation (including any piles, transition piece and secondary steel work such as J- tubes and personnel access ladders and platforms) and the tower. Delivery to nearest port to supplier. Warranty Excludes: OMS costs,RD&D costs
	Array cables	Includes: • Delivery to nearest port to supplier, warranty Excludes: OMS costs, RD&D costs
	Mussel aquaculture system	Including mooring, longlines, support lines, marker buoys, floating supports, new vessel including 599 kW motor, motor overhaul after 10 years, land facility, license
	Installation	Includes: • Transportation of all from each supplier's nearest port • Pre-assembly work completed at a construction port before the components are taken offshore • All installation work for support structures, turbines and array cables

		• Idem for aquaculture • Commissioning work for all but turbine (including snagging post WCD) • Scour protection (for support structure and cable array) • Subsea cable protection mats etc., as required Excludes: • Installation of offshore substation / transmission assets
	Transmission build	Supply, cable laying, and construction of transmission assets from where array cables enter the offshore substation.
DECEX	Decommissioning	Includes: • Planning work and design of any additional equipment required • Removal of the turbine and support structure to meet legal obligations • Includes further environmental work and monitoring • Removal of the items used for aquaculture
OPEX	Operation and planned maintenance	Starts once first turbine and aquaculture site is commissioned. Includes: • Operational costs relating to the day-to-day control of the wind farm • Condition monitoring • Planned preventative maintenance, health and safety inspections • Idem for aquaculture, including cleaning, monitoring, harvesting, transport to harbour • Replacement of longlines, support lines, marker buoys in years 5, 10, 15. Including removal of old system
	Unplanned service	Starts once first turbine is commissioned. Includes: • Reactive service in response to unplanned systems failure in the turbine or electrical systems.
	Operations phase insurance	Starts once first turbine is commissioned, taking the form of a new operational “all risks” policy and issues such as substation outages, design faults and collision risk become more significant as damages could result in wind farm outage. Insurance during operation is typically renegotiated on an annual basis. Includes aquaculture
	Transmission charges	Includes: OFTO / Generation transmission use of system (G-TNUoS) charges.
	OPEX Other	Fixed cost elements that are unaffected by technology innovations, including: • Contributions to community funds. • Monitoring of the local environmental impact of the wind farm.
	Gross AEP	The gross AEP averaged over the wind farm life at output of the turbines. Excludes aerodynamic array losses, electrical array losses and other losses. Includes any site air density

Annual energy production		adjustments from the standard turbine power curve.
	Wind farm availability	Energy production loss throughout the project life time due to unavailability of the wind farm system. Accounts for improvements in early years and degradation in later years. Includes: Availability of wind turbines, structure and array cables, accounting for scheduled and unscheduled downtime. Excludes: Transmission availability on substation and to shore and wider grid.
	Aerodynamic array losses	Typical wake losses within a 500MW wind farm, dependent on turbine rating.
	Electrical array losses	Electrical array losses between the turbines and the offshore metering point for a typical 500MW wind farm. Excludes: Transmission losses.
	Other losses	Lifetime energy loss from cut-in / cut-out hysteresis, power curve degradation, and power performance loss.
	Net energy production	AEP averaged over the wind farm life at the offshore metering point at entry to offshore substation.
Annual mussel production	Mussel seed	Mussel seed, about 6 months after settlement of larvae on ropes. Ready for transport to other areas for further growth
	Half-grown	Mussels about 12 months old. Ready for transport to other areas for further growth
	Consumption mussels	Mussels ready for consumption

Appendix 2: Assumptions

Baseline costs and the impact of innovations are based on the following assumptions.

Global assumptions

- Real (2016) prices
- Commodity prices fixed at the average for 2016
- Exchange rates fixed at the average for 2011 (that is, for example, €1 = €1.18). For GDP-Euro exchange rate, this is in line with average exchange rate second half of 2016.
- Energy prices fixed at the current rate

Synergy

Based on the discussion on costs saving by sharing Operation and Maintenance facilities (see section 3.4), the following synergies are assumed:

- Sharing vessels reduces costs for vessel (in CAPEX) for the mussel farm by 10%
- Because the wind farm provides a more monitoring of the area for the mussel farmer, mussel farmers costs for insurance (in OPEX) are reduced 5%
- Sharing environmental monitoring systems reduces this costs for the mussel farmer by 10% (in OPEX)

Wind farm assumptions

The general assumptions are

- 500MW wind farm, as part of a multi-gigawatt Round 3 zone
- Turbines are spaced at nine rotor diameters (downwind) and six rotor diameters (across-wind) in a rectangle
- A wind farm design is used that is certificated for an operational life of 20 years

- The lowest point of the rotor sweep is at least 22 metres above MHWS
- The development and construction costs are funded entirely by the project developer, and
- A multi-contract approach is used to contracting for construction.

The meteorological regime assumptions are:

- A wind shear exponent of 0.12
- Rayleigh wind speed distribution
- A mean annual average temperature of 10°C
- The P90 energy yield is 11 per cent lower than P50 (in base case)
- The tidal range of 4m and the Hs of 1.8m is exceeded on 15 per cent of the days over a year at Site Types A, B and C, and 25 per cent of the days at Site Type D, and
- No storm surge is considered.

The turbine assumptions are:

- The turbine is certified to Class IA to international offshore wind turbine design standard IEC 61400-3
- The 8MW turbine has a169m diameter, and a specific rating of 354 W/m².

The support structure assumptions are:

- A four-legged piled jacket with a separate tower is used, and
- Ground conditions are ”typical”, that is, most relevant to Round 3 zones, namely 10m dense sand on 15m stiff clay, only occasionally with locations with lower bearing pressure, the presence of boulders or significant gradients.

The array cable assumption is that a three core 33kV AC on fully flexible strings is used, that is, with provision to isolate an individual turbine.

The installation assumptions are:

- Installation is carried out sequentially by the foundation, array cable, then the pre-assembled tower and turbine together
- A jack-up vessel collects components from the installation port for turbine installation
- Two jack-ups are used for jacket installation and pre-piling, collecting components from the installation port, and
- Array cables are installed via J-tubes, with separate cable lay and survey and burial. Decommissioning reverses the assembly process to result in installation taking one year. Piles and cables cut off at a depth below the seabed, which is unlikely to lead to uncovering. Environmental monitoring is conducted at the end. The residual value and cost of scrapping is ignored.

Operations, Maintenance and Service assumptions are:

- Transmission charges for use of system are incurred as OPEX (the build is incurred as CAPEX), and
- Access is by work boats and mother ships or accommodation platforms for Site Type D, while jack-ups are used for major component replacement.

Appendix 3: Input parameters

CAPEX			OPEX and DECEX		
Sector	Item	€ m	Sector	Item	€ m
Wind	Project Consenting and Development to FID	71.7	Wind	Operation, maintenance and service (planned & unplanned, figures relate to post-warranty cost)	565.0
	Project management from FID to WCD	16.1		Operating phase insurance	143.5
	Construction phase insurance	18.4		Transmission charges	89.7
	Turbine (exc. Tower)	541.2	Mussel	Maintenance - cleaning	1.1
	Support structure (inc. tower)	257.4		Maintenance - monitoring	1.1
	Array cables	35.4		Maintenance - repairs	1.1
	Installation	137.2		Maintenance - unplanned service	1.1
	Transmission build	192.4		Harvesting - labour	4.4
	Construction contingency	119.8		Harvesting - fuel costs	23.5
Mussel	Project up to FID	0.7		Processing, packaging and storage	7.3
	Project from FID to WCD	0.7		Insurance	5.0
	Construction phase insurance	0.7		Material - longlines	15.0
	Moorings/ foundations	0.6		Material - support lines	2.3
	Infrastructure - longlines	5.0		Material - Marker buoys	0.3
	Infrastructure - support lines	0.8		Environmental monitoring	2.3
	Infrastructure - Marker buoys	0.1		Management	2.2
	Infrastructure - Floating supports	1.6		**TOTAL OPEX**	**864.8**
	Installation of farm and moorings/foundations	0.7	Wind	Decommissioning wind farm	89.2
	New vessel	28.2	Mussel	Decommissioning mussel farm	1.7
	Motor	3.0		**TOTAL DECEX**	**90.9**
	Land facility	11.7			

	License	0.2
	Construction contingency	5.7
	TOTAL CAPEX	**1,449.2**