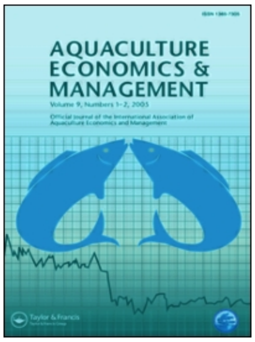

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The economic feasibility of seaweed production in the North Sea

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ABSTRACT

Seaweeds are increasingly seen as an alternative to land-grown products in food and feed applications. Interest in production of seaweeds in temperate waters is rising, in particular in combination with offshore wind energy generation. This article reports an investigation of the economic feasibility of seaweed production in the North Sea using economic modelling. Often, an overly positive picture of the costs and benefits of seaweed production is sketched. Based on current available information, offshore seaweed production in the North Sea is not economically feasible. Sensitivity analysis shows that revenues would have to increase by roughly 300%, all other things equal, to make a profit. A number of opportunities to improve the economic feasibility of a North Sea seaweed value chain are identified. Technical innovation and the design of systems that enable multiple harvests per year can reduce production costs. Successful marketing of seaweed as human food, and the development of biorefinery concepts can increase the value of the produced seaweed.

KEYWORDS

Economic modelling; north sea; seaweed; sensitivity analysis; wind energy

Introduction

In recent years, interest in seaweed production in the Northern hemisphere has grown for multiple reasons. Seaweeds can be used as feedstock in a wide range of production processes. In Europe, seaweeds are currently mainly used for the production of the hydrocolloids alginate, agar and carrageenan, used in the food industry as thickener (Bixler & Porse, 2011). Seaweed can also be used for food and food additives (Holdt and Kraan, 2011; de Boer et al., 2013), fed to animals (Wilding et al., 2006; Soler-Vila et al., 2009; Rust et al., 2011; Mesnildrey et al., 2012; Bikker et al., 2013), be used for the production of green chemicals (Wal et al., 2013; Wei, Quarterman, & Jin, 2013) or bioenergy (Sustainable Energy Ireland, 2009; Mata et al., 2010; Borines et al., 2011).

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It is also argued that cultivation and use of seaweeds can mitigate a range of major contemporary environmental issues. Through strategic positioning of production facilities, seaweed production can reduce ocean eutrophication as nutrients are taken up during growth and removed by harvesting the seaweed (He et al., 2008). Use of seaweeds, rather than fossil fuels, can contribute to climate mitigation (Sustainable Energy Ireland, 2009; Dave et al., 2013). The use of seaweeds as a feed additive for livestock can reduce soy imports, thereby combating deforestation in soy-producing countries, whereas use for fish feed can reduce fish catches and tackle overexploitation of fish stocks (Wassef et al., 2005; Valente et al., 2006).

The European Blue Growth strategy, published in 2012, recognizes the potential of marine protein production for strengthening the European economy.[1] Marine protein production can be particularly relevant for coastal and fisheries communities that are under pressure due to declining fish stocks and available fishing grounds. Concerns about the land-use impacts and water use of terrestrial crops grown for biofuel are driving efforts to explore the use of algae as a source of biofuels.

Growing interest in seaweed has led to experimental production in various European countries bordering the North Sea (Lüning and Pang, 2003; Kraan, 2013). However, information with regards to the economic feasibility of seaweed production in the Northern hemisphere is scarce. The aim of this article is to assess the economic feasibility of producing seaweeds in combination with offshore wind in the North Sea. The main research question addressed: 'Is seaweed production in the North Sea economically feasible?'

Increase in the installed capacity of offshore wind energy comes with significant spatial claims; the Dutch government estimates that 1,000 km^2 are required to meet long-term policy objectives for offshore wind. The large-scale development of offshore wind farms in the North Sea is considered to offer opportunities for aquaculture (Buck et al., 2004). This can include seaweed aquaculture as the synergy between these two production systems can reduce the costs for both seaweed production and offshore wind energy generation (Buck et al., 2004; van den Burg et al., 2013).

This article argues that under current assumptions, offshore seaweed production is not economically feasible. A positive business case is realized if revenues – either the price or yield – go up by about 300%.

Method

This study examines the economic feasibility of seaweed production in the vacant space within the confines of an offshore wind farm by use of an economic model. Based on scientific literature, reports, and interviews, insight was gathered into the current and potential status of offshore seaweed production in combination with offshore wind energy generation. A sensitivity analysis was carried out to examine the effects of changes in input parameters. In this analysis we focused on the following species: *Laminaria digitata, Saccharina latissimi, Palmaria palmate and Ulva lactuca* because they are indigenous to the North Sea (Reith et al., 2005; van den Burg et al., 2013).

Data collection

First, a literature review was conducted to collect information on the estimated production costs and revenues. Lack of reliable information on the costs of offshore production required us to also utilize the judgments of sector experts. This included scientific researchers with firsthand experience in seaweed production ($n = 2$), entrepreneurs who produce seaweed on a commercial basis ($n = 4$), and value chain representatives ($n = 5$). Contacts already existed with some of these interviewees, whereas the remainder were selected through the snowball method (Noy, 2008). Some of the respondents asked to remain anonymous. The collected data were used as input to the model. An exchange rate of €/US$ of 1.38 was assumed.

Model description

The model was developed using the following assumptions:

- Construction of the offshore wind farm is taken as already established, with the analysis focused on the potential benefits of co-production of seaweeds.
- Both the offshore wind farm and the seaweed production facility are operated by the same owner. Zero transaction costs are assumed between the two activities.
- Infrastructure facilities are not co-used (for example tying long lines to the foundations of wind turbines). Although this is described in some studies, experts argued that at this stage there is insufficient knowledge about the risk and opportunities involved.
- Synergy is expected in the labor and transport.

To analyze if the vacant space can be used, we used a simple linear model. The starting point is the offshore wind farm, which we presume is operational. Next, we assumed that there are two possible activities: do nothing or produce seaweed. The total net profit of the use of vacant space is maximized, where net profit of activity j is defined as the revenue minus the total cost.

$$\max \sum_{j} profit_j = \sum_{j} \left(revenue_j - TotCost_j \right)$$

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

$$Revenue_j = p_j * q_j * space_j$$

The total cost of activity j is defined as the fixed cost per hectare (cs_{fixed}) plus the maintenance cost per hectare (cs_{repair}) plus harvesting and transport cost (from offshore production site to in-land processing facility) per hectare (CS_{trans}) plus the labor cost per hectare (CS_{lab}) plus the material cost per hectare (CS_{mat}) plus the other variable cost per hectare (CS_{other}) time the assigned space for the activity.

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

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

$$\sum_j space_j \leq TotalSpace$$

Seaweed prices are based on the prices of the baseline year (p_{base}) adjusted with a price elasticity (elas). For the case of simplicity we assumed that the seaweed production outside of the offshore wind farm stays constant at level q_{base}.

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

The offshore windfarm operator can choose to leave the available space vacant. This option is included because, if the production of seaweed is unprofitable, it would be less costly to leave the space vacant. It is assumed that synergy exists between seaweed production and wind farms, sharing some of the transport and labor costs. This means that labor costs and transport costs for wind farms will be lower if seaweed production is implemented in the vacant space. If there is no seaweed production in the vacant space, the transport and labor costs can no longer be shared with the production of seaweed and these costs will increase for the offshore wind farm operators.

Results

Costs for seaweed production in the North Sea

Literature on the economics of seaweed production is scarce and covers various species, various production methods and environmental conditions. Comparability of different sources is low and data should be treated with caution. The FAO has initiated a series of studies to examine social and economic dimensions of carrageenan seaweed farming (Msuya, 2013; Robledo et al., 2013). Based on these studies, Valderrama et al. (2015) showed large differences in the economic performance of seaweed production. In the countries studied (Indonesia, Philippines, Tanzania, India, Mexico, Solomon Islands) seaweed farming is a profitable business. The production systems were small-scale and labor-intensive (Cai et al., 2013; Valderrama et al., 2015). Size of the systems varied between 30 × 10 meter and 1 hectare. Labor conditions included family labor (Hurtado & Agbayani, 2002) and wages below $1 per hour (Valderrama et al., 2015). Tropical experience with marine and brackish water seaweed production is therefore not comparable to seaweed production in marine temperate waters like the North Sea. Future North Sea seaweed production will not be comparable.

Currently, seaweed is not produced at a significant scale in the North Sea. According to FAO data, the countries bordering the North Sea produced no seaweed at all until 2007. The latest data report 40.000 tons of seaweed production in Denmark.[2] Various research projects investigated the technical feasibility of seaweed production in marine temperate waters including the North Sea, using different culture methods. In the first section, ongoing projects are reviewed, looking for information on the cost of seaweed production. In the second section, the costs of seaweed production in the North Sea are estimated based on expert judgment.

Results of the literature review on seaweed production costs in the North Sea

A German research project used a ring-system around the piles of wind-turbines. The costs for one ring are estimated at US$1,380 with a life span of 10 years. The rings are limited in size and each annually produced 0.04 metric tons of dry matter (DM) of seaweed (Buck & Buchholz, 2004). Costs per metric ton of DM then equal US$3,450. A Dutch study claimed that large-scale offshore production of *Gracillaria* and *Laminaria* is possible at costs between US$155 and US$564 per metric ton DM (Reith et al., 2005). This study draws on outdated data and most likely these figures represent average production costs for different production methods, countries and environments. Florentinus et al. (2008) report investment costs of US $55,200 per hectare for offshore seaweed cultivation in the North Sea, with expected yields of 30 metric tons of DM per hectare.

Lenstra et al. (2011) formulated three scenarios to calculate the production costs of systems varying in scale: 100 hectare, 1,000 hectare and 10,000 hectare. In the 100 hectare scenario, they assumed a total investment of US $345,000 per hectare. Operation and maintenance costs were set at US $1,035 per year, harvesting costs at US$144 per metric ton of DM. With an estimated yield of 50 metric tons of DM/hectare/year, indicated costs for a metric ton of DM seaweed were US$923. The most detailed information available is from a 1993 study near the Canadian coast (Petrell et al., 1993). This study concluded that initial investment costs for a 60 × 20 meter farm totaled US$61,463[3] (1992 data, including costs for boats, shed and dryers). Additional operational costs were concluded to be US$16,774 for production of 1.6 metric ton of DM. The data from Petrell et al. are over 20 years old; corrected for inflation these account for respectively US$88,164 and US$24,064.[4] Table 1 provides a summary of the costs of seaweed production in the literature.

This table illustrates of the uncertainty about costs of offshore seaweed production. It showed there is little consensus on the costs of seaweed production. Estimated costs differed by a factor of 100. This is only partly explained by the exclusion or inclusion of certain costs (for example, harvesting and transport costs). The overview also showed that expected yields varied greatly, going up to 50 metric tons DM per hectare.

Expert judgment on costs for seaweed production in the North Sea

In the Netherlands there are multiple ongoing research projects experimenting with marine offshore seaweed production. These research projects use two different cultivation systems, namely net cultivation and long-line systems. In the following paragraphs, the costs of seaweed production are estimated based on expert judgment.

There is consensus among consulted stakeholders that offshore production of seaweeds will be based on long-line techniques, already familiar to mussel farming.

The prospects for seaweed production within offshore wind farms have been much discussed. The stakeholders considered it unlikely that the long-lines will be attached to the wind turbines or foundations. Instead, it is assumed that the vacant space between the turbines can be used for seaweed cultivation (see Figure 1). The foreseen production sites are located offshore, 75–150 km from harbors. Based on experiences with seaweed cultivation, the respondents expect yields of 20 metric tons of DM per hectare (see also van den Burg et al., 2013). Expert judgement on costs assumed large-scale production to achieve economies of scale. A 4,000-hectare production facility was envisioned.

Fixed costs

The total investment for the installation is estimated at US$138,000 per hectare, including those elements which do not need yearly replacement (baselines, buoys, mooring and equipment). The current production costs in the Eastern Scheldt estuary range from US$34,500 to US$103,500 per hectare.

Table 1. Estimated costs for seaweed production in literature.

Technology	Seaweed species	Investment	Lifespan	Operational costs	Harvesting	Yield	$ per ton DM	Source
		$	*Year*	$ *year*$^{-1}$	$ *Ton DM*$^{-1}$	*Tons of DM*		
Ring	*Laminaria*	1,380 unit^{-1}	10	n.a.	n.a.	0.040 unit^{-1}	3,450 costs$^{(1)}$ + operational costs	Buck and Buchholz (2004)
Long-lines	*Laminaria or Gracillaria*	n.a.	n.a.	n.a.	n.a.		155 – 564$^{(1)}$ + operational costs	Reith et al. (2005)
Long-lines	n.a.	55,200 ha^{-1}	10	n.a.	n.a.	30 ha^{-1}	Ca. 360	Florentinus et al. (2008)
Long-lines	n.a.	345,000	10	1,035 ha^{-1}	144	50 ha^{-1}	923$^{(2)}$	Lenstra et al. (2011)
Long-lines	*Laminaria*	61,463	10	16,774	n.a.	1,6 farm^{-1}	16,630$^{(3)}$	Petrell et al. (1993)

1) excluding capital costs, opportunity costs, labor costs.
2) Based on 10% Return on Investment.
3) Including cost for transport, labor and storage.

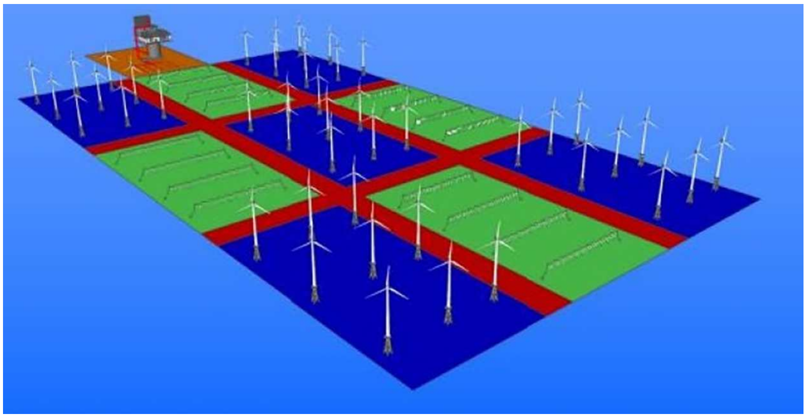

Figure 1. Design for combined wind and seaweed farm (based on Lagerveld et al., 2014).

For marine offshore application, experts expect these fixed costs to double and range between US$69,000 and US$207,000. In the economic modeling the average of these high and low scenarios was used: US$138,000. The expected lifespan of installations is set at 10 years, based on experiences. At an interest rate of 6.25%, it means that the annual repayment costs equal US$18,594.[5]

Labor costs

Estimating the labor costs is difficult in the absence of clear established procedures. Because we assume wind and seaweed facilities have the same owner (see model description), workers are seen as employees. Assuming that operation and maintenance of a 4,000-hectare seaweed production facility requires 16 man-years of work (16*261 days*8 hr = 33,408 hrs.) and labor costs of US$50/hour[6], total labor costs are set at US$1,670,400. This equals approximately US$418 per hectare. This excludes harvesting of the seaweeds (see harvesting).

Harvesting and transport costs

The total costs for harvesting and transport are set at US$2,860/hectare. The periodic harvesting of seaweed biomass can mechanically be performed by specially designed ships and equipment. Technically, this shows similarities to current systems used for offshore mussel farming. It is foreseen that seaweed producers will not invest in their own harvesting equipment because this equipment is only needed occasionally. Instead it is expected that they opt to hire contractors. Based on expert judgment, costs for the harvesting are estimated at US$1,380 per hectare, assuming deployment of vessels with capacity for mechanical harvesting of large areas of seaweed farms. This includes labor costs.

Transport is split up in three parts: from seaweed farm to harbor, unloading/loading and transport to the processing facility. Transport costs to the harbor are calculated on the basis of Suurs (2002). According to Suurs (2002), the greatest share in transport costs consists of the cost of loading and unloading. For an average transport distance of 200 km (including the ship's movements for harvesting), costs for transport are set at US$5.5 per metric ton (US$4.4 for unloading/loading wet seaweed and US$1.1 for transport). Since seaweeds consist of 12% DM, this amounts to approximately US $45 per metric ton of DM. This equals US$910/hectare. Transport costs to the processing facility are estimated at US$28.50 per metric ton of DM or US $570/hectare.

Material costs

In the foreseen production system, a secondary line with seaweed seedlings is wound around a base-line. New secondary lines with seaweed seedlings have to be added annually after harvesting. The expected costs of adding secondary lines with seedlings are estimated at US$1.38/m. As the lines are located 1 m apart, a hectare requires a total of 10,000 m of secondary lines with total yearly material costs for US$13,800/ hectare.

Maintenance costs

Information about the maintenance costs is not available. The production system is relatively simple and experts assume few repairs are needed. However, if maintenance is necessary, offshore operation makes it expensive. Maintenance costs are estimated to be 5% of the total annualized investment costs, equaling US$690 per hectare.

Insurance costs

The costs for insurance of the seaweed production facility are estimated at US $700 per hectare. If offshore seaweed production takes place within wind farms, it is expected that insurance costs for the offshore wind farm operators slightly increase. This increase is estimated by experts at circa US$135 per hectare.

Synergy with offshore wind energy

The marine offshore production of seaweeds is often studied in combination with other activities, most notably offshore wind energy (see e.g., Lagerveld et al., 2014 and the FP7 MERMAID project[7]). Expected synergy between offshore seaweed production and wind energy generation is foreseen in labor and transport (see Griffin et al., 2015 for synergy between wind farms and mussel cultivation). Synergy is not foreseen in sharing facilities or foundations. If maintenance vessels have to visit the offshore wind farm, they can also serve the seaweed production facility and vice versa.

If personnel are at the site and not able to work on the wind turbines, they can work some of the time on the seaweed facilities and vice versa. The control room and monitoring facilities (e.g., for weather conditions) can be shared. However, expected synergy is relatively low, at around 3% of total operation and management (O&M) costs of offshore wind. Based on Griffin et al. (2015) and experts consulted in the Blauwdruk project, synergy can reduce shareable O&M costs of labor and transport with 10%. With average O&M costs set at US$41/MWh, the expected cost reduction of offshore wind farm operators is set at US$1,445/hectare for fixed costs and US$817/hectare for transport (Lagerveld et al., 2014).

Estimation of revenues

In Europe, North Sea seaweed and derived products can potentially be utilized for the following purposes: human consumption, industrial gums, animal feed and green chemicals. Other uses that are outside the scope of this study, because of a lack of experience and data, are for example: biofuels, fertilizer, cosmetics, medicinal users and use as bio filter in Integrated Multi Trophic Aquaculture (IMTA) systems (Troell et al., 2009; Abreu et al., 2011).

Direct consumption by humans

Worldwide, human consumption is the most important use of seaweed both in volume and added value. FAO data (McHugh, 2003) showed that more than 6 million metric tons are consumed annually with the largest markets all in Asia (China 5 million metric tons, Republic of Korea 800,000 metric tons, Japan 600,000 metric tons). For a bulk packed consignment of 100 kg and over, prices vary between US$18 and US$23.5 per kg, with *Palmaria* achieving a price premium of about 50% over *Laminaria*. Accurate figures, however, are difficult to come by (Douglas-Westwood Limited, 2005).

The European market for directly consumable seaweeds is small, but appears to be growing. Exact data on trading volumes is lacking, but seaweed is not a common product in stores. Currently, locally produced seaweeds are sold as ‘wakame’ seaweed for prices around US$8.00 per 50 g. Fresh seaweed salad was sold in store for US$3.80 per 100 gr. (containing 70% seaweed), but this is imported. In various Northern European countries new products have been developed that use seaweeds for human food, such as the Dutch Weed Burger, seaweed crisps and mayonnaise.[8]

Hydrocolloids

Hydrocolloids extracted from seaweeds fall into three categories: alginates, agars and carrageenans. These are commonly used in food products such as ice cream, pet foods and vanilla custard to increase viscosity, and as an emulsifier. Of these, alginates are of particular interest since they are produced from the brown seaweeds that can be cultivated in the North Sea.

Sustainable Energy Ireland (2009) concluded that the world market for alginates is roughly 30,000 metric tons at an average of US$6,000–10,000 per metric ton of DM. Bixler and Porse (2011) conclude that in 2009 total sales volume of hydrocolloids was 86 thousand tons and the world alginate market totaled 26 thousand tons, worth US$318 million. This leads to an average price of US$12,000 per ton alginate. Bixler and Porse (2011) also conclude that total amount of harvested alginate seaweeds reached 95,000 tons DM in 2009. The average export price in 2009 for seaweeds for hydrocolloid production ranges from US$350 to US$3,400 per metric ton DM. The average price for Chilean dry *Lessonia* spp – for alginate production – was US$950 metric ton DM (Bixler & Porse, 2011).

The prospects for the alginate and thickeners market are not clear cut. Demand for thickeners in Europe is growing slowly and alternative thickeners are available. Global demand is estimated to grow slowly, at a few percent annually (CBI, 2011), but research showed that there is a danger of market saturation (Reith et al., 2005). The demand for competing products (such as gelatin) is already decreasing (Sustainable Energy Ireland, 2009). However, demand for thickeners in other countries is likely to grow as this demand for processed food increases. This might put pressure on the availability of seaweed-based thickeners. Availability of seaweeds for alginate production has not been a problem during the last decade but can be expected to present supply and costs problems in the near future (Bixler & Porse, 2011).

Animal feed

One of the foreseen future uses of seaweed is application as an animal feed ingredient or additive. The feed market is promising, as it is a large industry which processes significant amounts of raw materials. The total amount of soy used in the Netherlands for feed (2010–2011) equaled 2,353,000 metric tons.[9]

We calculated the economic value of several 'intact' (not refined) seaweed species by use of a feed optimization program (Bestmix[10]). This program allows the calculation of the economic value for feed applications. Based on the characterization of the seaweeds, the program analyses which current ingredients can be removed from the feed-mix and calculates total value of those ingredients. The expressed value of seaweeds thus represents the avoided costs for other feed ingredients. The economic value was expressed as the price (metric ton of dry product, 94% DM) which resulted in a 5% addition of seaweed into a grower pig diet. Based on these assumptions, the economic value was US$0.00/metric ton DM for *Laminaria digitata*, US $61.60/metric ton DM for *Saccharina latissima*, US$168.22/metric ton DM for *Palmaria palmate* and US$67.29/metric ton DM for *Ulva lactuca*.

Setting a value for North Sea seaweed

The various applications of seaweed come with different market values, with prices for human food and alginates higher than the economic value for use in animal feed. Although human consumption offers the highest prices, current consumption levels can be met with small-scale production in estuaries and do not require large-scale, offshore production.

To quantify expected value of seaweeds produced in the North Sea, it is assumed that half of the product is used for production of hydrocolloids and half for animal feed. The price that hydrocolloids producers are willing to pay for seaweed sales is expected to be US$950/metric ton of DM. It is not expected that demand for hydrocolloids will increase so much that all seaweeds can be used for this purpose. The second application of seaweeds is use in animal feed. The sales price for use in animal feed is set at US$160/ metric ton of DM. Consequently, average price is set at US$555/metric ton DM.

It is recognized that large-scale production of seaweeds for alginate production will increase supply and lead to lower prices for seaweeds. Information on the price elasticity of alginate unfortunately is not available and we opted for a relatively low price elasticity of 0.02.

Economic modelling

Model simulation results

The model simulations showed that seaweed cultivation within offshore wind farms is currently not profitable. Based on the input data formulated above, the seaweed production in the offshore wind farm would result in a loss of circa US$23,834 per hectare per year. The negative profit for wind farm reflect the higher costs for wind farm operators if– since prices are too low – no seaweed cultivation takes place and no synergy can be realized. Table 2 provides an overview of the input and output of the model, based on the analysis above.

However, since marine offshore cultivation of seaweeds is not a common practice in the North Sea, there is uncertainty about some of the input parameters. The question is how sensitive these results are for changes in the

Table 2. Overview of input parameters and output.

Description		Seaweed	Synergy for wind farm operator
Fixed costs	$ Ha^{-1} yr^{-1}	18,594	0
Labor costs	$ Ha^{-1} yr^{-1}	418	−1,445
Harvesting and transport costs	$ Ha^{-1} yr^{-1}	2,860	−817
Material costs	$ Ha^{-1} yr^{-1}	13,800	
Maintenance costs	$ Ha^{-1} yr^{-1}	690	
Insurance costs	$ Ha^{-1} yr^{-1}	700	135
Price	$ Ton DM^{-1}	555	
Price elasticity		0.02	
Yield	Ton DM Ha^{-1} yr^{-1}	20	0
Available area	Ha	4,000	4,000
Total costs of production	$ Ha^{-1} yr^{-1}	37,062	
Effect of synergy with offshore wind	$ Ha^{-1} yr^{-1}		−2,128
Gross revenue	$ Ha^{-1} yr^{-1}	11,100	
Result	$ Ha^{-1} yr^{-1}	−23,834	
Breakeven price	$ Ton DM^{-1}	1,747	
Breakeven yield	Ton DM Ha^{-1} yr^{-1}	63	

base data. Sensitivity analysis was done to shed light on the economic consequences changing seaweed value and increased yields.

Sensitivity analysis

The marine offshore production of seaweed under the given assumptions is not viable in terms of profitability, but changes in the seaweed market could result in higher prices. Changes can consist of an increased demand for seaweed for high-value food applications, an increased demand for alginates to be used as thickener in foods or extraction of high-value food and feed additives.

Sensitivity analysis was carried out to analyze how much seaweed price needs to increase to be profitable. The results show that with a price of US $1,747/metric ton of DM, seaweed production becomes profitable (see Figure 2). This means that the price of seaweed needs to increase by roughly 300% from current estimates to make profit.

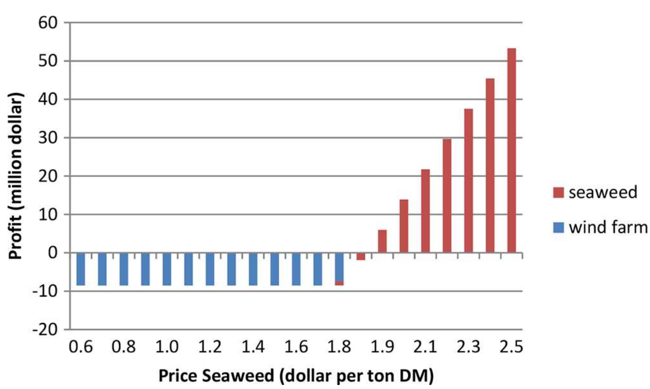

Figure 2. Sensitivity to changes in seaweed price.

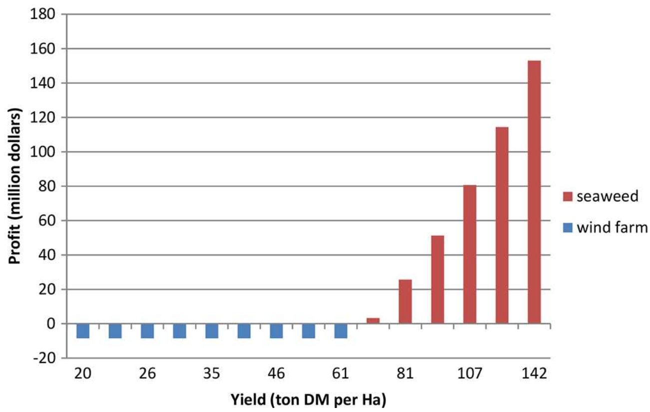

Figure 3. Sensitivity to changes in yield.

Also, it is not unlikely that increased knowledge of offshore seaweed production and improved quality of the seedlings can result in higher yields per hectare. Current research efforts also focus on the possibilities to have multiple harvests per year, combining various seaweed species into one production system. In the base case it is assumed that 20 metric tons of seaweed can be produced on 1 hectare. Figure 3 shows that production per hectare needs to increase to around 60 metric tons per hectare to be profitable – assuming costs for production and transport do not increase. Again, this is an increase of circa 300%.

Conclusions: The prospects of seaweed production

Based on current information on the costs and benefits, offshore seaweed production in the North Sea is not economically feasible. The combination of offshore wind energy and seaweed production does not change this; the expected synergies in O&M do not turn seaweed aquaculture into a profitable business. Adding to that, Wever et al. (2015) argue that the risks of co-use are significant and render development of co-use concepts difficult. Other types of aquaculture – such as mussels or fin fish – might be more profitable (Buck et al., 2010) .

Clearly, some publications sketch an overly positive picture of the costs of seaweed production. Yet it is too early to draw a final conclusion on the economic viability of developing a North Sea seaweed value chain. There are still many uncertainties about the exact costs of production and the potential revenues. The market for seaweed products is diverse. Human consumption offers highest values but there is currently only a small market demand for seaweeds. Direct consumption by animals offers low value. It is economically more interesting to produce feed additives from seaweeds, but more research into these applications is required (van den Burg et al., 2013). Use of seaweeds for the production of biofuels seems unlikely in the near future because low prices are paid for biofuel material.

Looking at the production costs, the initial investment in installation and the annual purchase of seedlings constitute the largest costs. There are a number of opportunities to improve the economic feasibility of a North Sea seaweed value chain. Technical innovation and the design of systems that enable multiple harvests per year can reduce production costs. The potential synergy with offshore wind energy needs to be explored further as this could reduce costs as well.

North Sea produced seaweed faces heavy competition from Chinese produce. Chinese producers are criticized for their environmental impact caused by heavy fertilization (Cao et al., 2007; Li et al., 2011). If North Sea produced seaweed can claim to be more sustainable, the challenge is to prove such claims (for example through certification) and ensure additional value. The societal benefits of seaweed cultivation, for example bioremediation of contaminated waters, can add to the total value of seaweeds. This raises the question how such benefits can be converted in financial benefits, for example through Payment for Ecosystem Services schemes (Gómez-Baggethun et al., 2010).

Available literature generally focuses on single-use of seaweeds. The possibilities to combine different applications through advanced biorefinery might be key to the development of a feasible seaweed value chain. More data on the possibilities to establish a cascade of applications, for example the extraction of valuable hydrocolloids, followed by extraction of functional food additives and use of remaining material as feed ingredient or source of biofuels, is required.

Notes

1. http://ec.europa.eu/commission_2010-2014/damanaki/headlines/press-releases/2012/09/20120913_en.htm (9-4-2014).
2. http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en (01-10-2015).
3. Based on the 2014 exchange rate CAD/USD = 0.911 (29-4-2014).
4. 1993 = 85.6, 2013 = 122,8: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/econ46a-eng.htm.
5. http://www.thecalculatorsite.com/finance/calculators/loancalculator.php (6-11-2014).
6. Based on average labor costs in Netherland, http://appsso.eurostat.ec.europa.eu/nui/show.do (01-10-2015).
7. http://www.mermaidproject.eu (12-12-2014).
8. http://www.wereldvanzeewier.nl/ (6-11-2014).
9. http://www.pdv.nl/lmbinaries/pdv10-11.pdf (12-12-2014).
10. http://www.adifo.be/en/products/raw-material-management-multiblend-least-cost-feed-formulation-software (17-12-2014).

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