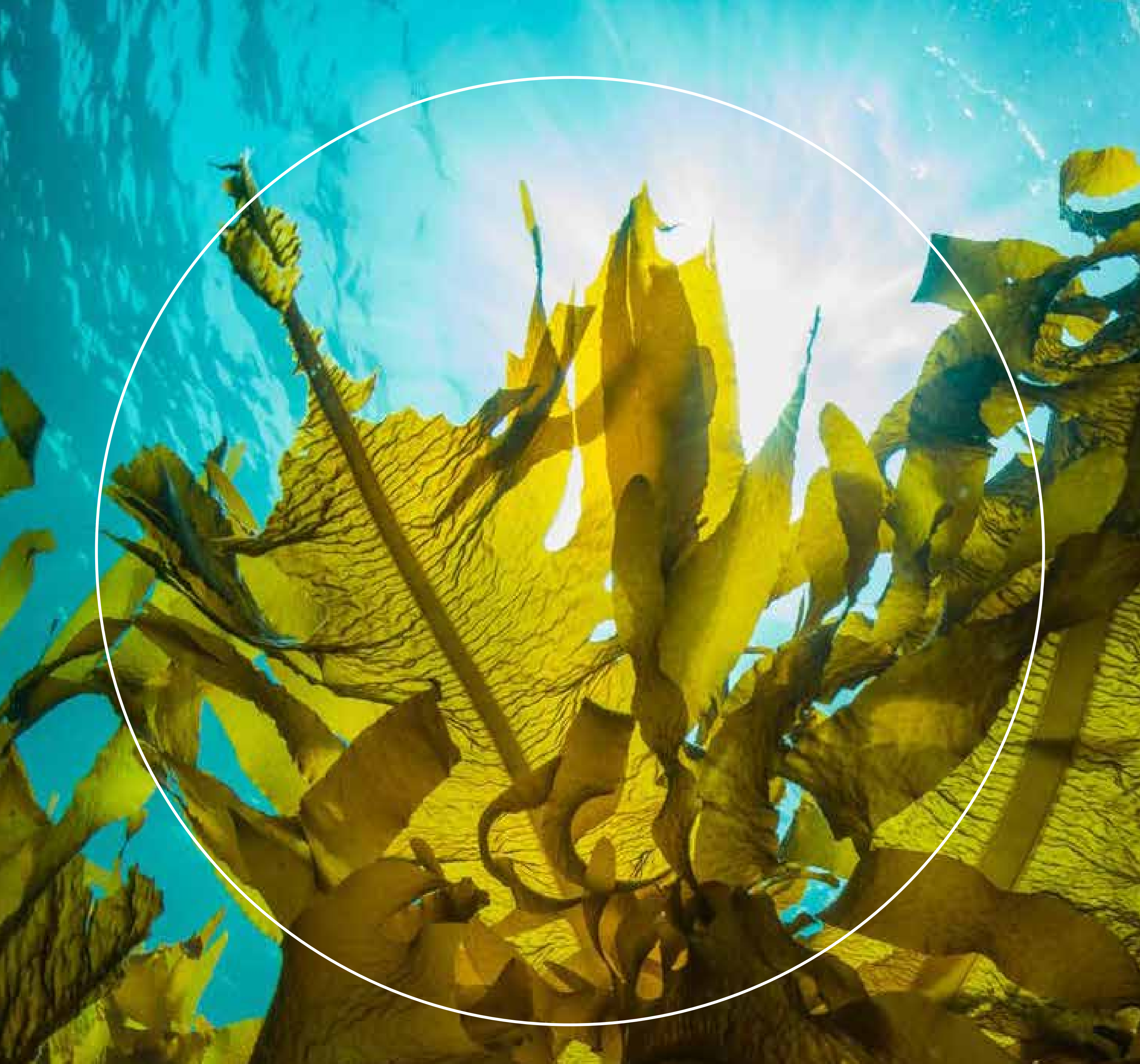

The business case for seaweed aquaculture in the North Sea

Learning from international experiences

Elisa Ciravegna, Sophie Koch, Sander van den Burg

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The goal of this study, conducted under the Proseaweed programme, is to learn from international experiences about the business case of seaweed farming in the Dutch North Sea. This report provides an overview and analysis over the limited data on the costs computed in previous studies. Three interviews with promising companies were conducted: Ocean Rainforest, Artic Seaweed and The Seaweed company. Literature and case studies were used to gather qualitative data on factors leading to successful seaweed farming, so-called success factors. The results show that site selection with ideal water conditions is essential for a good harvest and even the potential for longer operating windows. These conditions are not found in the Dutch North Sea and innovations would be needed.

Key words: production cost, Europe, value chain, upscaling, seaweed industry, site selection, success factors, Saccharina latissima, North Sea, Alaria Esculenta, Laminaria digitata

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Preface

Seaweed is living a renaissance and there are high hopes for this climate change mitigating, fast growing, versatile and sustainable new resource. The seaweed sector in Europe is growing, but still in its infancy. The Netherlands, with its history in aquaculture and fisheries, is investigating how seaweed farming could become profitable for companies and thus a sustainable new resource from the Dutch coast. As this young history of the industry in Europe shows, there is not yet a lot of data to learn from. This report reviews the existing economic quantitative and qualitative data on seaweed farming in Europe and looks at three promising international European companies in order to learn from some of their success factors.

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Summary

The goal of this study, conducted under the Proseaweed programme, is to learn from international experiences about the business case of seaweed farming and find out if the lessons learnt can help the business case of seaweed farming in the Dutch North Sea. There is limited data on the current economic status of seaweed companies available. This report provides an overview and analysis of the costs computed in previous studies, adapting them to the same units of measure to facilitate a comparative view. To the extent possible, the prepared dataset does provide information on the different farm sizes, different cultivation methods, different conditions and different lengths in the study period. The study contributes to understanding this limited quantitative data and looks at qualitative data in the form of success factors. With success factors, the study team means actions, practices and tools that can be adopted to maximise productivity and reducing production costs and thus making companies more viable. The requirements collected within the literature were confirmed by the companies interviewed: Ocean Rainforest, Artic Seaweed and The Seaweed company. Outlined requirements were adopted to the Dutch North Sea case in order to create a more profitable business case of seaweed cultivation. These success factors are then looked at for their applicability to the Dutch seaweed industry. The results show that site selection with ideal water conditions, steady cold water temperatures and good nutrient flow, are essential for a good harvest and even the potential for longer operating windows. These conditions are not found in the Dutch North Sea, due to surface water temperature variations. Innovations like submersible systems or advances in temperature resistant strains could be a solution to allow multiple harvests offshore in the Dutch North Sea. Yields can be optimised with selective breeding and the optimised timing for harvesting, and costs can further be reduced by mechanisation and automation. Some of these factors are only applicable in the future, but others, such as synergies with other industries, can be implemented immediately.

1 Introduction

In Europe there has been increasing interest in seaweed farming, seaweeds are seen as a relevant source of biomass, such as food, feed, materials, biofuels, fertilisers and as a gelling agent. In addition, it is argued that seaweed farming provides positive environmental externalities such as mitigating ocean acidification and maintaining ecosystem services such as generating habitat (Duarte et al., 2020; Duarte et al., 2017; Theuerkauf et al., 2019; Xiao et al., 2021). The seaweed industry can also have a considerable social and economic impact, as many new job opportunities are expected to be created in the sector. According to the Seaweed for Europe report, the European seaweed market in 2030 could be worth up to €9.3bn (Vincent et al., 2020). Furthermore, under the right market conditions, producers in Europe could reach about one third of this market representing a value of €2.7bn, generating about 85,000 new jobs (Vincent et al., 2020).

So far the European algae market represents a marginal portion of global seaweed production, while Asian suppliers account for around 87% of global market (Ferdouse et al., 2018). Various initiatives intend to strengthen the seaweed sector, for example, at policy level Farm to Fork, a recent European strategy part of the New Green Deal will accelerate the transition to a more sustainable, fair and health food system. The European Commission highlighted that seaweed aquaculture has a strategic potential to contribute to blue growth by providing renewable and low-carbon products for the bioeconomy (European Commission, 2012).[1] It is argued that algae will play an important role in the ambition to achieve the European Green Deal, which is intended to accelerate the economic transition towards a more sustainable, equal and healthy food system. Research projects such as GENIALG[2] and SeaMark[3] provide input for increasing the sustainable production and sustainable harvesting of algae culture in Europe. The goal of these efforts is to increase the local seaweed industry to have a successful large-scale seaweed farming in Europe. In a study by van den Burg et al. (2016), concerns about the economic viability of large-scale seaweed farming in the North Sea were raised. International experiences, however, show us that farming is feasible in different locations.

The aim of this study, conducted under the Proseaweed programme, is to learn from international experiences about the business case of seaweed farming and find out if the lessons learnt can help the business case of seaweed farming in the Dutch North Sea. This led to the main question: looking at the economic perspective, how can international experiences contribute to advancing seaweed farming in the North Sea? The following sub-questions are guiding the research:

1. What can we learn about the business case for seaweed farming from promising European experiences?
2. How are these international experiences relevant for the Dutch North Sea?
3. Based on these lessons learned, can we develop the business case for seaweed farming in the North Sea?

The first two questions look particularly into the costs of those companies and if they differ to the farms in the Dutch North Sea. It also focuses on which costs might be of importance for the Dutch North Sea case. This third question looks further into specific business cases and questions if the operating conditions are comparable or is there are differences that make the business case incomparable.

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[1] See also the establishment of the EU4Algae forum in 2022: https://cinea.ec.europa.eu/news-events/events/eu4algae-info-session-2022-06-20_en

[2] https://genialgproject.eu/

[3] https://seamark.eu/

2 Methodology

To respond to the three formulated questions above, the study makes use of literature review and case-studies. Table 2.1 shows the linkages between the research questions and research methods used.

Table 2.1 *Methods per research question*

Question	Literature review	Case study interviews
What can we learn about the business case for seaweed farming from successful European experiences?	x	x
How are these international experiences relevant for the Dutch North Sea?	x	x
Based on these lessons learned, can we develop the business case for seaweed farming in the North Sea?		x

The literature overview provided the information for the quantitative data, resulting in the economic data overview. Both literature and case studies provided qualitative results, like actions, practices and tools that can be adopted to maximise productivity and reducing production costs and thus making companies more viable. These factors are referred to as success factors.

2.1 Literature review

Through the literature review, we collected quantitative and qualitative data on seaweed production and the value-chain. Existing literature on economic data concerning seaweed farms was looked at to define the factors that determine and influence the costs and revenues of seaweed companies and also the cost itself.

Literature search was done in the bibliographic database Scopus with the earliest paper dating back to 1999. The search terms were built on three strings:
1. Seaweed* OR macroalgae*
2. "cost* of production*" OR "production cost*" OR "revenue* of production*" OR "production revenue*" OR "business case*"
3. "North Sea*" OR europ*

Whereas the first two search strings were searched for in the abstract, title and keywords, the last one in all fields of scientific articles. The resulting 25 articles were scanned for relevance by reading the abstracts. This search produced scarce results in terms of articles relevant to our study. Therefore special attention to the cited articles within these scientific articles was paid, and further relevant reports and articles were discovered. Economic data from 6 publications and 1 report was collected in tables to gain an overview over the existing data to see if comparisons are possible to eventually be able to make generalised statements on costs.

This quantifiable economic information was gathered from these sources and sorted into the following cost structure so that a comparison could be allowed:
- **CapEx (capital expenditure):** long-term costs including boats, equipment and infrastructure for hatchery, cultivation structures, nets and ropes.
- **OpEx (operational expenditure):** short-term recurring costs related to the hatchery, during seeding, cultivation and harvesting and maintenance.
  - Labour (average salary for fisheries varies per country estimated length of season)
  - Material (additional seasonal ropes, buckets, buoys)
  - Energy and transportation (fuel used during the production and harvest)

Qualitative information on factors that lead to a successful business case, was gathered from more than these 7 papers. Information was collected per each step in the value chain of seaweed cultivation.

For this report we categorised the companies into small-scale farms and large-scale farms, since the material for the cultivation sites and transportation costs vary greatly between the two. While a small scale site, in our cases up to around 10 ha, can be harvested with one boat and is labour intensive, an large scale farm, in our cases up to 4,000 ha, would need several hours (75-150 km (van den Burg et al., 2016)) to be reached for harvesting, thus uses a lot more fuel, the boats (several) would either be more automated, or demand much more labour and capital costs. There is not one definition for the scale or when it is considered off shore or near shore, the differentiation for this report was made by the study team, separating data on the estimations for the large scale case from the data of the existing small scale farms.

The estimated revenues for large-scale seaweed farming for the Dutch North Sea case are briefly mentioned referring to the publication from van den Burg et al. (2016). Published data on revenues from the farms and research projects were not further compared, as they depend on the market and cannot be influenced. There is currently no generalised, detailed and reliable information on the value of seaweeds in Europe available.

2.2 Case studies

To complement the literature review, three case studies were chosen for in depth analysis of their success factors, economic strategies and risk factors. The data collected was qualitative and did not feed into the economic data overview. The motivation of investigating case studies was to complement, compare and confirm the desk research with success factors demonstrated in reality.

The three seaweed cultivation farms were selected as case studies, because of their extensive experience in this young industry. Even if the companies are not yet economically independent, their business models show promise for success to investors. It is for this reason and the fact, that they also have run into difficulties in building their companies, faced failures, that they provide a repertoire of experience for things to do and not to do. Three interviews were held across the three case studies, with Kim Kristensen, Managing Director of 'Arctic Seaweed',[4] Urd Grandorf Bak, head of Research and Development of 'Ocean Rainforest'[5] and Stefan Kraan, Chief Scientific Officer of 'the Seaweed Company'.[6] A questionnaire with mostly open questions was used and send to the interviewees beforehand. Please view Appendix 1 for the interview guide. The interviews were held in English and online, the transcripts can be found in Appendix 2.

4 https://aseaweed.com/
5 https://www.oceanrainforest.com/
6 https://www.theseaweedcompany.com/

3 Results from the literature review

3.1 Quantitative results

Small-scale cultivation

Table 3.1 gives an overview of five of the seven studies (two studies concerned large-scale farming) looking at small-scale farms' cost structure with data from the literature review. Some of the publications are based on real farms, others on research projects. Therefore their economic data, their calculations for profitability, was also based on data gathered from either projects or real existing farms.

Focusing on the length of the seeding lines, the yields and the costs from seeding to harvesting, we gathered comparable data for capital costs and operational costs per kg seaweed. Whenever available, we noted what is included in the costs, e.g. hatchery, rental or buying of a boat. It was not possible to list the costs per step in the value chain or to divide them into material costs, salaries or commodities, as not all studies represented the costs in the same way and some just gave the total. Therefore, Table 3.1 provides an overview of the costs adjusting them to be on the same units to facilitate a comparative view.

Table 3.1 *Overview of production costs for small scale seaweed farming in Europe*

Small scale						
	Variable/units	**Denmark**	**Ireland**		**Sweden**	**Faroe islands**
		6 tests sites, 3 Farms	**Project**	**Farm**	**Farm**	**Farm**
Production	Species	*Saccharina latissima*	*Laminaria digitata*	*Alaria esculenta*	*Saccharina latissima*	*Saccharina latissima*
	Life Span	10 years	3 years	20 years	10 years	8 years
	Yield		7.25t/km/yr (dw=15%)	12t/km/yr (dw=10%)	8t/km/yr	6t/km/yr
		7.65 t/ha/yr		48.4 t/ha/yr		35t/ha/yr
Total OpEx			**151,159 €/14.4km/yr**	**10,813 €/1.210km/yr ***	**43,600 €/ha/yr**	**12,609 €/ha/yr***
Long- term cost >5 y (CapEx)	Total		**130,128 €/14.4km/3yr**	**100,140 €/1.210km/20yr ***	**67,810 €/ha/10yr**	
	broken down to year and ha or km		**3,012 €/km/yr**	**4,138 €/km/yr**	**3,391 €/ha/yr***	**15,784 €/ha/yr****
Total costs	**Individual unit**	**116,000 €/ha/10yr***	**580,945 €/total/ 3yr *****	**15,820 €/6ha/yr ****	**46 988 €/ha/yr****	**28,394 €/ha/yr**
	€/kms/yrs	**116,000 €/1.1km/10yr *****	**580,945 €/14.4 km/3yr**	**15,820 €/1.210 km/yr**	**46,988 €/2.34 km/yr**	**28,394 €/2.5 km/yr**
	€/km/ yrs	**105,455 €/km/10yr**	**40,343 €/km/3yr**			
	€/km/yr	**10,546 €/km/yr**	**13,449 €/km/yr**	**13,074 €/km/yr**	**20,081 €/km/yr**	**11,357 €/km/yr**
Source		Zhang et al. (2020)	Watson and Dring (2011)	Collins et al. (2022)	Hasselström et al. (2020) **	Bak et al. (2020)***

ww = wet weight, fw = fresh weight, dw=dry weight. Fw and ww represent the same, but we respected the definition the authors of the papers chose.
All * are found in Appendix 3.

The last row of Table 3.1 shows the aggregated variables in order to compare the different studies and farms. The main challenge faced in this study was to make the reported variables homogeneous, but there are inconsistencies to have a complete comparison between the reported studies.

It can be observed that three of the five studies focused their production on *Saccharina latissima*, which is the most common seaweed cultivated in Europe (Araújo et al., 2021), the other two cultivated species are *Laminaria digita* and *Alaria esculenta*. Projects have different durations, which is especially relevant for the long-term cost allocation (CapEx). To obtain more uniform and potentially comparable total values, CapEx costs were divided by years of project life-span and adjusted for site size, which may lead to higher yearly CapEx due to a shorter project length. For 4 out the of 5 studies the hatchery-related costs are included in their total output, with the exception of study in Sweden (Hasselström et al., 2020), which does not specify the inclusion of this cost in the production total. Zhang et al. (2022) includes licences for cultivation, supplementing their study with very price list of all material needed. Only the Faroe Islands case included those costs in the calculations (Bak at al., 2020), Watson and Dring (2011) and Zhang et al. (2022) do not include processing and Hasselström et al. (2020) do not give further information if it was included or not. The farms described in Ireland and Denmark (Collins et al., 2022; Zhang et al., 2022) specify that boats were rented and the costs were included, in the Faroe Islands case (Bak et al., 2020) it is not mentioned whether the boat is rented or owned but the hourly costs of the boat operation are defined. Another step in the value chain is the drying process, a labour and energy-intensive step which therefore significantly impacts total costs (Seghetta and Goglio, 2020; van Oirschot et al., 2017).

Our overview of 5 studies in Table 3.1 shows costs in the range of €10,000-20,000 for one km of cultivation rope for one year of cultivation and harvest for a European seaweed farm.

Our sources show yields of wet weight (ww) per hectare ranging from 7-48 tonnes: 7.65 tonnes in Denmark (Zhang et al., 2022), 35 tonnes in the Faroe Islands (Bak et al., 2020) and 48.4 tonnes in Ireland (Collins et al., 2022) and between 6-12 kg of ww per metre: 6 kg in the Faroe Islands (Bak et al., 2020), 7.25 kg in Ireland (Watson and Dring, 2011), 8 kg in Sweden (Hasselström et al., 2020) and 12 kg in Ireland again (Collins et al., 2022). The conversion to dry weight varies between 10-15% of wet weight (Collins et al., 2022; Watson and Dring, 2011).

Large-scale cultivation
Table 3.2 shows the calculations based on the estimates of large-scale production in the Dutch North Sea from 2013 and 2016, the remaining two of the seven studies. It was not possible to compare it to data from existing European farms, as there are currently only estimations for the costs and revenues of large scale farming available. Here again, we focused on the operational and capital costs spent per kg of seaweed produced.

Table 3.2 *Overview of estimates of production costs for large-scale offshore seaweed farming in Europe*

Large scale			
	Variable/unit	**Netherlands**	
		Estimates based on experts judgement	
Production	Species		*Saccharina Latissima*
	Life Span	10	10
	Site Typology	long line offshore applied near shore	offshore, long line
	Site Size	10,000 ha	4,000 ha offshore multi use
	Yield	20 tonnes dw/ha/yr	20 tonnes dw/ha/yr
total OpEx		**769 €/tonne/yr or 15,380 € /ha/yr**	**20,444 €/ha/yr**
Long- term cost >5 y (CapEx)	Total	**100,000 € /20 tonnes/10yr * = 100,000 €/ha/10yrs**	**152,766 €/ha/10yr**
	broken down to year and ha or km	**10,000 €/ha/yr**	**15,276.6 €/ha/yr**
total costs	**€ /ha/yr**	**24,380 €/ha/yr**	**35,720.6 €/ha/yr**
	€ /km/yr	**2,438 €/km/yr**	**3,572 €/km/yr**
Source		van Den Burg et al. (2013)	(van den Burg et al., 2016)*
	*	average of the low and high scenario	converted to EUR with the average exchange rate of 2016: EUR=USD 1.107

In Table 3.2 it can be observed that for the same yield, 20 tonnes dw/ha/yr in both studies, the total costs reported in the study from 2016 (van den Burg et al., 2016) are higher than the estimates from 2013 (van den Burg et al., 2013). This is due to updating some costs to latest prices. Seedling and harvesting are included and considered in the OpEx costs. The average cost of production of these two estimates is €3,050 per km per year. As can be expected from upscaling, these costs are lower than the small-scale farming costs. The yield of 20 tonnes dw per hectare (250 tonnes ww with an average conversion of dw=12.5%ww) is however by a magnitude of 83 bigger than the small-scale farming yield (average of 3 tonnes ww per ha). This leads to question if the data on yields should be updated with more recent data. Therefore, the cost could also vary with updated estimates. Scenarios with reductions in the costs seem still possible (van den Burg, 2019).

Regarding the price of seaweed from large-scale cultivation, sensitivity analyses show, that the price for seaweed as it was calculated for 2016 offshore farming need to increase by 300% in order to be profitable. Even in combination with wind farms it was not considered economically feasible and profitable (van den Burg et al., 2016). However with reductions of capital costs up to 50% through combined use, reductions through boat hire, reduced plant material costs, and increased yield, the price per dry matter ton seaweed could go down to €1,200 as compared to €5,200 with the base scenario (van den Burg, 2019) and production of rather high-end products like food can be expected to be profitable.[7]

3.2 Qualitative results

Qualitative results were found in the literature review as well as in the case studies. The case study results are in the following chapter.

To complement the quantitative data, the relevant literature was also analysed for qualitative factors that can positively influence the productivity of- and reduce cost for- a seaweed cultivator. By addressing each step of the value chain of seaweed cultivation, we present in the following paragraphs some success factors and how they can be positively influenced leading to maximising productivity, minimising the loss and reducing the cost. A detailed overview is available in Appendix 4.

Site selection
The selection of the site is of particular importance as it can have a positive or negative impacts on the cultivation itself and the surrounding environment. There are some physical aspects to take in account:

- *Site per se*
  A site should potentially be kept out of areas of endangered species, as the farm could potentially be harmful to the surrounding environment (Campbell et al., 2019).
- *Temperature*
  It is recommendable to choose a site where there are no extreme temperature variations. Ideally, temperatures shouldn't go below 15 °C during spring and summer time (Edwards and Watson, 2011).
- *Depth*
  A minimum depth of 10 metres is recommended (Edwards and Watson, 2011). It is also possible to cultivate deeper, but production costs and material used would increase, for this reason is generally unprofitable. The maximal cultivation depth could be determined, depending on light penetration in the water column and light needed. The variations in light are thought to play are more important role for the growth variations than nutrient level and seawater temperature (Bak et al., 2018). Cultivation in the North sea faces the challenge of highly dynamic sandy sea beds and breaking waves leading to turbidity and less light penetration (Bak, 2022).
- *Water currents*
  Algae culture generally requires sites with adequate water exchange. Exposure to currents rather than waves is preferable for nutrient turnover, without risk of damage. Currents with medium to high flow velocities (between 5 and 10 cm s^{-1}) are considered ideal (Edwards and Watson, 2011). Biofouling is a phenomenon that is related to particularly sheltered locations (without enough water exchange) (Bak et al., 2018; Handå et al., 2013; Marinho et al., 2015), limiting the growth phase and preventing multiple

[7] https://cordis.europa.eu/project/id/727892/reporting

harvests (Bak et al., 2018; Bruhn et al., 2016). However, not all farming structures withstand excessive exposure to waves and currents (Bak et al., 2018).

- *Salinity*
  Avoid sites with brackish water, such as estuaries or where other large volumes of freshwater run into the system from streams and rivers (Edwards and Watson, 2011).

Farm infrastructure/Cultivation systems
There is not one most successful cultivation structure, it very much depends on the water and site conditions and the quantity of seaweed farmed. However, the various systems have different advantages.

Different cultivation systems, such as longline, ladder, grid, ring, buoyed frame and MACR (MacroAlgae Cultivation Rig) are for different environmental conditions (Zhang et al., 2022). Offshore seaweed cultivation depends on a lot more mechanisation (van den Burg et al., 2019). Installation is among the most expensive production cost, in (van den Burg et al., 2016) the total estimated initial investment is about €153,000[8] per hectare. These structures have to withstand waves, tidal driven flow, orbital flow and buoyancy of the system (Macleod, 2022). Collaboration with engineering companies can reduce the construction costs (Tamosaitis, 2022). Over-engineered structures to assure that they survive in difficult conditions may push costs, however it doesn’t necessarily mean a success factor (Bak et al., 2018). Farming in offshore conditions, historically high installation costs linked to complex engineering efforts, still didn’t prevent damage to the cultivation system, which ultimately hindered the development of offshore farming (Bak et al., 2020). Newer solutions like the MACR from the Faroe Islands, based on a simple structure are low in cost and have proven its technical readiness (Bak et al., 2020). The MACR system reduced installation costs with a spatially efficient design and re-using anchors, chains, ropes and buoys from other industries (like fishing and finfish aquaculture) (Bak et al., 2020).

As for the North Sea, experts consulted in 2016 were of the opinion, that offshore production of seaweed will be based on long-line techniques. Knowledge from mussel farmers already practicing this technique can possibly gained (van den Burg et al., 2016).

Seedlings
A successful yield is strictly dependent on the quality of the seedling, but the annual purchase of these represents at the same time a considerable cost. According to van den Burg et al. (2016) the costs of adding seeded lines are estimated at €1.25 per metre. Owning a hatchery would reduce these costs. Another cost-efficient scenario would be to adapt an existing hatchery (Watson and Dring, 2011) and even co-culturing different species to divide the costs (Watson and Dring, 2011). Selective breeding (Bak et al., 2020; Bak et al., 2018) as well as automated seeding, can also reduce operational costs of farming (Bak et al., 2020; Macleod, 2022). Selective breeding may provide an opportunity to increase the yield despite higher temperature, which is a challenge the North Sea faces (Bak, 2022) and also lower the costs (Coleman et al., 2022). Selective breeding may provide an opportunity to increase the yield despite higher temperature, which is a challenge the North Sea faces (Bak, 2022). Automated seeding, can also reduce operational costs of farming (Bak et al., 2020; Macleod, 2022). A rather novel method to seeding, the direct seeding method uses less energy and has a smaller carbon footprint (Zhang et al., 2022). Building on the direct seeding method, research on two step seeding to maximise the contact between the surface and to facilitate attachment, is still ongoing with the aim to reach scalability (Macleod, 2022). Crop domestication may be a solution to reduce costs and increase cultivation control by having more reliable quality of the crop, have it compatible with farming machines, and assuring scalability (Ebbing, 2022). Coleman et al. (2022) add that reducing nursery and grow-out duration could lower the costs as well.

Cultivation and Harvesting
During cultivation and harvesting several measures can be focused on to improve yield:

- *Multiple harvests*
  being able to do multiple harvests per year, can increase the production per hectare significantly and help to become profitable (van den Burg et al., 2016). With the MACR system used in the Faroe Islands, the CapEx per tonne dw of cultivated seaweed was reduced up to 75% (with 6 harvests per growth line deployed), since it allows to partially harvest multiple times and thus doesn’t need the costly reseeding

[8] Converted to EUR with the average exchange rate of 2016: EUR=1.107 $.

(Bak et al., 2020). To make multiple harvest in the North Sea a reality, further research into a production system based on combining multiple species to achieve year round production would be needed (van den Burg et al., 2016).

- *Upscaling*
  Another way to increase production would be to lengthen the growth lines and increase the total production per area surface and thus decrease the production costs (Bak et al., 2018). When upscaling, the CapEx will be reduced as a function of economy of scale, and production and implementation costs will be lower per yield (Bak et al., 2018). Systems with a greater yield obtain a greater revenue stream (Zhang et al., 2022) which should be focused on to reduce cost of production (van den Burg et al., 2016).
- *Optimal harvesting time*
  To avoid fouling but still retrieve the maximum possible yield, the optimal harvesting time is key (Zhang et al., 2022).

Other measures can be focused on to reduce the costs:

- *Automation and mechanisation* of the harvesting could reduce the costs (OpEx) and improve the return on investment (ROI) associated with the cultivation structure (Bak et al., 2018; Coleman et al., 2022).
- *To rent* the necessary vessels, which may be available along the coast from rother industries, is more cost effective than buying a boat for harvest (SAMS and Imani, 2019).

Processing

Processing steps, such as drying, are energy demanding and manpower-intensive (Seghetta and Goglio, 2020; Zhang et al., 2022), but on the other hand, having drying capacities will minimise spoilage (SAMS and IMANI, 2019). It has to be carefully considered what processing facilities (drying, storing) would be needed if production in the North Sea area were to increase (van den Burg, 2019).

Synergies with other industries (transportation, hatchery, processing)

Working together with other local producers (oysters, mussels) could be beneficial when sharing space, suitable sites, labour, or other resources like infrastructure, for instance fishing boats, onshore facilities for processing, landing points, transportation routes, and thus reduce costs all the while increasing productivity (SAMS and IMANI, 2019). Zhang et al. (2022) suggest, sharing a hatchery can significantly reduce costs. van den Burg (2019) goes further saying cost reduction through combined use with wind farms are possible. For scenario calculations the capital costs were even reduced to 50% rendering the industry more profitable (van den Burg, 2019).

Other factors outside of the value chain

There are factors that a company cannot directly have an influence on but should be aware of and consider them in their set up.

- *Social licence*
  More likely to be there when a company has strong local connections and is rooted in the community. However, even if a company is new, social licence could be built with keeping the value gained local. A company with strong local connections or that is rooted in the community will be able to maintain social licence to operate (SAMS and IMANI, 2019).
- *Market*
  When up-scaling production in the North Sea, it has to be considered, if that demand is already there (van den Burg et al., 2019). The European market for seaweed has grown, and since a lot relied on wild harvest in Europe, cultivation could be a solution to the growing European market (SAMS and IMANI, 2019). To meet the costs of seaweed production in the North Sea, a mix of low- and medium- value markets would be needed. The food market could provide this (Buschmann et al., 2017).
- *Funding*
  Governmental funding helps to set up seaweed farms, some countries benefit more from it than others.
- *Technical expertise*
  Expenditures can be expected to reduce with the years of experience of the operational crew (Bak et al., 2018; Coleman et al., 2022). Operational efficiency will grow over the years with experience as well (Bak et al., 2018). Larger organisations are capable to employ experts or operate with contract farming model, which allows them to benefit from technical assistance (SAMS and IMANI, 2019).

In general, a wider perspective, not only focussing on production, but also integrating aspects further upstream of the value chain, like market, sales, transportation and processing, allows a more integrated picture and is necessary for a successful business case of the seaweed farming in the Dutch North Sea (van Berkum and Dengerink, 2019; van den Burg, 2019).

4 Results from the case-studies

4.1 Ocean Rainforest on the Faroe Islands

Introduction to the case
Ocean Rainforest was initiated in 2010 with the idea to reduce CO_2 through the cultivation of seaweed and in 2013 they were able to put the first lines in the water. Today the company counts about 17 people. Ocean Rainforest mainly produces two products from *Saccharina latissima*: dried algae in different sizes (pieces or powder) and fermented algae. When cultivating *Saccharina,* they also have *Alaria esculenta on the lines from wild seeding*. Dried seaweed (*Saccharina latissima* and *Alaria esculenta*) is today mainly sold for human food, while the fermented seaweed is mainly sold as a pig feed additive, as this product is found to be very effective and nutritious.

Ocean Rainforest is looking to scale up, especially in the Faroe Islands, but also in other areas such as Norway, California, Alaska, and Iceland. The goal is to reach 1,000,000 tonnes in 2030. As a business strategy, they want to create high value seaweed products and achieve greater mechanisation to handle large amounts of biomass. In addition, they want to implement selective breeding to achieve higher yields.

Success factors
- Multiple harvests: the long operational window from April to October allows the company to have multiple harvests. Advantages are cost reduction and the distribution of a larger amount of product over a wider window, which facilitates the processing stage, but also that by cutting the blade of the seaweed further away from the base, mixing the more fibrous part of the stem into the product is avoided and thus a cleaner product is obtained.
- Using existing infrastructure and equipment from the fishing industry: the Faroe Islands have a lot of fishing and aquaculture equipment that is no longer used by that industry and can be bought at a good price (old vessels, buildings, ropes…).
- The environmental and water conditions: The conditions in the Faroe Islands are very good for the seaweed business. It is important to have stable conditions: and the water temperature in the Faroe Islands is below 15 degrees, there is no ice, it is well mixed, so no stratification, which are conditions that allow a good flow of nutrients. This is a difference to other European countries where summer temperature can reach above 20 degrees. Finally, clean water is great for cultivation because even at a depth of 10 m below sea surface, the algae will receive sufficient sunlight.
- Ocean Rainforest's cultivation structure called MACR (MacroAlgal Cultivation Rig) is very innovative and can deploy lines in deeper water (up to 150-metre depth) where the water conditions are better, and more nutrients are available.

Strategies to reduce costs
The company's main strategy is to increase the yield by doing more harvests in the same year, currently they manage to do six harvests on the same string, two harvests per year. In the processing step of the value chain, the drying is still very expensive, and they hope to be able to lower costs here.

Major risks
- Weather: storms could represent a big risk for production, but after years of experience, Ocean Rainforest's knows their structure can tackle storms.
- Seeding is a crucial stage. If something goes wrong with the seeds there can be great damage, but since they reuse the line for 3 years, they always have something to harvest.
- Finally, there could be external factors, such as species like shrimp or attacking algae, but with the longer operational window, not everything is lost.

View on seaweed farming in the Dutch North Sea
Regarding the Dutch North Sea, it would be necessary to find optimal environment and water condition. One suggestion is to go more offshore where it is easier to find cold, stable water around 15 degrees, and also to find a site where the water is not turbid for better sunlight penetration.

4.2 Arctic Seaweed in Norway

Introduction to the case
Kim Kristensen is the CEO of the Artic Seaweed company that operates in Norway since 2016. The company produces *Saccharina latissima and Alaria esculenta* mainly addressing the food market. The company's goal is to expand its size and volume in the next 5 years.

General needs for the industry
Scaling up seems to be one of the main factors to being profitable in Europe, but this depends but many factors: technology, biological issues, quality of seed stocks, distribution of planting techniques, employees. Added to these factors is the limitation of having only one crop per year in Europe, this turns out to be a major disadvantage not only because of the risk of losing the whole yield but also because of the limited possibility of testing new optimisation techniques that can be implemented only once per year. The trial-and-error operation is fundamental for an emerging industry. It affects all stages of the product value chain, from the seed suppliers, who may sometimes lack sufficient stocks in quantity and quality, to the market. Inexperience of for instance seed suppliers can hinder the production, but with a maturing industry, this can be overcome.

Success factors
- Equal efficiency on all steps of the value chain: It is important to have efficient mechanisms in all production steps (seeding, harvesting etc.): at the moment the most evident bottleneck is the drying process, not yet as highly efficient and highly capable as the rest of the value chain.
- Quality of seeds: Having good seed is crucial for a good harvest, not only for quality but also for the right time of sowing. Therefore, to overcome the inexperience of seed providers and to significantly reduce costs, a good alternative is to have one's own hatchery; Artic Seaweed has thus planned to establish their own hatchery to become partly self-sufficient, while still buying some on the market to diversify the risk at this stage of the value chain.
- Collaboration with other industries:
  - Sharing of infrastructure: In the future it could be beneficial to collaborate between different types of industries to be able to exploit the same infrastructure. This could mean producing products with different seasonality (e.g., seaweed and crabs). However, even with many fish farms in Norway. It is at the moment difficult to share the same equipment, because it has to be adapted to each production and washed before and after each different usage.
  - Circular approach: In Norway companies are looking to solve the heat processing problem by using waste heat from different kinds of industrial processes. However, the transportation to the waste facilities is very long.
- Cold temperatures: cold temperatures allow more stability for the algae, like it is the case for Iceland or Greenland. This leaves room for the processing.
- Bigger operational window: the Norwegian shoreline stretches from North to South, which allows some farms with cultivations along the coast to benefit from a wider time window moving northwards.
- Tracking the right data: tracking the product and collecting data and information once the seaweed is out of the water, as compared to having too many costly in water measurements can help the company be profitable. This also creates an experience to share.

Strategies to reduce costs
The company's cost strategy is to try to optimise OpEx costs by trying to increase its production per minute. Artic Seaweed rents a boat and hires seasonal workers during the planting and harvesting period, therefore it is of interest to reduce the time spent on these periods. Another factor that can be helpful in cutting costs is the further mechanisation of the process, however it would be helpful if this was standardised in the future.

Furthermore, government funding programmes can trigger investments in this business, but each country has different conditions with regard to this.

Major risks

- The weather
  Since the operation window is very short and equipment is very expensive to rent bad weather could increase costs.
- Biological risk
  This is a big risk because it is often out of one's control, e.g. the seed stock is not good, environmental conditions are not conducive to growth, fouling occurs, or other species interfere with cultivation.
- Site selection
  It is necessary to strike a balance between an exposed site, where seaweed grows better but the risk of having higher costs and losses due to bad weather is greater, and a more sheltered site along the coast that does not, however, guarantee the same result in terms of yield.

View on seaweed farming in the Dutch North Sea
Infrastructure sharing can also be an asset for companies operating in the Dutch North Sea where there are many wind farms that provide an excellent anchor point for seaweed cultivation. A well-planned collaboration can be an excellent way to cut costs and allow scaling up in the future.

4.3 The Seaweed Company in Ireland and the Netherlands

Introduction to the case
Stefan Kraan is the CSO and co-founder of The Seaweed Company, founded in 2019 in Ireland. Today the company has about 44 employees working in Ireland, the Netherlands, India, and Morocco. In Europe they mainly produce *Alaria Esculenta* for human food consumption and bio stimulants; in India and Morocco, red and green seaweeds are produced for animal feed. The company is keen to implement circular bioeconomy by being present in the entire production value chain.

General needs for industry
The company faces a problem that many European companies also have to deal with: the bottleneck of the drying step in the processing. Current technologies (dehumidifier, drying container, and polytunnel) are good for a small production volume, but since the goal, for the Seaweed company, as for many others, is to scale up these will no longer be adequate. They require a lot of manual labour which is very expensive in Europe. This year the company tested an experimental dryer that was unprofitable because of the significantly increased cost of diesel. In any case, this trial-and-error process is part of the learning curve for this industry, which has a lot of potential to grow. Sharing experience and knowledge is also a crucial part, in this young growing industry.

Success factors

- *Market*
  Because each step in the value chain is as important as the others, it is crucial to have a clear business idea, it is not enough to achieve a good volume of product if you do not have a market to sell it. Because this is a key point for The Seaweed Company, they are partnering with seaweed companies that cannot sell their products in the private market, giving them the seeds and then also the opportunity to sell directly back to them at a lower price, if they couldn't sell their product on the open market. This is to keep the industry operational and alive.
- *Experimenting with new techniques for production optimisation*
  The company has tested many different techniques especially in the agricultural stage of production, for instance different densities of the growing lines. Thanks to these trials it is now able to diversify the product according to the customer, for example, for snack producers it is important to have a thin seaweed, while for meat substitute producers it will be essential to have a long and fibrous product.

Strategies to reduce costs
It is very difficult to report numbers regarding production costs at this life stage of the farm. At the moment The Seaweed Company bears a cost of about €60,000 for growing 10 ha. The goal is to scale up in size and volume so that costs can be covered, and more profit can be achieved, but this will take several more years. An efficient way to cut the cost of hatchery is to switch to direct seeding, which is much cheaper and therefore could be a great resource for the European industry.

Major risks
- Weather: winter storms are a risk for cultivation during its growth in water, this could be avoided with engineered structures, but these are very expensive. In addition, bad weather is also a risk during the harvest season, as the window is short (about two months), and one could lose the yield completely.
- Other external variables such as electrical damage in the hatchery or an oil spill in a nearby area that could ruin the seaweed and make it unusable for human consumption.

View on seaweed farming in the Dutch North Sea
To cultivate in the Dutch North Sea, as the water temperatures can exceed 18 degrees in coastal waters and becomes harmful to, for instance *Alaria esculenta* A good area to grow in the Dutch North Sea could be the Eastern Scheldt with its good water flow and turn over, compared to the Western Scheldt. To be profitable in the Dutch North Sea, companies need to increase production to square kilometres. In addition, it may be profitable to combine more activities with IMTA. Finally, it might be worthwhile to aim in the main cultivation of *Alaria esculenta*, which turns out to be a more valuable product especially for the food market, which is the most flourishing in Europe. However, *Alaria esculenta* is less stable in the heat than *Saccharina latissima* and so it is necessary to harvest earlier and risk having less product.

5 Discussion

5.1 Success factor overview

Success factors from the reviewed literature and case studies are summarised in Table 5.1. The collected information on these success factors relate to the Dutch North Sea are categorised into how feasible they are to be implemented and what it would take to implement it.

Table 5.1 *Overview of the success factors and their necessities to implement in the Dutch North Sea*

Level	Success factor	Explanation	Possible in the Dutch North Sea	Requirements to fulfil
Geographical	Longer operating window	Allows for multiple harvests from one seed line which reduces the capital expenditure per yield. Allows to reduce costs by using infrastructure for several farms along the coast reaching maximum growth one after the other.	Maybe in the future	Temperature changes are to be expected during the year,[9] but with submersible systems, strains that are temperature resistant or resistant to biofouling or multiple species could be a solution (selective breeding).
	Ideal site	Balance between further offshore and riskier for weather conditions, but better for productivity. Ideal environmental conditions (temperature <15 degrees, light penetration, no turbidity, no stratifications, enough nutrients, currents with 5-10 cm/s, no brackish water, water depth >10 m). Infrastructure close by. Other companies for collaboration close by.	To an extend	Options have different advantages: **Eastern Scheldt** for near shore cultivation, but still not suitable for multiple harvest for instance. **Offshore** cultivation has other advantages, like better water conditions and collaboration is possible, but technological development isn't ready yet.
Company	Direct seeding	Reduces energy cost, allows for better harvest.	Yes	Implement approach.
	Owning a hatchery	Owning a hatchery will reduce costs and allow for seed supply security through diversification of the source.	Yes	Investing in a hatchery or planning a co-use of a hatchery.
	Optimal timing of deployment and harvest	Leaving the seaweed in the water long enough for maximum growth but not risking fouling.	Yes	Experience and expertise knowledge on seaweed cultivation, can be sub contracted.
	Scale up all chains of the value chain at the same speed to avoid bottle necks (processing)	If production is possible to scale up, but processing facilities that depend on manual labour, like drying, can't process the harvested amount, it create a bottleneck, slowing the whole production down.	Yes	Detailed planning and preparation to scale up processing facilities, storage and transportation according to the production upscale speed.
	Using own infrastructure for other cultivations in the off season	Maximize use of capital costs and reduce energy costs by using for example the hatchery for other species at different times, or using the boat, storage or cooling facilities for other activities easily combinable with seaweed aquaculture, like finfish and mussel cultivation.	Yes	Thorough planning necessary.

9 Current average temperatures of the North sea are between 13 and 14 degrees(Mathis et al., 2015), however summer peaks of 18 degrees are possible (https://www.seatemperature.org/north-sea#:~:text=Unsurprisingly%20the%20sea%20is%20colder,64%20%C2%B0F)%20in%20August).

Level	Success factor	Explanation	Possible in the Dutch North Sea	Requirements to fulfil
	Knowing the market and producing for the market	Reducing loss through market adapted production.	Yes	Expertise on market is needed to understand how much demand there can be. Expertise on cultivation is needed to adapt the cultivated species to specific market needs (food versus feed versus cosmetics).
Industry	Synergies with other companies and industries to use their infrastructure	Reduce electricity cost and capital investment through sharing existing infrastructure or facilities (hatchery, storage, freezer, transportation, heat, multi-use platforms).	Yes	Well planned collaboration early on.
	Sharing of knowledge and expertise, trial and error of an emerging industry	Mussel farmers in the Netherlands have experience with long line aquaculture. Farmers as well as hatcheries can learn from one another by sharing lessons learnt.	Yes	Exchange with other industries like mussel aquaculture and with stakeholders from same industry.
Other	Technical innovations to reduce costs	Expansive manual labour could be replaced my mechanisation in harvesting or some processing steps.	To an extend	Technical development needs to advance.
	Permits and funding easily accessible	If governments facilitate the process of cultivation permits and support the seaweed industry with funding, it could foster the development of the industry.	To an extend	Depends on other factors out of the scope.

Some success factors can be applied on a company level, independently of the geographical location or governmental support structure, like choices can be made to assure a steady production. These in the literature identified key factors to success, were confirmed by the case studies. Applied to the Dutch North Sea case these are:

- Owning a hatchery: it allows for less dependency on seed stock suppliers, both for price and diversifying the source of seedlings to buffer occasional bad quality or unavailability.
- Scale up on all parts of the value chain to avoid bottlenecks. In the case of going offshore and producing large scale, the processing steps, such as drying, need to be able to handle the quantities of seaweed produced.
- Direct seeding: if near shore or offshore, our data sources agree, that direct seeding is the future for cultivation in Europe, as this cuts costs significantly and allows for a good harvest.
- If the water condition allow, have multiple harvests: this will lower CapEx by increasing productivity, meaning more crop from the same seeding (Bak et al., 2018; van den Burg et al., 2016).

Another very important factor highlighted through the literature and interviews was more geographically dependant: the site selection. Several key variables are determined by it, such as water temperature, weather conditions, wave intensity, etc. Companies working in the Dutch North Sea may face challenges in comparison to companies located elsewhere in Europe regarding these environmental conditions. The ideal temperature for seaweed growth in Europe should be steadily < 15 degrees, in the Dutch North Sea the temperature on the coast is higher (on average around 20 degrees), which leads to a higher risk of fouling and makes multiple harvests impossible. The North Sea coast is also characterised by considerable water turbidity, due to its sandy seabed, which makes it difficult for sunlight to penetrate low enough during seaweeds' growth phase. The search for a location providing the most favourable conditions of these variables for seaweed production, is crucial. The Easter Scheldt was suggested as a suitable near shore cultivation site. It still doesn't have the ideal water conditions, but small scale farming would be possible until large scale technology is ready to be used. Further off the shore, water conditions are better, but environmental conditions are less predictable, with an increased the risk for storms. This not only entails higher safety risks but also higher operating costs for the days the equipment is rented but the crew has to wait for the storm to pass. For the Netherlands, the difficult choice between safer and shallow sites and more exposed but better sites may also be made easier in the future with more automated harvesting and technical structures that withstand offshore conditions. Offshore also seems the only possibility to have a longer operation window with steadier temperatures. Even if surface temperatures still vary, submersible systems, temperature resistant strains or cultivating several species are possible future developments making multiple harvests a reality. The many offshore wind farms could be used as potential moorings for seaweed lines, plus the Netherlands have an historic involvement and expertise in aquaculture that can be used to create synergies with other local industries (Edwards and Watson, 2011). But not only offshore, in general another variable to consider in the choice of site may also be the existence of infrastructure from other industries like fisheries or shellfish with which it could be possible to collaborate. This can lead to a more rapid information sharing, facilitating new technical innovations, and to an effective reduction in costs due to the sharing of facilities (such as electricity) or some equipment (such as vessels). It is also possible to combine different productions, taking advantage of the seasonality of seaweed. It can be combined with other cultivations, such as mussel or finfish, using the same equipment including boats, cooling facilities, and storage facilities. Being a very young industry, there is still a lot of room for experimenting and trial and error to pursue the perfect recipe for scaling up the business. Crucial at this stage, is the sharing and transparency of information and data in order to establish the know-how for the European industry.

Easy and rapid access to the production licences and the necessary funds to start up a business, as some of the case studies benefit from, would also be a facilitating factor for future Dutch seaweed farmers. In this context, the possibility of financial support proves to be very impactful, but it is necessary that this support has a market vision and is not only aimed at subsidising the start-up of the individual company. Having a long-term goal is crucial to establish this business. Taking these success factors into consideration, large-scale offshore farming emerges as the most likely successful business case.

5.2 Demand for seaweed

Finally, a long term question that concerns not only the North Sea, is whether there will be enough demand for European production that aims to scale up on a large scale (van den Burg, 2019). It is critical to establish a viable market that can handle increasing production and can be differentiated from the Asian market, which has a lot of experience in seaweed production and produces huge volumes. Our research showed the importance of having a high-quality product that respects all food security regulations and that is mainly addressed to human consumption. *Alaria esculenta* seems to meet this purpose, but it also has several problems growing in waters with low temperature stabilisation. A flexibility to address the different needs clients have, will strengthen the business case. Our sources see potential for growth in Europe, also for the Dutch North Sea, but at the moment it is complicated to have a data-based perspective. The results of investment will likely only be seen in 3-5 years.

5.3 Need for more data

There is in fact little consensus on the costs of seaweed production and yields. Other authors support the facts that it is difficult to draw final conclusions on the average costs of seaweed farming, due to not enough published data available (Zhang et al., 2022). Other sources also describe the unreliability of the data, since estimated costs are extrapolated from small tests, instead of actual operational experience (Bak et al., 2020). Further data on the ROI of existing companies would be needed to be able to compare farm structures effectively (Bak et al., 2020), however these are often confidential (Zhang et al., 2022). Also noted by Collins et al. (2022), the existing literature has different scales, employing different species, different cultivation methods, regional differences, different lengths of studied periods (van den Burg et al., 2016). Our research confirms all of these difficulties.

6 Conclusion

The common goal of Europe's emerging seaweed industry is to scale up, which is necessary to reduce production costs and increase yield (van den Burg et al., 2016). At the moment production costs in relation to company size are still too high to make a significant profit.

1. **What can we learn about the business case for seaweed farming from successful European experiences?**

International experiences with seaweed farming show variation in the costs structure of seaweed farming but also show that the total cost of production are in the same order of magnitude. Variation in fixed costs and operating costs are visible. This might reflect differing production processes or differing ways to report the economic data.

Success factors for seaweed farming include owning a hatchery and making use of the advantages of collaborations with other industries to lower the material costs. Using direct seeding seems to be the future of seeding, as it reduces energy costs and allows for an improved harvest. Other factors are more on an expertise level, like judging when the ideal time for harvest is, or on a managerial level, like planning the scaling up of the company without any bottle necks in the value chain or producing the right seaweed for the market. Here again, collaboration can help a company to gain this experience, or else, expertise can be hired or contracted.

2. **How are these international experiences relevant for the Dutch North Sea?**

Not all factors that lead to success in other countries are relevant for the Dutch North Sea, for instance conditions that cannot be influences like the stable water temperatures allowing longer operating windows near the shore. However, these experiences can be used as a base to find these conditions, in the Dutch case, possibly offshore. To receive funding from the state or have the licencing process less complicated, would be factors that may change in the future for the Netherlands, but are for the moment also out of a cultivator's influence.

3. **Based on these lessons learned, can we develop the business case for seaweed farming in the North Sea?**

Compared to other case studies further North, the Dutch North Sea has less favourable environmental conditions, but there is potential to make up for this with technology and innovation. Ideal water conditions with steady temperature below 15 degrees and a constant flow of nutrients, essential to allow for multiple harvests, may only be reached in offshore conditions. To be profitable offshore, it would have to be large scale, and the market needs to be ready for it. Both factors can be aligned in the near future as the market is growing and the necessary technological advances for offshore cultivation structures are not yet ready for implementation. Using direct seeding and newest advances in selective breeding will further optimise productivity at reduced costs. The coming years should be used to prepare for divers synergies with other industries, as these are not spontaneously put into place, not only to share infrastructure with wind parks, or to share costs on processing steps, storage, transportation etc. but also to share expertise from other aquacultures, and technical experts for instance for site selection, timing of the harvest and market analysis. Our results align with the projections made in the literature, the potential successful Dutch North Sea business case will most likely be offshore farming(van den Burg et al., 2016). It can therefore not really be compared to the studied literature and case studies, but lessons learnt from the case studies and a compilation of success factors are very valuable for the growing industry.

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Appendix 1 Interview guide for case studies

Part A. General questions

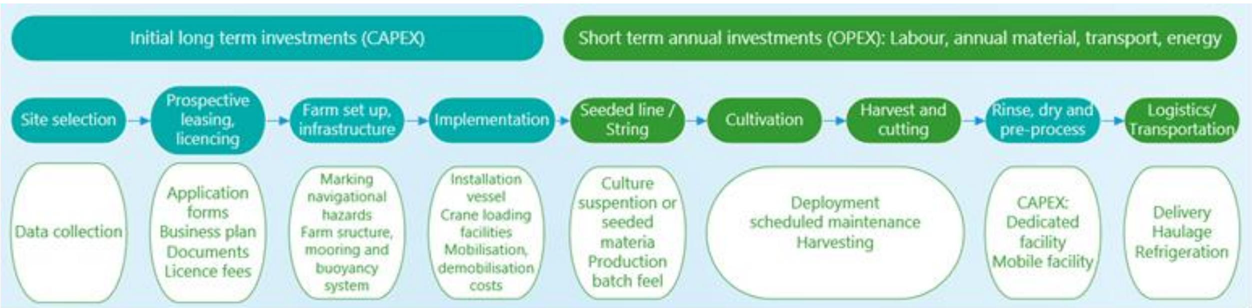
- Can you briefly introduce your seaweed company to us? (What is your role?)
- What is the size of your company? (number of employees, permanent and seasonal)
- When was the company founded?

What are your final products? What form are these? (wet or dry)
What cultivation technique do you use? (onshore, offshore, long line, grid..)
What species of algae do you cultivate?
What is the market purpose of your production? (food, feed, cosmetics, energy..)
What is your current yield (total, and per ha per year)?
How do you view your future business? (expanding in size, diversifying, etc.).

Part B. Specific questions on success factors

We found several success factors, like using existing infrastructure, optimal environmental conditions…
In the history of your company, can you recognize one success factor that was particularly relevant for your company?
What are factors where you still see possible improvement in your company?
Is there one "success factor" that had no relevance?
Do you know other cases where a specific success factor was particularly relevant? Do you know another success story and the relevant factor?

More focused on the Dutch North Sea:
What do you think are conditions that make the Dutch North Sea a successful/**un**successful place to farm seaweed? Do you have examples?
What would need to happen to make it a successful business case?
What do you think can be a successful model for the Dutch North Sea?



Part C. Economics and risks

Now we would like to understand a bit more about the economics of the company, without being to detailed, in case that is confidential. From our research we drew up the different steps of seaweed farming and a rough estimate of general costs involved.
Focusing on the seaweed value chain, up to which step do you operate?
In which step would you know and like to reduce costs?
In which step do you see a particular success for your company (advantage) where other companies or countries in other seas might have difficulties.

In case there's time, an optional question:
Which step in the chain has the biggest risks in its expenses? For instance risk of unforeseen costs, or extreme variation in costs, due to variables you have no control over (weather, market, etc.).

Appendix 2 Interview transcripts

Friday 3rd of June 11 am, Interview for the case study in the Proseaweed – Learning from international experiences project
Interviewer: Sophie Koch (WUR)
Note taking: Elisa Ciravegna (WUR)
Interviewee: Urd G. Bak (Ocean Rainforest
Case study 3: Ocean Rainforest (OR)

Part A. General questions
Ocean Rainforest (OR) was initiated in 2010 with the idea to reduce CO2 through the cultivation of seaweed in the sea. In 2013 OR put the firsts lines in the sea. Urd Bak was employed in 2014 as a research and innovation manager for the company, after achieving the Master's in Environmental Biology, and then started a PhD in 2016 in collaboration with the company and DTU, Denmark.

Today the company counts 10 people in the Faroe Island, 4 in California, 1 in Copenhagen and 1 in Chile: in total around 17 people. But during the harvest, due to their long harvesting period (April – October) they hire 2-4 people hourly to help in the processing, harvesting, and deploying new lines in October.

At the moment OR produces mainly two products, dried seaweed from *Saccharina latissima* in different sizes (pieces or powder), and fermented seaweed. OR has also recently started testing *Alaria esculenta*.

The dry seaweed (*Saccharina latissima* and *Alaria esculenta*) are normally for human food products and the fermented seaweed is for pig feed, as this product reduces diarrhea and mortality in the piglets. Their cultivation structure is called MACR, it is on a nearshore site, which means that it is not far from the coast but has very rough and exposed conditions (very big waves), sometimes rougher than the real offshore structures.

Yield per year: it is difficult to say a specific number, because there is the potential to harvest or what you get from an average if you include all damaged lines and all not so well performing lines So OR's yield is: 4 kg of wet weight per metre (m)per year. On 6 ha OR has 40.000 m of growth line. On each of these m they have 4 kg per year (or 2 kg per harvest, since they harvest multiple times). So on 6 ha, 160 tons were harvested, so <u>per 1 ha is 26.6 tons of wet weight per year</u>. OR growing structure is also vertical, with 10 m lines going down towards the seafloor. This means that their yield per m isn't 2D like for other yield, but actually 3D. Therefore they give different numbers of yields per metre, one is per m2 of production, on is per metre of growing line.

OR is looking into up scaling mainly in Faroe Island but also in other places like Norway, California, Alaska, Iceland. The aim is 1.000.000 tons in 2030. As a business strategy they want to create a higher value of the seaweed product and reach more mechanisation to handle larger amounts of biomass. And finally selective breeding to produce a higher yield. OR have their own hatchery, they will produce 300,000 m seeding material for the autumn.

Part B. Specific questions on success factors
1. Multiple harvests: One of the easiest ways to reduce cost is doing multiple harvests, which they can do their harvesting window is from April to October. In addition to reducing the costs, doing multiple harvests also means cutting the seaweed not at the base, but further down the blade which produces a better and cleaner product. You avoid cutting the stem and the more fibrous part. The bottle neck is the amount of seaweed that can be pick up from the sea in one day. At the moment it is around 5 tons per day. The processing facility is half manually and half mechanized.

2. Using existing infrastructure: the Faroe Islands have a lot of fishing and aquaculture equipment that is no longer used by that industry and can be bought or rented at a good price (old vessels, buildings, ropes…).
3. Good environmental and water conditions: it is important to have stable conditions, below 15 degrees. No ice and very well mixed sea water, without stratification, which allow a good nutrient flow. This is a huge difference compared to the Netherlands.
4. Seeding method: at the moment OR is doing manual seeding and direct seeding because it is cheaper. The risk of direct seeding is that if you want to put bigger plants in the water in October to have more biomass in April (an important step especially for other farms that have to harvest everything before the water gets very warm) you risk having those bigger plants washed away by the current when seeding. It's better to plant small plants, but then the risk is to have less harvest in the spring. But for OR this is not a problem, as they keep the line for three years and do six harvests with the same seed strings. So in conclusion for OR it is a big benefit and it is also very useful to scaling up.
5. Cultivation structure: OR structure (MACR) can deploy line in deeper water location where the water flow is better and where more nutrients are for the seaweed to absorb. These are better conditions then in completely still water. Finally, clean water is great for cultivation because you can grow there even at a depth of 10 m, but the algae will always receive sufficient sunlight.
6. Circular approach: In Iceland thermal can be used in the drying stage.

Dutch North Sea
For the Netherlands it is important to go more offshore and find a place where the water is not too warm in the summer (< 15 degree) and doesn't have stratification. In addition, the North Sea is also very shallow, and it has sand on the bottom, with the turbidity the water quality became very bad and the light cannot penetrate.

Part C. Economics and risks
OR does every step in the value chain.
For the CapEx and OpEx the latest numbers are in the 2020 paper with 4 harvests, even if they manage to do as many as 6 at the moment. The CapEx is reduced today, but it's not published with according yield numbers. Costs from 2018 to 2020 increased because more lines were put in. In the table in 2020 the calculation was made using 6 kg per metre (and not 4) that is the real potential average in the grow line.
In the processing stage the drying is still most expensive step.
Harvesting and processing are the most valuable stages. With the longer harvesting window they can also work for a long time.

Risks:
- Storms are a big risk in general but not that severe for OR, their structure has however held all these years.
- If something goes wrong with the seeding, that could also be a big risk, but since they reuse the line for 3 years, they always have something to harvest.
- At one point they risked losing everything because shrimp attacked the algae and were eating it, but the severity of the risks are diluted, since they harvest several times and it is not al dependent on one harvest.

Tuesday 24th of May 1 pm, Interview for the case study in the Proseaweed – Learning from international experiences project
Interviewer: Sophie Koch (WUR)
Note taking: Elisa Ciravegna (WUR)
Interviewee: Kim Kristensen (Arctic Seaweed)
Case study 1: ARCTIC SEAWEED (AS)

Part A. General questions
Kim Kristensen: CEO of the company, founder and co-owner of the company.

4 fixed employees, but 22 during harvest. 3 interns, 12 seasonal staff and 3 hired technical staff in addition to the fixed employees. It is a growing company. The company was founded in 2016. The final products are seaweed in a wet stabilized form. The cultivation technique 'near shore', sheltered, but with close to offshore conditions. The cultivation structure is their own invention and a modular farm structure, a submersible modular farm. The brown algae, *Saccharina latissima* and *Alaria esculenta* (mainly focused on the last) are cultivated. They only address the food market.

As yield, a production of 500 metric tons of wet weight is planned for next year. It is measured by kilos per metre.

The 5 years plan is to expand in size and volume in order to become profitable with the economy of scale. The company currently produces in too small volumes, which is too expansive to be profitable. The right technology and the right people are needed. Currently AS sees the food market has a capacity up to about 10,000 tons, around these numbers, there will be the point at which things will change in terms of production costs. Originally, there was a three-year plan to produce 1,000 tons, at which there would have been a break-even point for our profitability. Now we're five years into it and we see that it will be a few more years before we reach the 1,000-ton market, because it depends on many factors like technology, biological issues, quality of seed stocks, distribution and planting techniques. All these things add up to complexity, and harvest is only once a year. If something fails, it has to be waited one year before all our optimisations can be tested.

Big lessons learnt from past failure: A system designed for large volumes had been developed, but the seaweed didn't grow. Only last year the reason for this was found: Seed stock from a Dutch company had been bought, which worked amazingly during the first year when it was tested in a small scale of pilots. However with scaling up, those results couldn't be achieved anymore, not knowing what was wrong. At first the engineers thought it was a technical problem, but eventually it was realized that the stock was a monoculture, so there were only male gametophytes. The seed provider company probably didn't know that, because they generally work on a small scale too and they too, learnt with this case. What they supplied this year was very good. However they are not able to supply all the volume needed, so the seed supply needs to be diversified in the future.

Part B. Specific questions on success factors
Examples of success factors:
- The possibility to do multiple harvests a year,
- Using existing infrastructure (for instance like in Norway from the salmon industry),
- Optimal water and environmental conditions (nutrients, temperature, waves, etc.),
- The optimal cultivation structure,
- Shortening processing (for example in France the possibility to skip the mechanic drying process).

Arctic Seaweed:
- It is a **totality** of the factors mentioned. Having a very efficient seeding mechanism doesn't help without a very efficient harvesting mechanism, and vice versa.
- Also vertical integration is important: your **own hatchery** will provide the flexibility to have your own seeds stock available. The risk of a break in the supply chain can be mitigated, furthermore expenses can be reduced. Seed stock can then still be bought additionally, not to have all the eggs in one basket. The **right seeds**, at the right time in the right quality and quantity is critical for a good cultivation.

- National **funding programmes** help innovators a lot. It helps to trigger the investment, as projects can be funded 50% by the government and thus reduces the risks. But a kind of proof of business concept from an independent third party that believes in the project is needed. To get EU funding for instance, has very big timescale but also expectations though (it also gives more money).
- About the **existing Norwegian infrastructure**, AS doesn't completely agree that it is a benefit. Because producing seaweed and producing fish is completely different. For example, for freezing the product and down to packaging, potentially existing fish processing plants could be used. But often those plants don't have the capacity or it may not be wanted because the whole plant would have to be cleaned up before and after which would be too expensive. But some companies share processing plants to process the seaweed and crab, as they have matchable seasonality. Maybe in the future looking more into integrating different types of agricultural and you can see the benefits of collaborating.
- **Climate condition:** Benefitting from sun drying isn't allowed here in Norway for food safety reasons, if you're going to use seaweed for food. However, it is a challenge here that the temperature is relatively high, as we need to stabilize the algae very quickly after harvest by drawing down the Ph with salt. Greenland for instance has preferable conditions, with a harvesting air temperature of 8 degrees max (?).
- Direct drying in these volumes is not currently possible, but there are many companies looking at **high-efficiency, high-capacity drying processes that use waste heat** from different kinds of industrial processes. There is a lot of heat from waste that could be used, but it also depends on the location of this waste. If the seaweed needs to be transported to it, it will have to be stabilized.
- **Scaling up in the processing** line is our current focus. The deployment system is already very efficient with so mechanical seeding, which allows us to deploy 30 kilometers a day. The harvesting system, being mechanized, is, so we significant amount per day can be harvested. But the bottleneck is processing because that's still manual and we can't produce enough per hour. Producing more kilograms per minute reduces the costs for boat and people are by the minutes.
- There's a huge advantage of **renting the boat** instead of buying it, because it is only used twice a year for four weeks.
- Unique success factor: the **Norwegian shoreline stretches quite far from the South to the North**. This means that the operational window moves northwards. That means that in the south harvest is in April or May, but in the far North, harvest is in June, July, and August. With farms along the coastline, one can have a much longer operating window, and a very efficient farming system allows you to utilize it.

Dutch North Sea:
Not a lot of knowledge about the Dutch North Sea and local conditions. However, in the Netherlands have a lot of infrastructure coming up in windmill energy, which could provide anchoring possibilities. This could potentially an opportunity for a collaborative approach using these infrastructures. A potential success factor could be the shared infrastructure allowing for scaling up. (multi-use factor)

Part C. Economics and risks
Arctic Seaweed operates on the whole value chain but the storage.

Cost per kilogram or cost per kilometer are useful to compare. Without volumes you can't compare. Important for a business are CapEx and OpEx and of course the focus is on the OpEx. A totality of factors is again required to influence OpEx:
- The best people, especially a good management team, which creates an efficient systems. You have a very short production window, so you need to get as much out per hour as you can.
- It is important to mechanize. But currently, there is no standard, so that means the numbers will differentiate between each one.

Main risks:
- One of the main risks with offshore farming is **weather:** Mechanical assistance is needed to pull ropes out of the water, and that is a very expensive and its deployment depends on the weather. So only extremely high volumes make such mechanization profitable.
- Biologic risk (big risk):
  - If the quality of the seed stock isn't good you can't deploy and you won't have any yield until the next year.

- Or if the environmental conditions are very bad one year (for example, a winter without sunlight), plants won’t grow as fast and as big as you would like to have them.
- There may be seasonal variations, where fouling on the organisms can occur.
- Another example of incontrollable risk: spawning of fish on the kelp, and the whole harvest was lost.

- To use sensors in the water isn’t a solution, as the data cannot be influenced once you have it. What’s needed is better traceability of the product. I think on the production side you need to get more traceability and more data after the seaweed is out of the water.
- **Weather**: A day of bad weather forces huge additional costs because 22 people and a very large ship cannot go out to sea to work on a stormy day, but they still have to be paid.
- **Site select**: In an exposed site seaweed will grow better, however that adds the risk of losing money during harvest if the exposed site isn’t accessible due to bad weather. It’s a balance between better seaweed in exposed sites and less risk of losing money during harvest in near shore sites.

Tuesday 25th of May 10 am, Interview for the case study in the Proseaweed – Learning from international experiences project
Interviewer: Sophie Koch (WUR)
Note taking: Elisa Ciravegna (WUR)
Interviewee: Stefan Kraan (The Seaweed company)
Case study 2: THE SEA WEED COMPANY

Part A. General questions
The company was founded in 2019. Initially, the start-up was financed in order to start the business. The three founders met during a collaboration with a company in the Netherlands, and within a few months they founded: The seaweed company. In one year other 6-7 people joined the group, and recently after the arrival of a big investor the company has been able to expand further. So now in the Netherlands, we have about 12-14 people. In the meantime, there was also a set up in India in two places on the East Coast, with a lot more people because labor is cheaper. In total, it now employs 42-44 people: 12-14 in the Netherlands where the finance, business development, logistics, and health and safety departments are based; 5 (3 part time) in Morocco; and the remainder in Ireland and India

The company is horizontally integrated: they do biostimulants, animal feed, human food, biomaterials and pharma. Biostimulants are sold mainly in the Netherlands, and an agreement has just been signed to start a regenerative agriculture project in several places in Europe. As for feeds, they are sold to poultry farmers in Europe, mainly in the Netherlands, but also in some places like the United Kingdom and Belgium. The goal is to be present in the whole value chain and to implement circular bioeconomy, for example, a pig farmer with about 1,000 pigs who grows his own crops to feed the pigs and uses the algae-based biostimulant that will then go to feed the pigs, if hamburgers are made with that meat, the algae is present in the whole product chain.

The cultivation system is very different between the countries. *Alaria esculenta*, algae for human consumption, is produced in Ireland. Seeds are grown, and these are sown directly on strings-the company no longer uses the seed string method. The process is very mechanized, with minimal human labor. In India, for example, it’s very different, because social impact is important. Therefore the company provides as many jobs as possible, which is feasible due to cheap labor. Seaweed cultivation is a very accessible job, plus the cultivation is vegetative and it does not require high technology (the brown seaweed that is produced in Ireland has sexual reproduction). Production in India and Morocco is mainly for animal feed.

Yield: In India they work in plots (1 plot is 200 lines of 60 m) each plot produces 2 tons and the cycle is 40-45 days, so it is possible to harvest 6 times a year. There’s not much innovation in cultivation technique in Asia. It’s a vegetative system that’s been implemented for 30-40 years and it works, so right now, no need to change it. If a harvest fails in India, because of the monsoons for example, you have 5 more chances to reach profit. In Europe it’s different because you only have one harvest per year. You produce the seeds, they are planted in September-October harvested in April-May. *Alaria esculenta* can be sold at 30-40 euros per kilo. It’s safe to say that the learning curve in this business is still very steep. Initially the company had to learn how to seed and produce the grids efficiently, now the next bottleneck is drying, which could be a big problem for all industry players in Europe. Today’s technologies (dehumidifier, drying container, and polytunnel) are good only for small quantities, but volumes will increase in the future. One problem is related to the fact that too much manual labor is needed to hang the algae, and in Europe this is very expensive. This year the company tried to rent an experimental dryer that was being powered by diesel, but with its price increase it will be impossible to make a profit. It is still a good attempt to be able to learn with the goal of scaling up.

Part B. Specific questions on success factors
With respect to the agricultural stage (grid, structures, lines), the company has experimented and tested a lot in the past two years, including different distances of the lines from each other, planting density on the lines, etc. For example, they have noticed that if you have a very high density in the lines, the plants only grow up to one meter in length and are very thin. If you space the lines more between them, you get very large plants, 3-4 meters long. This is useful to diversify the product according to customers, for example, snack producers require thin seaweed. But if it is a meat substitute, it is necessary to have longer, fibrous

seaweed. So it’s important to consider the market you’re in, and this is something that is sometimes underestimated, thinking that the important thing is to optimize production volume.

The processing step of drying is an issue to scaling up.

Another very important factor is the market. Many people start this business without having a good business perspective, and end up with unsold seaweed in March and April. This also happens because in the past there was a state policy that promoted this activity by giving aid to be able to start growing, but no thought was given to establishing a proper market. In order to create an industry, The seaweed company is creating a partnership that provides seeds for everyone in the project to be able to grow their own seaweed, giving them the opportunity to sell their harvest on the open market, but giving them an additional aid of being able to sell what they were not able to sell on the market to The seaweed company at a lower price. In this way the producers stay alive and can be successful in this business.

It’s very important to share knowledge and experience at the beginning of the business, it’s not possible to think about going it alone.

Dutch North Sea (in comparison with IRELAND):
In the North Sea, it is difficult to grow *Alaria esculenta* because in summer the temperature can exceed 18 degrees in coastal waters, which is very harmful to this seaweed. So, most companies in Northern Europe focus on *Saccharina latissima* because it is much more heat stable. However, the problem with *Saccharina latissima* is that it can’ t be used in food production because it has too much iodine. Arsenic is another problematic component of this species that makes it useless for animal feed. For these reasons, The seaweed company has opted to produce *Alaria esculenta*, which means that in order to cope with the high temperatures, you have to harvest earlier (May or the second week of April). Therefore, from a food security perspective, it is still better to grow *Alaria esculenta* for a shorter period than *Saccharina latissima*.

A success factor would be to be able to have a valuable crop that can be sold and cover all investments, so that profits can be made. But this is still 20 years away for the North Sea. The costs will not be covered until we move to square kilometer scale production. But for that you need very expensive infrastructure, because you have to design it to be resistant to storms to other bad weather elements. At the moment it might not be advisable to grow in the western sheldt because it turns out to be a very polluted area, the eastern sheldt could be an ideal area to cultivate seaweed, because there is very good water flow and turnover. This could be a very profitable factor especially if you combine it with IMTA, where you can have algae, oysters and fish in one system.

Part C. Economics and risks
The company currently grows about 7 hectares and has a harvest of 40 tons of wet matter. For *Alaria esculenta* it is good to have 3-4 kg per meter (can go up to 6-7), *Saccharina latissima* might go a little more because it is a heavier alga (<10 kg per meter).

In relation to cost, it does not make much sense to talk about cost per hectare because it depends on how many lines or grids are cultivated. As far as site selection is concerned, it did not entail any additional costs for the company that created a joint venture with a person who had a 30-hectare plot and it was decided to start cultivation there (it is a difficult cost to estimate). The license to cultivate is 250 EUR per hectare each year (in Ireland).

Farm set up: 10 hectares in cultivation at the moment that costs about 60K, including labor. The lines cost 80 cents per meter. After a lot of experiments, the company has 260 lines of 100 s.

It is not possible to say how much one year of production including hatchery, cultivation, maintenance, harvesting could cost.

The only way for the algae industry to survive in Europe is to switch to direct seeding and abandon seed strings, which currently cost 1 euro or 1.5 euro per seed string. But this will lead to two schools of thought:

some will continue with seed strings and some will switch to direct seeding (where hatchery costs can be avoided), so you will have different cost structures to compare.

Risks in the value chain:

- Hatchery, for example the air conditioning could break down and you can lose the whole seed stock. But this is a controllable risk.
- Seeding, does not pose great risks if carried out in the correct way.
- Weather, winter storms when the crop is growing, that can be prevented by overengineering but it brings high costs.
- Food safety of the harvest, is very difficult to manage because it does not depend directly on the farm, but also depends on who is around, for example there could be a spill or something else, and the harvest may not be suitable for human consumption.
- Drying and storing the harvest is concerned, you have a window of two months to complete the harvest, so if the weather is very unfavourable at this time you really risk losing the whole harvest, that could be the biggest risk.

Appendix 3 Overview on the costs of seaweed cultivation

Small scale						
	Variable/units	**Denmark**	**Ireland**		**Sweden**	**Faroe island**
		6 tests sites, 3 Farms	**Project**	**Farm**	**Farm**	**Farm**
Production	Species	Saccharina latissima	Laminaria digitata	Alaria esculenta	Saccharina latissima	Saccharina latissima
	Life Span	10 years	3 years	20years	10 years	8 years
	Site Typology	longline (three different ways)	continuous rope culture	Long line system	Long line system	Near shore exposed (offshore possible) Macroalgal Cultivation Rig
	Site Size	5 longlines with 220 m = 1100 m/ha/year	14 400 m rope *	11 lines of 110 m on 6 ha	2.34 km per ha	9 ha, 1 ha = 10x250 growth lines
	Output		100 t ww (15 t dw)	14 520 kg ww / 110 m line		
	Yield		7.25t/km/yrs (7.25 kg/m/yrs ww(15%=dw)	12t/km/yrs (11* 110m lines, 14 520 ww / 110 m / year (10%=dw))	8t/km/yrs (8 kg ww/km/yrs and 3.35 kg dw/ton/ha	6t/km/yrs
		7.65 t/ha/yrs Average yield of the 9 examples kg fresh weigh (fw). DW differs a lot		48.4 t/ha/yrs (290 400 kg per 6 ha (10%=dw))		35t/ha/yrs (58 kg/m2/yrs)
Short-term costs (OpEx)	Material	Incl.	36 159 tot/ yrs **	Incl.	15 829 €/ha/yrs	12 609,4 €/ha *
	Labour	Incl.	85 000 €/tot/yrs	Incl.	27 226 €/ha/yrs	
	Energy	Incl.	30 000 €/tot/yrs	Incl.	545 €/ha/yrs	
Total OpEx			**151 159 €/14.4km/yrs**	**10 813 €/1.210km/yrs ***	**43 600 €/ha/yrs**	**12 609,4 €/ha ***
Long- term cost >5 y (CapEx)	Total		**130 128 €/14.4km/3yrs**	**100 140 €/1.210km/20yrs ***	**67 810 €/ha/10yrs**	
	Broken down to year and ha or km		**3 012 €/km/yrs**	**4 138 €/km/yrs**	**3 391 €/ha/yrs ***	**15 784,2 €/ha/yrs ****
Other value chain steps	Licence	Incl.95 € for 10 years			Not included	
	Certification label	Incl.				
	Hatchery	Incl. (rent)	Incl.	Incl.		Incl.
	Processing (drying)	Not included	Not included	Not included		Incl.
Total costs	**Individual unit**	**116 000 €/ha/10yrs***	**580 945 €/ total/3yrs *****	**15 820 €/6 ha/yrs ****	**46 988 €/ha/yrs ****	**28 393,6 €/ha/yrs**
	EUR/kms/yrs	**116 000 €/1.1km/10yrs *****	**580 945 €/14.4km/3yrs**	**15 820 €/1.210km/yrs**	**46 988 €/2.34km/yrs**	**28 393,6 €/2.5km/yrs**
	EUR/km/yrs	**105 455 €/km/10yrs**	**40 343 €/km/3yrs**			

Small scale						
	Variable/units	**Denmark**	**Ireland**		**Sweden**	**Faroe island**
		6 tests sites, 3 Farms	**Project**	**Farm**	**Farm**	**Farm**
	EUR/km/yrs	**10 546 €/km/yrs**	**13 449 €/km/yrs**	**13 074 €/km/yrs**	**20 081 €/km/yrs**	**11 357,44 €/km/yrs**
	*	Includes: renting of the hatchery, renting of the monitoring and harvesting boat, dismantling, labour, pumps, material, electricity for every step.	30 * 30 m (900 m2) with 450 m rope. There will be 32 units of this, 6 units per h, so for the 32 units: 5.3 ha are needed	Very detailed supplementary data available, list of what is included. Boats are rented	3 391 **€**/ha/yrs = (719 **€** (5 yrs material)/5) + (2 337 **€** (10 yrs material)/10) + (335 (10 yrs labour)/10)	Include: cultivation, maintenance, harvesting, hourly cost of vessel and labour
	**	The dry matter content of the biomass is sensible to the handling/dewatering of the biomass before drying, which is not standardized in the studies included.	Only consumable and common costs, that are not CapEx (from Table 7 and 12, view supp material)	CapEx divided per year	All costs had been divided by 2 to have the value per ha.	Include: expenditure for the growth ring and lines, material cost (ropes, anchors, chains..), hourly cost of vessel and labour
	***	Average 116 000 EUR/ha/10 year with a range 103–139 k €/ha/10-year with an exception of L1A (319)	Bank interest as cited in the source study were excluded, to be comparable to other studies			US dollars from the publication were converted into EUR with the average rate of 2018: 1 EUR=$1.1811
Source		Zhang et al., 2020	Watson and Dring, 2011	Collins et al., 2022	Hasselström et al., 2020 **	Bak et al., 2020***

Appendix 4 Factors influencing the cost and revenue structure of seaweed companies

What determines cost and revenues?
Factors that will determine the costs and revenues. Improving cost efficiency and overall financial viability of the company will depend on minimising the costs and maximising the revenues.

Cultivation and operating costs		
Costs types	**Depends on**	**Which further depends on**
Production / cultivation efficiency	Growth rate	species (biological productivity of a species)
		cultivation site with available nutrients and light
	Mortality	Risks like Biofouling
		Cultivation method (technological advances)
		Species resilience (temperature changes, etc.)
		Predator control
	Density in relation to system design	Cultivation method
		Technical innovation in growing-out techniques for longline and raft culture
	Efficiency in size grading, restocking.	Cultivation technologies (industrial or manual)
	Installation cost	Total initial investment compared to revenues
	Cultivation scale	
	Unit per area	
	Breeding (Wild seeds or hatchery seeds: more expansive but provides the opportunity for selective breeding and giving opportunity for triploid production (added value))	
More efficient breeding	technological breeding innovations	
More efficient harvesting	Harvesting method, Technological advances and development in harvesting	
Per capita costs	Geographical origin	
Production site	Geographical origin (?)	
Transportation	Methods	
	Distance	Location of site

Processing costs	
Type of processing necessary	Various pre-treatment operations
More efficient processing	Technological advances and development in processing

Revenues	
Geographical area	Price for product
Other valuable products on the farm (e.g scallops)	Supplementary income
By products such as alginates, mannitol and iodine could offset production costs	
Concentration of ingredient	Processing quality
Market (willingness to pay), higher price for green food social and political interest in the market ?	Awareness of ecosystem services (green food, etc.)

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