North-Sea-Weed-Chain Sustainable seaweed from the North Sea; an exploration of the value chain

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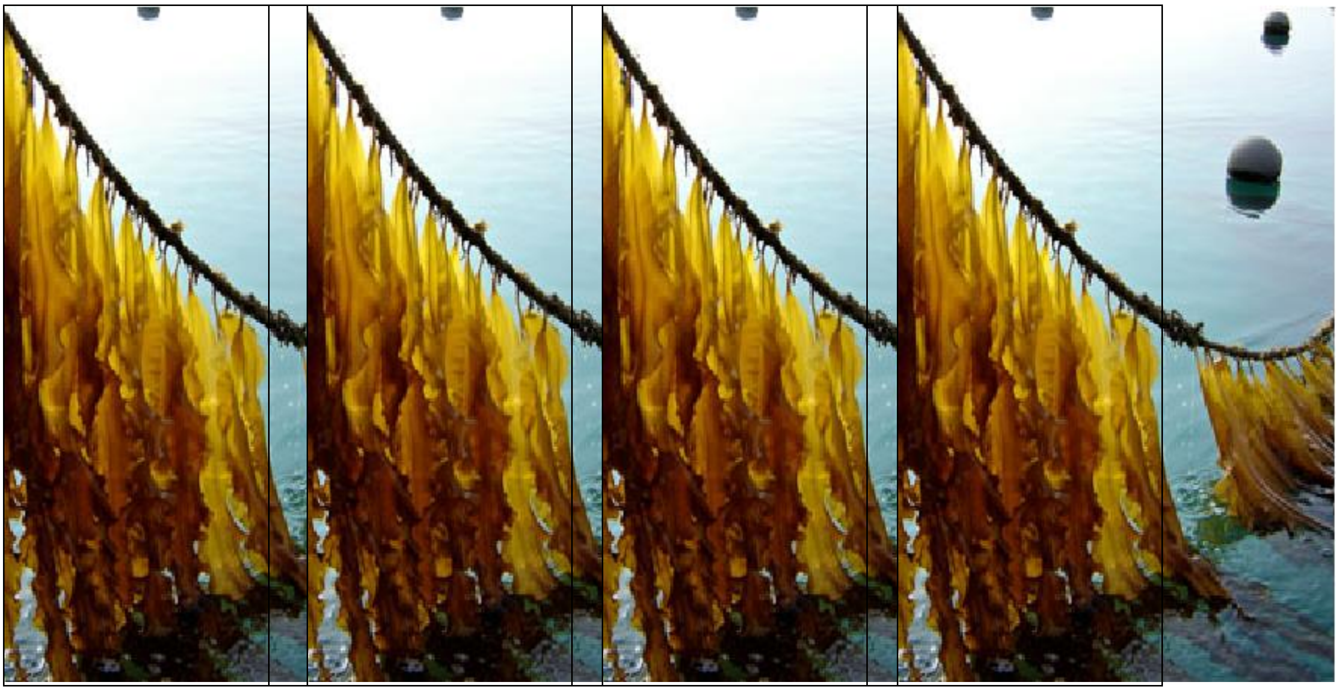

North-Sea-Weed-Chain

Sustainable seaweed from the North Sea; an exploration of the value chain

TNO innovation for life

Deltares Enabling Delta Life

ECN

MARIN

WAGENINGEN UR For quality of life

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Content

1. Executive Summary

Seaweed is seen as one of the most promising aquaculture crops of the future, yielding products ranging from human food, animal feed, cosmetics, bioplastics and fuel. The cultivation of seaweed in increasingly busy coastal waters poses many challenges.

In this project five applied research institutes, ECN, TNO, WUR-DLO, Marin and Deltares, worked closely together to assess a seaweed value chain, covering issues relating to engineering for offshore cultivation, growth of seaweed and carrying capacity of locations, extraction of carbohydrates and proteins as well as the economic costs and benefits of production. This required a multi-disciplinary approach to tackle various critical hurdles in developing an economically viable seaweed industry.

The physical boundary conditions of selected North Sea locations (wave height and currents) were input for computational fluid dynamic calculations of the most appropriate seaweed support construction. Model outcomes were compared to physical tests on scale models carried out in a large wave tank. These results were used to assess the ability of cultivation infrastructure to withstand regularly occurring storm conditions at sea. This has indicated that further technical developments are required to cope with the dynamics and the expected current / wave loads at most offshore locations.

In laboratory tests the growth rates of seaweed species, as function of water quality and other environmental parameters, were determined. These parameters were used to set up a numerical model to calculate potential yields of seaweed production at different locations in the North Sea. Furthermore the effects of different harvest frequency on the production of seaweed were assessed. Increasing harvest frequency appears to have little effect on yield, allowing cost reduction. However, we did find changes in the ratio of carbohydrates to proteins in sea lettuce, *Ulva sp.*, in response to physical conditions in the cultivation set-up. This means that the ultimate product for which seaweed is cultivated can dictate design and positioning of installations.

Pure mannitol, both a building block and a food ingredient, was successfully isolated from sugar Kelp (*Saccharina latissima*) along with alginic acid. *In vitro* research indicated that the remaining fraction is valuable as feed component for monogastric animals (e.g. pigs).

The consortium, based on its know-how in food and feed, and chemical building blocks, selected species specific valorisation strategies for *Ulva* and *Saccharina*. These valorisation strategies integrated this know-how by encompassing all these applications in one cascading value chain.

Finally we compared the total estimated costs for production of seaweed with the economic revenue of the seaweed products. As production costs are strongly scale dependent, we assessed the effects of a realistic level of up-scaling of production. Even in the up-scaled plant, the costs of production are still around six times higher than the benefits. This number suggests that developing a seaweed value chain is within reach. Investments in optimisation will improve yields of biomass and selective breeding will result in higher production of extracted substances. Also on the costs side, technological developments will lead to lower costs. Cost reductions in the biobased economy of a factor ten have been achieved with sustained research and long term funding thereof. Next to this we do realize that prices for protein are rising and that the prices for oil are very inpredictable.

The outcome of this project warrants optimism about the future of seaweed. The Dutch maritime industry together with the Dutch agriculture sector can develop a large-scale economically viable seaweed cultivation sector. With this new form of aquaculture The Netherlands can contribute to important transitions towards sustainable energy, sustainable proteins and a bio-based society.

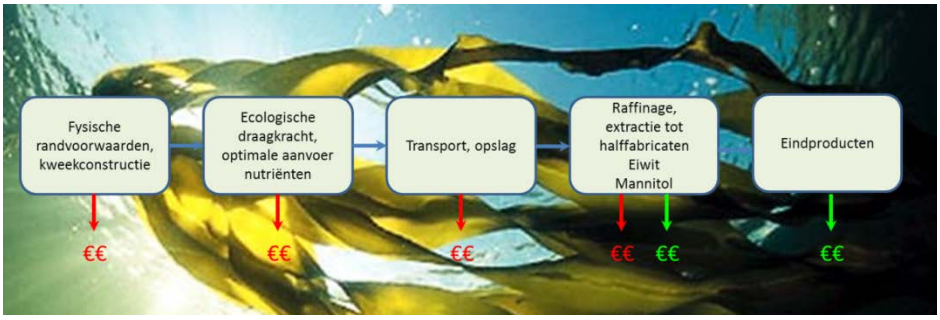
Last but not least, this project has forged a solid base for productive and very enjoyable future cooperation.

2. Nederlandse samenvatting

Proloog; samenwerken; het geheel is meer dan de som der delen
In het project Noord-Zee-Wier-Keten hebben vijf instituten (MARIN, TNO, Deltares, ECN en DLO) intensief samengewerkt aan een waardeketen van zeewier. De beschikbare expertise van de instituten beslaat de gehele zeewierketen, van productie op offshore locaties tot business cases voor verschillende eindproducten. Samenwerken blijkt essentieel om de potenties die zeewier biedt te verzilveren. Samenwerken gaat echter niet vanzelf. Er is een gezamenlijk doel voor nodig, complementaire expertises, een wil om samen te werken en de mogelijkheid om tijd te besteden om elkaars taal te leren spreken en je te verdiepen in elkaars kennis. Het samenwerken beperkte zich niet tot de instituten; ook partijen buiten het consortium hebben een essentiële bijdrage aan het eindresultaat geleverd.

2.1 Zeewier; oogst van de toekomst

Zeewier is een potentieel belangrijke voedselbron en grote duurzame koolstofbron voor de biobased economy. Met de groeiende wereldbevolking is het noodzakelijk om voor ons voedsel meer te kijken naar de zee als 'landbouwgebied'. Boeren op zee is een grote uitdaging. Het vereist grote investeringen in infrastructuur. Voordat ondernemers hierin kunnen investeren moeten realistische vooruitzichten zijn op kweekmogelijkheden en winstgevende eindproducten. Dit project had tot doel de verschillende schakels in de keten van zeewierproductie tot vermarkting tegen het licht te houden. Duurzaamheid van de productie is hierbij leidend geweest.



Figuur 1. Illustratief overzicht van het project. Alle schakels zijn verbonden met elkaar.

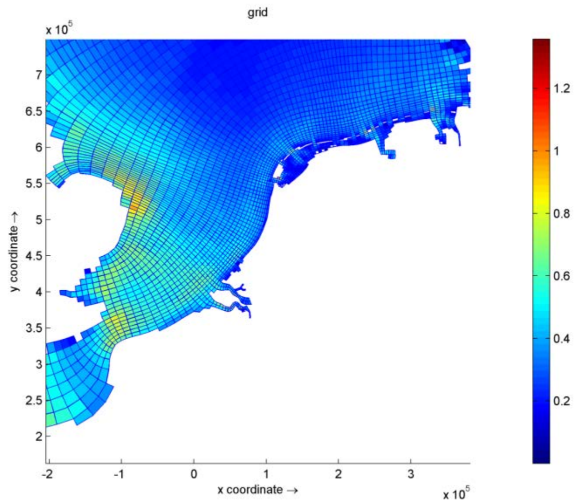
2.2 Projectopzet; een duet van lange en korte termijn

Omdat we maar een jaar de tijd hadden stelden we onszelf ten doel om aansprekende en tastbare resultaten neer te zetten en hiermee het bedrijfsleven te interesseren voor lange termijn onderzoek. Ofwel, een korte termijn resultaat als 'teaser' voor lange termijn ontwikkelingen. We hebben twee tastbare producten als einddoel gesteld en ons daarbij niet te veel laten leiden door haalbaarheidsdiscussies. Niet praten, we wilden aan de gang!

1. Zeewierkaas; een kaas gemaakt van eiwitten die geëxtraheerd worden uit *Ulva lactuca*. Dat levert een kaas waar geen dier aan te pas komt en die dus geschikt is voor veganisten. Van te voren wisten we dat de eiwitextractie erg lastig is. Daarom willen we ook onderzoeken of de eiwitrijke Ulva geschikt zou zijn als veevoer. De vraag hierachter is of zeewier een duurzamer alternatief kan zijn voor soja
2. Mannitol geraffineerd uit *Saccharina latissima* (suikerwier). Mannitol is een niet-dik-makende zoetstof (en daarmee ook een eindproduct) dat gebruikt kan worden in de voedingsmiddelenindustrie, en tevens een halffabricaat waaruit allerlei biobased producten gemaakt kunnen worden zoals bio-plastic.

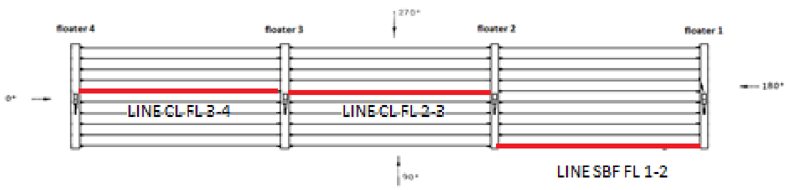
Voor beide producten moesten we een keten kiezen waarmee we het product in één jaar zouden kunnen realiseren. Voor de kaas uit eiwit paste het in het tijdschema om *Ulva* te kweken in gecontroleerde omstandigheden in Yerseke. De *Saccharina* moesten we inkopen, gezien het groeiseizoen (sept–mei) èn de korte looptijd van ons project (één jaar).

Omdat we óók kennis voor de langere termijn over het teeltproces wilden opdoen hebben we naast de acties gericht op deze tastbare producten een kennislijn opgezet die gericht was op de mogelijkheden en onmogelijkheden van een teeltlocatie op de Noordzee. Daartoe zijn de teeltproeven gebruikt om gegevens te genereren. Die gegevens waren invoer voor berekeningen met het stromingsmodel Delft3D om te bepalen waar in de Nederlandse Noordzee een teeltlocatie voor zeewier zou leiden tot goede oogsten. Op basis van die berekeningen en andere overwegingen is een locatie 25 km offshore van Egmond gekozen als 'onze' fictieve TO2 testlocatie.



Figuur 2; Het studiegebied voor het DELFT 3D model.
Waardes geven de snelheid in m/s aan.

Deze locatie ligt op open zee en dus moet er terdege rekening gehouden worden met golfbelasting. Een technische subgroep uit het project heeft zich, op basis van literatuur studies, gebogen over de meest duurzame constructie voor zeewierteelt. Daarbij is uitgegaan van onder andere het gebruik van duurzame materialen (zeewierlijnen), geen emissies, geen verlies van materiaal, zo min mogelijk slijtage en onderhoud. Mede op basis van literatuur studies is een constructie gekozen en met deze constructie zijn proeven in de binnenwatertank van MARIN uitgevoerd.



Figuur 3; het ontwerp van de teeltconstructie waarmee sterkte berekeningen zijn uitgevoerd. De rode lijnen geven aan waar de sterkte metingen zijn uitgevoerd.

Eerst zijn weerstandsmetingen verricht aan twee typen zeewier. Daarnaast is een schaalmodel gemaakt van het de gehele constructie waarbij gekeken is naar de prestatie van het gehele systeem bestaande uit drijvers, zeewierlijnen en het afmeersysteem. Met de gegevens van dit fysieke model zijn tevens numerieke modellen opgezet, die bedoeld zijn om vragen te beantwoorden zoals: Welke golf- en stroomcondities kan het ontwerp verdragen en hoeveel weerstand kan het zeewier hebben in dergelijke condities? Hoe zwaar moeten de verankeringen zijn? Technisch gezien is een ontwerp mogelijk waarbij alle zware condities van de Noordzee getrotseerd kunnen worden. Daar hangt echter ook een prijskaartje aan. De uitdaging is daarom om een geoptimaliseerd ontwerp te creëren, waarbij antwoord wordt gegeven op de hamvraag: wat zijn de kosten van zeewierteelt op de Noordzee, wat gaat het opleveren en hoe krijgen we zicht op een haalbare business case?

2.3 De resultaten

In Yerseke wezen de teeltproeven van Ulva aan dat een oogst per seizoen van 20 ton droge stof per hectare in één groeiseizoen (april –aug) een haalbare kaart is. Uit proeven van de Wierderij weten we dat *Saccharina* in één groeiseizoen tot 15 ton droge stof op kan brengen. Omdat de ene soort in de winter groeit en de andere in de zomer kunnen we de teelten combineren; dit levert dan een totale jaarproductie op van 35 ton droge stof per ha per jaar. Dat is meer dan er op land met welk gewas dan ook bereikt kan worden. De proeven hebben ook uitgewezen dat het qua opbrengst niet uitmaakt of *Ulva* elke week of eens in de drie weken geoogst wordt. Dit zijn de hoeveelheden, maar voor de waarde van de opbrengst is kwaliteit nodig, en wat zit erin?

Figuur 4; Één van de zes raceways waarin Ulva is gekweekt.

Wat al langer bekend is in de literatuur, bleek ook uit onze proeven. De samenstelling van zeewier verandert door de groeiperiode heen en is ook afhankelijk van het kweekmedium. De gehalten aan eiwitten in *Ulva* in raceways namen af met een factor 3 (van ongeveer 12% tot 4%) maar namen toe in meer statische kweekbakken (van ~4% naar ~13%). Uiteraard is dit een oogstoptimalisatie opgave. Vanuit de teeltlocatie in Yerseke is de *Ulva* in meerdere batches naar de labs van zowel ECN als DLO gebracht. De extractie van eiwit uit *Ulva* was minder succesvol. Om de eiwitten uit de celwanden te krijgen zijn meerdere methoden geprobeerd, maar met weinig succes. Dit blijkt een hardnekkig probleem waardoor de kaas er nog niet is gekomen.

Saccharina hebben we ingekocht in Noorwegen afkomstig van de proeven van Hortimare. Opgave daarbij was om 1000kg nat zeewier vanuit Noorwegen naar Nederland te transporteren en geschikt te houden voor verwerking. De logistieke vraag van opslag bleek later in de business case van groot belang te zijn. Hier kwam de ervaring van een ander project van pas. In een EU project AT@sea (waar o.a. ECN in participeerde) is een pragmatische experimentele aanpak uitgeprobeerd en die bleek te werken; silage (eigenlijk 'inkuilen') van zeewier. Een werkwijze waarmee je van witte kool zeer lang houdbare zuurkool maakt. Het bleek te werken. De *Saccharina* is in Noorwegen in een 1000 l tank met melkzuurbacteriën luchtdicht verpakt en onder enige druk gezet. Vervolgens op transport naar Nederland gezet. Daar is het ECN ermee aan de slag gegaan om mannitol uit het zeewier te destilleren. ECN heeft het volgens een gepatenteerde methode voor elkaar gekregen om van 1 kg (DS) zeewier circa 200 gram zuiver mannitol te maken. Op de wereldmarkt wordt € 2 à 3 per kg betaald voor mannitol. Dit resultaat helpt de business case van zeewier in elk geval de goede kant op.

De kaas is niet gelukt, mannitol is wel gelukt. Dan blijft de vraag of zeewier een duurzame alternatief zou kunnen zijn voor soja schroot, dus geschikt voor veevoer. Batches van zowel *Ulva* als *Saccharina* zijn naar het WLR gebracht voor in vitro onderzoek naar verteerbaarheid van de zeewier voor eenmagige dieren, zoals varkens. De resultaten waren bemoedigend, maar het moet gezien worden als tussenresultaten.

In de analyses zijn drie zeewiersoorten onderzocht op hun verteerbaarheid. Het bleek dat *Saccharina, Laminaria digitata (vingerwier)* en *Ulva* een drogestofverteerbaarheid hadden van 60-70%. In vergelijking had sojaschroot een verteerbaarheid van 90%, waarbij opgemerkt moet worden dat soja een lange geschiedenis heeft van veredeling met behulp van klassieke en moderne genetische technieken. Voor zeewier is dit een startwaarde; er heeft nog geen veredeling plaatsgevonden, er is nog niet geoptimaliseerd naar oogstmoment en er is nog niet geëxperimenteerd met toevoeging van enzymen of gebruik van andere technieken om de vertering te verbeteren. Een zo hoge startwaarde geeft aan dat de toepassing van zeewier als diervoeder veelbelovend is. Maar daarmee is niet alles gezegd; er zijn nog 2 kanttekeningen:

1. Het hoge gehalte aan anorganische stoffen (mineralen) in zeewier blijft een punt van aandacht.
2. Na extractie van stoffen (bijvoorbeeld rhamnose via raffinage van Ulva) daalde de verteerbaarheid van het residu. Dit betekent dat bij cascadering van zeewier (van hoogwaardige naar laagwaardige stoffen) ook rekening gehouden moet worden met de waarde(daling) van de restproducten.

Deze experimenten leverden informatie op over toepassingen van zeewier en zelfs over de mogelijke opbrengsten. Om zicht te krijgen op de kosten moeten we in gedachten terug naar volle zee.

Zou onze fictieve installatie op de locatie 25 km offshore van Egmond het golfklimaat overleven en hoe lang is de verwachte levensduur? Vanwege de beperkte tijd en middelen is alleen de eerste stap van een iteratief proces doorlopen. Er is een ontwerp gemaakt, gebaseerd op de huidige inzichten voor zeewierteelt op open zee. Met een computermodel is dat ontwerp doorgerekend ten aanzien van kans van falen, levensduur en stabiliteit. Het bleek dat het huidige ontwerp van de zeewierteelt installatie zou falen bij golfcondities met een significante golfhoogte (Hs) hoger dan 4.2 m. Helaas blijkt dat in circa 20% van de tijd deze conditie voor te komen. Het betekent dus dat de kandidaat constructie te licht ontworpen is (eerste stap van de iteratie). De conclusie van het technisch onderzoek is dat sterkere afmeerlijnen en zeewierlijnen noodzakelijk zijn om de zware condities van de Noordzee te weerstaan. Uit het onderzoek is echter ook gebleken dat het zeewier slechts weinig krachten heeft te verduren aangezien een gedeelte van de belasting in de afmeerlijnen wordt afgevangen. Dit betekent dat er goede oogsten te verwachten zijn mits de afmeerlijnen gekozen worden op basis van de extreme condities. Verder is er ook inzicht verkregen in de vermoeiingsbelasting van het ontwerp voor golven met een significante golfhoogte lager dan 4.2m. Dit pakte positief uit. Volgens berekeningen kan de installatie langer mee (20 jaar) dan vooraf ingeschat (15 jaar). Dit is alleen op basis van vermoeiingsberekeningen. Praktijkervaringen geven lagere levensverwachtingen.

2.4 De ontknoping; kan het uit?

In de berekeningen van de business case komen alle resultaten van het TO2 project bij elkaar.
Voor de economische analyse hebben we een conceptueel proces model gebouwd van een raffinageproces op basis van lab testen. Met dat conceptuele model is doorgerekend wat zeewier op kan leveren. Het blijkt dat zeewier waardevol is door de vele toepassingsmogelijkheden; ontwikkelingen van betere procestechnologie kan de economische waarde van zeewier nog fors verhogen. Echter, het telen op zee is nog een te kostbare bezigheid. Dat komt enerzijds door het ruige zeemilieu waardoor installaties robuust moeten zijn, en de levensduur nu eenmaal beperkt is. Anderzijds zijn de zaailijnen (lijnen met daarin het zeewierzaad) nog behoorlijk aan de prijs. Al met al is er nu nog een mismatch tussen wat zeewier oplevert en wat het kost om zeewier te telen van ongeveer een factor 5 à 6. We hebben aangetoond dat opschaling op dit moment nog geen soelaas biedt, het zeewier brengt nog te weinig op. Bedenk wel dat de procestechnologie van zeewier nog maar net begonnen is. Uit ervaring (en geschiedenis) weten we dat technologische ontwikkelingen vaker hebben geleid tot overbruggen van veel grotere initiële discrepanties. Dit zit ruim binnen de bandbreedte.

2.5 De belangrijkste resultaten op een rij

- We kunnen samenwerken en we willen de samenwerking vanaf nu voortzetten. Voor de ontwikkeling van zeewier is het ook nodig. Zeewier kent teveel afhankelijkheden waar multidisciplinaire kennis voor nodig is.
- We hebben succesvol *Ulva* geteeld en daarbij aangetoond dat (geëxtrapoleerde) opbrengsten van 20 ton DS/ha/jr haalbaar zijn. Samen met de kennis verkregen op de Wierderij dat *Saccharina* tot 15 ton ds/ha/jr oplevert geeft dat een duidelijke indicatie dat met zeewier productiesystemen haalbaar zijn van 35 ton DS/ha/jr. Dat is veel meer dan met land gebonden teelt wordt gerealiseerd.

- We hebben de variaties in samenstelling door het groeiseizoen gemeten. Het blijkt dat *Ulva* het hoogste eiwitgehalte heeft naarmate de kweek langer duurt (althans in kweekbakken). De glucose neemt toe bij kweek in raceways, maar is juist weer constant in kweekbakken.
- We hebben zuiver mannitol via raffinage uit zeewier weten te halen.
- We hebben de verteerbaarheid van zeewier als diervoeder aangetoond.
- We hebben een ontwerp integraal doorgerekend op hydrodynamische krachten, stabiliteit en vermoeiing.
- We hebben de twee hier beschouwde zeewierketens financieel doorgerekend.
- En we hebben afgelopen jaar heel veel aandacht vanuit de media voor zeewier gehad.

2.6 Aanbevelingen

De marktpotentie van zeewier lijkt onbetwist. De groeiende aandacht voor zeewier leidt tot vele start ups van bedrijven. ‘I sea pasta’ (een zeewier *Himanthalia elongata* (zee spaghetti) die lijkt op, en gebruikt kan worden als, tagliatelle), ‘the Dutch Weedburger’,.... enz. Het zijn startups die hun producten direct op het bord van de consument brengen. De Dutch Weedburger wordt inmiddels naar Frankrijk geëxporteerd, de man achter ‘I sea Pasta’ heeft grote ambities om exponentieel te groeien.

- Omdat er nu weinig zicht is op de kwaliteit en de veiligheid van het voedsel ontstaat er een behoefte aan duurzaam, gecertificeerd zeewier dat getraceerd kan worden. Aandacht voor voedselveiligheid en het certificeren van zeewier is nodig.
- T.a.v. van Noordzee; Zeewierteelt op volle zee is vooralsnog financieel niet haalbaar. Het scheelt nog factoren, geen orde van groottes. De verschillen tussen kosten en baten zijn wel overbrugbaar met technologische ontwikkelingen. We bevelen aan om arrangementen voor meervoudig ruimte gebruik op zee op te stellen waarbij maximale synergie gezocht moet worden(zie onze visie).
- We hebben ons in dit project beperkt tot drie robuuste soorten waarvan er eigenlijk maar 2 nader zijn onderzocht. Er zijn veel meer soorten met evenzo kansrijke toepassingen; bijv. roodwieren zoals *Palmaria palmata* (dulse), maar ook bruinwieren die verschillende toepassingen hebben op verschillende locaties.
- Waarschijnlijk zijn er nog honderden soorten te verkennen die misschien nog aantrekkelijker zijn dan de hier gekozen soorten die momenteel de meeste aandacht krijgen. Een brede scan naar mogelijkheden en toepassingen is zeer aan te bevelen. Daarbij is het fundamentele onderzoek naar de biochemie van zeewier onontbeerlijk; het vormt de basis van de kennis.
- De fundamentele kennis is ook van belang voor het kweken van soorten. Door de opkomende “I sea Pasta” is er een behoefte om *Himanthalia* te telen. Dit lijkt nu een lastig te telen soort te zijn, maar serieus onderzoek is er nog niet naar gedaan. Ook voor bepaalde roodwieren groeit er een behoefte aan teelt.
- De zoektocht naar teeltlocaties is een integrale optimalisatie. De fysieke en chemische omstandigheden op de teeltlocatie bepalen de (tijdsafhankelijke) samenstelling van het zeewier. Dit werkt naar twee kanten. Zeewier heeft ecosysteemdiensten die we ten behoeve van beheersopgave kunnen inzetten. Anderzijds, de samenstelling van het zeewier wordt ook bepaald door de teeltlocatie.
- Niet alleen zeewierkweek, maar ook andere vormen van aquacultuur zullen in de toekomst verder offshore gaan. Ontwikkelingen in offshore engineering m.b.t. kweekfaciliteiten, informatiesystemen zullen ook andere bedrijfstakken ten goede komen, ontwikkelingen in deze takken kunnen ook gebruikt worden in de zeewiercultuur.
- En omdat de teelt nog in de kinderschoenen staat, is dat met de procestechnologie niet anders. Dit rapport bevat een eerste biorefinery processchema. Dat moet echter geoptimaliseerd worden naar meer soorten en meer stoffen, waarbij gestreefd wordt naar optimale valorisatie van alle hoofd- en bijproducten.
- Tenslotte, maar niet het minst belangrijk, zijn de maatschappelijke aspecten. We moeten ervoor zorgen dat de ontwikkeling van de veelzijdige toepassingen van zeewier op blijvende maatschappelijke steun kan rekenen. Dat doen we door de maatschappelijke buitenspelregels te kennen en ervoor te zorgen dat duurzaamheid te allen tijde bovenaan staat in de productieketen van zeewier.

2.7 Visie

Na de resultaten en de aanbevelingen willen we de gelegenheid te baat nemen om onze visie neer te zetten voor de toekomst. In onze visie liggen er over 15 jaar grote zeewiervelden in multifunctionele offshore locaties. Met een totale oppervlakte van 5000 km2 op het Nederlandse deel van de Noordzee draagt zeewier substantieel bij aan transities naar duurzame eiwitvoorziening én naar een overgang van fossiele naar duurzame energie. Onderzoek en ontwikkeling hebben geresulteerd in een aantal grote energieparken op zee waar golfenergie generatoren een windmolenpark omringen. Die golfgeneratoren bevatten zonnepanelen die gekoeld worden met zeewater. Door de koeling van het zeewater én door de reflectie van het licht leveren de zonnepanelen 30% meer rendement dan wanneer ze niet gekoeld zouden zijn. Binnen die ring van golfgeneratoren is de significante golfhoogte in het windmolenpark gedecimeerd, en dat heeft meerdere (positieve) effecten.

1. De ruimte binnen de ring is geschikt gemaakt voor zeewierteelt met een lichte teeltconstructie.
2. Het onderhoud van het windmolenpark wordt veel gemakkelijker; men kan vaker bij een windmolen. Dat vergroot de productie van het park (minder stilstand).
3. Bovendien gaat de levensduur van de windturbines omhoog, omdat de palen minder belast worden door het gedempte golfveld.

Dit iconische Dutch design project levert duurzame energie en duurzaam geteelde zeewier als grondstof voor food en feed toepassingen door te combineren waar Nederland groot in is; maritieme techniek en agrosysteemkennis.

3. Introduction

3.1 Background

The growing world population leads to a growing demand for food, energy and raw materials. To feed the world more agricultural land is needed. This leads to a loss of natural ecosystems and degradation of biodiversity, especially in tropical rainforests. There is a need to find new sustainable sources of proteins. Besides this, there is also an urgency to find sustainable alternatives for fossil energy. Wind and solar power do generate electricity, but still there will be a need for biofuels which can be used in the current infrastructure for car transport and for the power supply in industrial areas.

A potentially substantial contribution from the sea with its unused resources is obvious, but requires a multidisciplinary approach for a sustainable and profitable solution. With the establishment of a seaweed chain a contribution can be made to the above-mentioned demand. In close cooperation Dutch TO2 institutes are equipped and prepared to provide knowledge for make a success on a large scale, based on the experience they have already gained on small scale research. During and after this project the TO2 consortium aims to involve private parties to invest in future research, pilots and seaweed-related business developments, thereby investing into a more sustainable society.

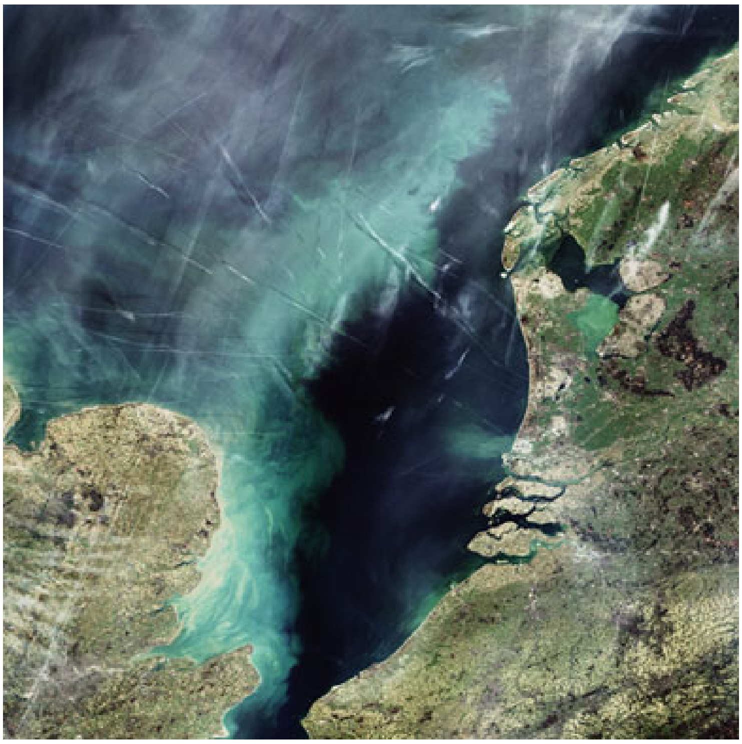


Figure 3-1; Study area for seaweed farming.

3.2 Goal and approach

The goal of this project is to develop an environmentally sustainable and economically viable seaweed chain design. In order to reach this goal an essential tool has been identified which is the multidisciplinary collaboration in different fields of expertise; the physiology and growth of seaweed through processing and marine engineering at sea.

Significant innovative breakthroughs are needed to develop the whole seaweed chain. Seed, cultivation, harvest, transport, bio-refinery and knowledge of the market need to be considered as an integrated system for which a holistic approach is required to achieve an optimal result; the design of an environmentally sustainable and economically viable seaweed chain.

Currently, there is much attention to the production of large volumes of low-grade fuels such as biogas or ethanol from seaweed. However, it is much more profitable to convert seaweed to products with a higher added value like food, feed and biobased products, and only use the residual fractions for conversion to fuels and biogas. Initially, based on available knowledge and expertise a brief overview of the main potential treatment processes and the expected yield is demonstrated. In this research two business cases will be defined; production of mannitol and the production of seaweed cheese.
However, before the seaweed can be refined seaweed must first be cultivated, harvested and transported to onshore locations. Certainly with regard to these aspects, there are already many questions in the field of marine technology, marine ecology and Marine Spatial Planning (MSP). The key question is how we can grow seaweed in the harsh North Sea conditions. How strong and durable should the construction be? So far the maritime engineering knowledge has hardly been used in the feasibility assessment of seaweed production chains.
It must be noted that the harvesting technology is left outside the scope of this project.
In addition policy questions on marine spatial planning (MSP) will briefly be treated in the research. The MSP will be based on both an "Ecosystem based approach and the associated governance aspects of such developments. In order to address all mentioned fields of expertise the following work packages have been defined:

- Physiology of seaweed
- Governance
- Spatial Aspects
- Technical feasibility
- Processing
- Economical feasibility
- Sustainability

The structure of the project and coherence between the work packages is illustrated by figure XX. It is a rather complex figure because the work packages are interlinked with each other. The site location of a seaweed farm for instance, determines the technical requirements, but will also influence the chemical composition of the seaweed and so the time to harvest and even the financial benefit of the crop.

3.3 Overview

All work that has been executed in the various work packages is integrated in one story line. So there is no separate description in what has been done by one of the institutes in one of the work packages. The story starts with an introduction to the project; what is the aim, who are the players, how is the project structured and what are the perspectives (why do we do what we do?). This chapter refers to the great challenges of society to find better ways to feed the people on this world, with less negative impact, find alternatives for fossil energy and turn our economy into a bio based economy.

Setting that scene, we start with a down to earth overview (chapter 2) of the existing seaweed farms in Europe. After that the first results of this project start in chapter 3; the knowledge of the physiology of seaweed is the basis for experiments of cultivation of Ulva and research to achievable grow rates. Given this information (what is needed for an optimal growth of seaweed) chapter 4 outlines a site selection. Where on the Dutch North Sea is the most suitable place to start a sea farm for seaweed cultivation. Given a location we have also information on the wave spectrum and the tidal currents. This is crucial information for the design of a construction to cultivate seaweed. That technical research is written down in chapter 5. The processing aspects are in chapter 6.

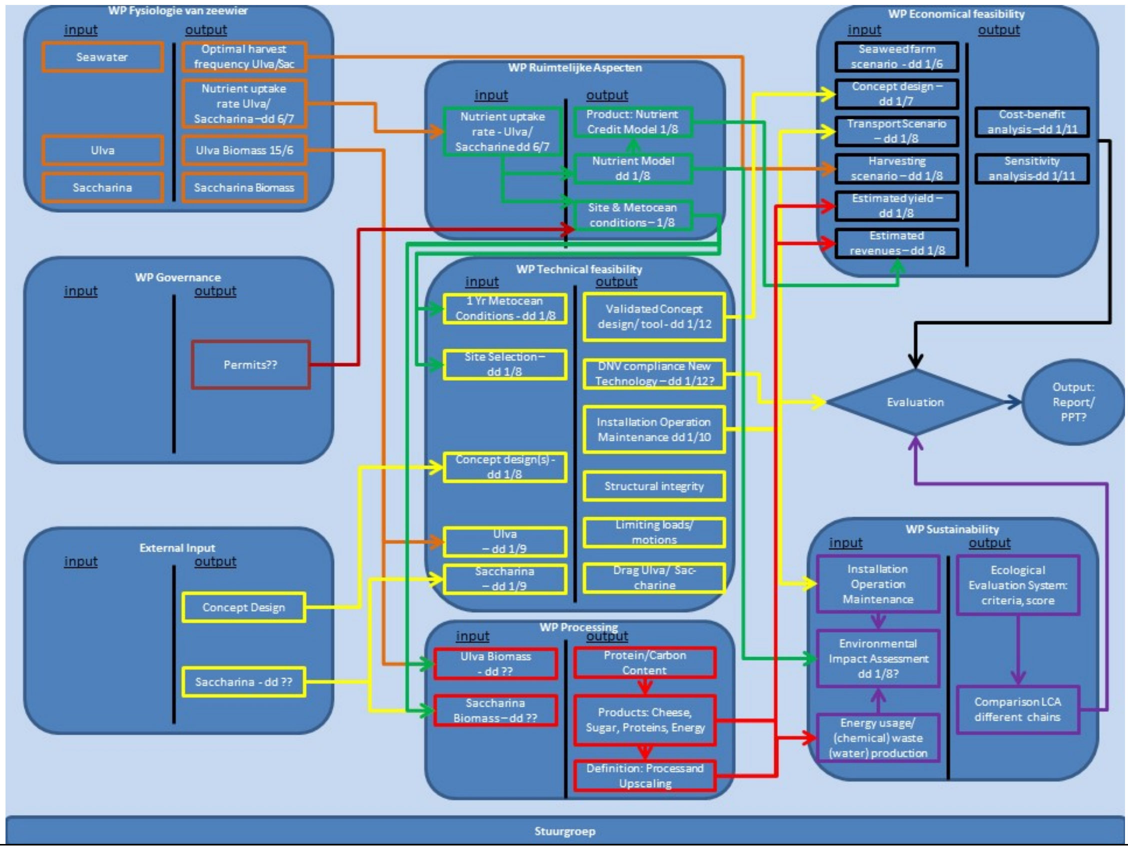


Figure 3-2; the conceptual design of all interconnections between all work packages.

4. Project Participants

4.1 Project participants

In this chapter a brief description is given of all the project participants and the envisaged role they have played in this project. An important side goal of this project is to strengthen the cooperation between the applied research institutes in the Netherlands. In 2014 the Dutch government reserved a budget for the so called TO2-institutes[1] with the mission to establish a better cooperation between the different institutes. This mission actually preludes on the wish of the minister of economic affairs that applied research institutes in 2018 will work closely together in composing their research programs. In this project 5 of these TO2 organisations have worked together:

1. TNO
2. MARIN
3. Deltares
4. ECN
5. DLO (in which ALTERRA, LEI, WLR, PRI, FBR en IMARES)

4.2 Project organisation

The project had a project management existing of René Lindeboom, Jaap van Hal, Willem Brandenburg and Floris Groenendijk (overall project manager). During the year, 7 project meetings were organised on different locations. During these meetings the interfaces between the work packages were discussed, the progress was monitored and we discussed what to do after this one-year-project. We realized that involvement (and if possible commitment) of industrial partners is of utmost importance. That is why we invited external speakers (Cargill, DSM and IHC/MTI) for our meetings. We also planned to install a steering comité of external partners from industry and give them a real influence in our project. However, the time was too short to organize that. Waiting for the steering group to be fully installed would result in a back log of work to realize the project. The effort is not without result; we still have good contacts with people form industry.

4.3 Project approach

Because a year is a short period for cooperation on a multidisciplinary project with a lot of organisations, we had to choose, right at the beginning of the project, a very concrete goal. The challenge was to consider the whole value chain of the seaweed ánd to interest companies for the seaweed research. Based on these two challenges we have chosen for two concrete products from seaweed;

1. Extraction of protein from Ulva lactuca and make cheese of it. This would be an innovative product that will be very attractive for a press release. A cheese without an animal, so appropriate for vegans. This would be a very media appealing result.
2. In the second tranche we want to extract mannitol from Saccharina latisima. Mannitol is a non-caloric sweetener. It is also a basic product for all kinds of chemical applications like bio-plastic.

With these end products in mind we started to work on various aspects along the whole seaweed value chain. We started to cultivate *Ulva* in Yerseke. With the cultivated *Ulva* experiments were organised to extract the protein. Because we only had one year, it was no option to cultivate *Saccharina*. We decided to obtain that from Hortimare. Besides these short terms concrete products we addressed research topics that must be tackled in order to develop a seaweed industry for the future. For instance: if we claim that seaweed might be a sustainable alternative for soya, we have to prove that animals can digest seaweed products. If we claim that seaweed is a promising feedstock for transitions, we have to prove that seaweed can be cultivated in an

[1] *TO2 means Toegepast Onderzoek Organisatie.*

economical viable way. If we really want a site on the rough North Sea, we have to prove that we can make an installation that will be successful, even in stormy conditions. With this variety of research topics we started with the project. And so has a maritime engineer learned something of the chemical analyses of seaweed and has some biologists learned about the drag forces in a mooring line. That is a multidisciplinary approach!

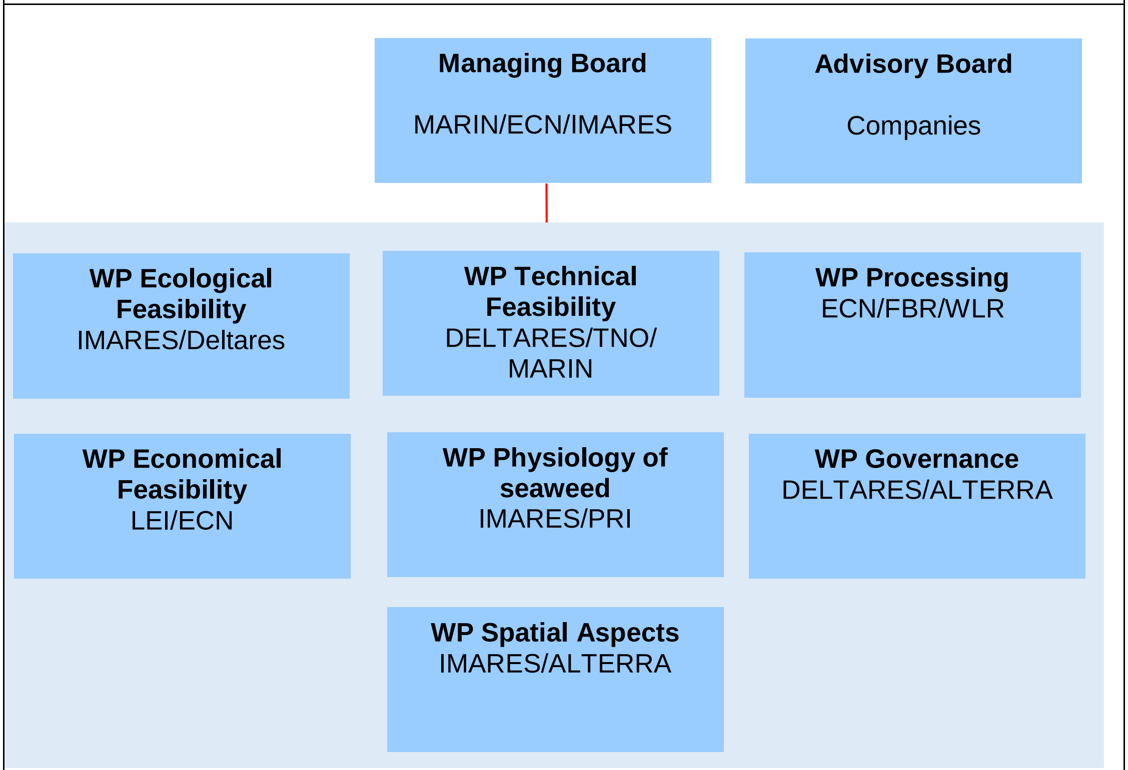


Figure 4-1:workpackages

5. Current developments

5.1 Seaweed and Products

In the Dutch part of the North Sea there are several endemic species of seaweed. In this report we only work with three of them. The first one plays a role in a computer model; from the other species we examined the compounds.

Laminaria digitata (fingerseaweed) is composed of a wide sheet, which is divided into finger-shaped part leaves. The plant's stem is thick and pliable. The finger attaches to the roots which in turn settle on stones under water. In some places it is true "kelp forests" that also harbor many other types of algae and marine fauna. The weed grows in the Netherlands since 1871. The seaweed can grow 2- 3m, and under favorable conditions, even 4 meters long. The color varies from dark brown to golden brown / olive brown / olive green. The "leaves" grow from the base of the plant. The number of leaves, and the length, are related to the growth area. In sheltered areas are few and shorter leaves. If there is less shelter the number of leaves can be increased to 10-12 per plant. The leaves are, therefore, longer. The properties vary by season, age of the weed and habitat. Fingerweed has a lifespan of about 3-6 years. In the fall the growth is reduced, where the growth is to be risen again in spring / summer.

Habitat: *Laminaria digitata* grows along the North Atlantic coast on rocky ground to a maximum depth of 20 meters.

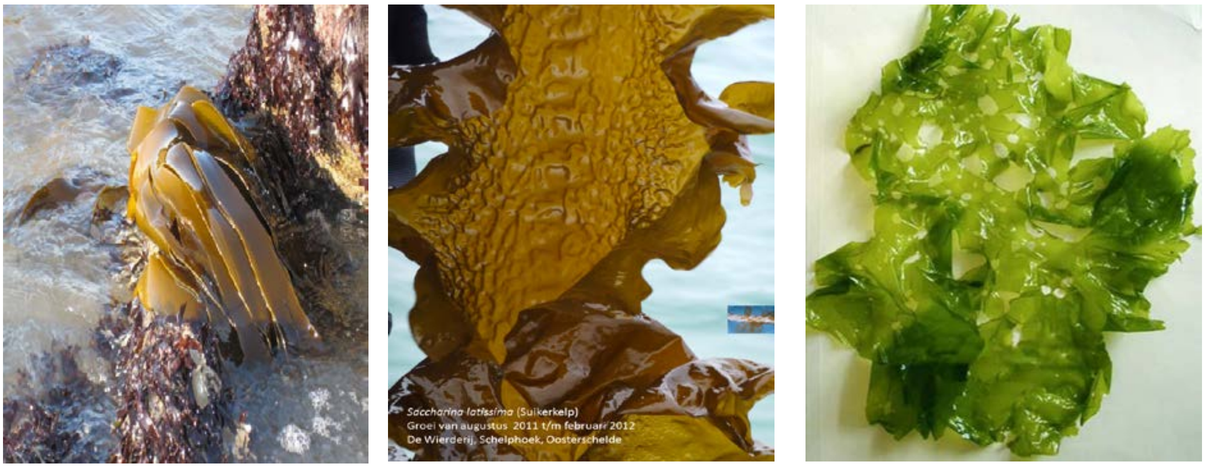


Figure 5-1; Laminaria digitata; Saccharina latissima and Ulva lactuca

Saccharina latissima is a large brown seaweed among the species that can form kelp forests. It consists of a relatively short stem with an unbranched sheet that can be up to 2 m long and 30 cm wide. The foliage is often wavy and puckered, but also just smooth. The weed shows a firm and leathery surface. No midrib exists, although the finer bumps in the middle would suspect a midrib. The whole is fixed to the substrate with a bunch of small roots. *Saccharina latissima* is a perennial plant.

Habitat: Low in the intertidal zone to 20 m depth in areas with clear water. However in the Netherlands the plant can be found less deep. On rocks and stones, sometimes on wooden or metal structures - such as harbor piers and pillars of drilling rigs. Most like somewhat sheltered places; Yet the species is also found in the open North Sea. Often comes together with the finger seaweed *Laminaria digitata* - which is distinguishable because the latter has a mostly smooth and clear branched leaf.

Ulva lactuca (sea lettuce) is bright green in color. The very thin, broad, flat leaves are soft, wavy and transparent. They look like lettuce leaves and grow to 50 cm in several similar forms. Nearly circular or oval or long and thin with tattered edges and punched holes. Laver looks and feels like wax paper, with a silky texture. Most species are only one or two cells thick. It grows on a surface where it clings on with a small "foot". These surfaces can include stones and shellfish.

5.2 Seaweed farming in the Netherlands

Dutch seaweed farms are operating on a small scale. Three initiatives are known until now and described below. In each of the farms, harvesting is carried out manually and the technology deployed has not reached maturity yet.

A first seaweed farming test location was opened in the Oosterschelde in Zeeland in 2011. This (Wierderij) has a size of 56x10 meters and is located in the sheltered waters in the protected area of the Schelphoek on Schouwen-Duivenland. Researchers investigate the performance of several species under mild but realistic conditions. The three species studied are identical to the species studied in the TO2 project: *Laminaria digitata* (vingerwier), *Saccharina latissima* (suikerwier, formely named *laminaria saccharina*) and *Ulva lactuca*. The Wierderij facilitates different types of research. One example is the execution of tests with different materials on which seaweeds can grow (Brandenburg, 2015).

A second initiative is the (NoordzeeBoerderij), which operates a test farm 10 kilometers offshore Texel since 2015, see Figure *5-2* below. The NoordzeeBoerderij initiative aims to connect and accelerate seaweed production in the Netherlands. Emphasis is on storytelling and facilitating via the seaweed platform. The NoordzeeBoerderij collaborates with (research) institutes and governmental stakeholders.

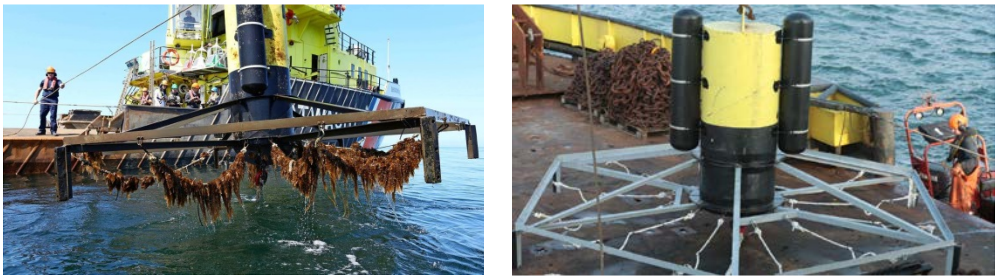


Figure 5-2: Noordzee Boerderij seaweed farm, pictures from maritiemland.nl

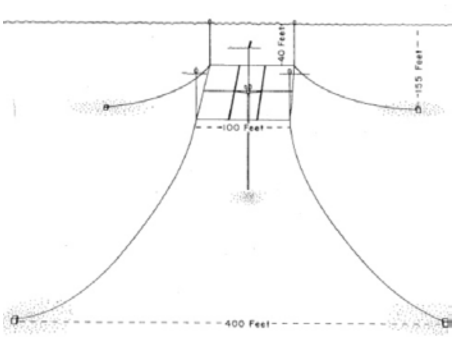
Two different production systems have been tested on the test farm of Noordzee Boerderij, but most of the information on the tested systems is kept confidential. The first production system is a line based system with a length of 50 meters. The second system is a wheel based system with a diameter of 5 meters. The seaweed is grown at a depth of around 2 meters.

The third initiative is the commercial seaweed farm run by a company called (ZeeWaar). Zeewaar has a small scale sheltered location in the Jacobahaven in the Oosterschelde where seaweed is grown. Zeewaar has developed a specific production process and a series of commercial products. Zeewaar collaborates with (research) institutes like NIOZ, Hortimare, Stichting Zeeschelp, WUR/PRI, en SIOEN.

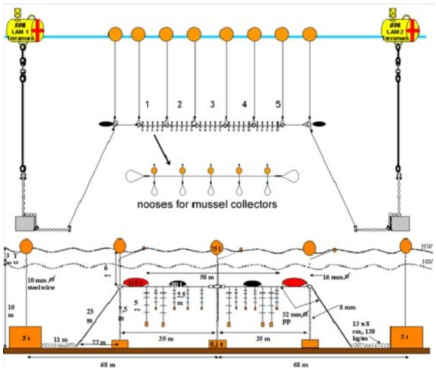
Figure 5-3: ZeeWaar seaweed farm overview, pictures from zeewaar.nl

5.3 Seaweed farming outside the Netherlands

Two sources that provide an overview on the support structures that have been applied until now to grow seaweed are: a desk-study from 2007 by researchers from the US based Pacific Northwest National Laboratory (Roesijadi, 2007) and a German literature survey from 2012 by researchers from the Alfred Wegener Institute for Polar and Marine Research (Buchholz, 2012). Both sources describe several projects and experiences, mainly of initiatives from Europe and North America. All projects until now have been experimental with relatively small structures and small scale applications. The two main projects carried out in the past that are described are the Marine Biomass Program from the USA and a German research effort, in which the longline concept has been developed, see Figure *5-4*.



a) Marine Biomass Program (US) for Macrocyctis plants, dated 1975-1985



b) Longline system from AWI (Germany) by Buck and Buchholz, dated 2006

Figure 5-4: Support structure examples for seaweed production (Roesijadi, 2007)

The several support structures that were part of study performed in the Marine Biomass Program (1968-1990) were developed for Macrosystis pyrifera production. Plants were grown at depths of 20 meters down to 150 meters during tests using small scale moored floating structures. Figure *5-4*a shows a sketch of one of the four structure that were built. Detailed information has not been found on the starting points of the design or on the structure itself. Information is provided in Roesijadi (2007).
Buck (2007) provides a description of the experiences with the longline system, see Figure 5-4. The longline system was developed to grow mussels. Two longline system type structures have been tested offshore at locations 25 kilometre north of Bremerhaven at a water depth of 12-15 meters. One longline system used steel cables for mooring and seaweed growing, the other system applied polypropylene cables. The growing depth was around 5 meters below water surface. The steel longline cable failed twice: during a storm and as a result of a collision with a sailing yacht. The polypropylene longline has not failed and survived wave heights up to 6.4 meters and currents of 1.52 m/s. The longline projects of Buck have been documented in detail via both scientific papers and more general reports.

More recently, there has been a lot of European (research) effort on the development of a seaweed value chain including support structures the past 5 years. Examples are found on low TRL projects like (European project AT~SEA) and the (European project Mermaid). Examples of local Dutch practical initiatives are (NoordzeeBoerderij), (ZeeWaar) and the (Wierderij). An apparent commercial mid-scale initiative using the longline system is called the MacroBiotech project of developer Ocean Rainforest. This is a recent development in the Faeroes region (Gregersen, 2015). These developments have led to novel or improved concepts, but not much technical information has been released via publications.

5.4 Comparison of Seaweed in Europe and Asia

Seaweed farming and consumption predominantly takes place in Asia. China, Japan, the Philippines, Indonesia and Korea are the main production countries. Seaweed is grown in shallow waters and is being harvested by hand. The large scale production close to the shore causes environmental issues like distortion of balance of nutrients and decreasing biodiversity. FAO (Kapetsky, 2013) shows that the annual production of seaweed ha a turnover of $ 5.5 -6 billion and increases steadily by 5%. Publication on Asiatic seaweed (research) projects are scarce. One relatively well known institute is the Chinese Academy of Fishery Sciences (CAFS), with Prof. Fang Jianguang being the lead scientist on seaweed research. A Chinese commercial organization is the Gather Great Ocean Algae Industry Group that operates in and around China, but also in Australia. This organization develops new technologies on aqua culture and has strong links with CAFS.

A large research project, titled the Marine Biomass Program, on the applicability of seaweed as biofuel has been carried out in the USA in the period from 1968-1990. The low oil price has caused this project to terminate on 1990. Publications on this project can be found, for example via (Roesijadi, 2007). No further information is found on seaweed projects in the USA. There is seaweed industry present in Canada, but not any seaweed projects that are located offshore have been identified.

The EU project NetAlgae has mapped the stakeholders of the seaweed value chain in 2012 and 2013. (NetAlgae, 2012) also presents the history of seaweed harvesting activity in Europe, the current production and the techniques used in the different countries. Due to the lack of competitiveness of the European industry compared to its Asian counterpart and despite the rising world demand, the production of seaweed in Europe has decreased in the past decade. The processing industries raise doubts concerning the usefulness of remaining based in Europe and partly compensate for the lack of European product by using external supply. New markets may reverse this trend, such as the increase in edible seaweed production, which is currently a niche market, the growing demand of the biotech sector, or the development of bio-fuel based on seaweed. The rise of conservation claims however may modify models of wild stock exploitation and increase the appeal of a sustainable seaweed farming sector.

A recent development that is significant in size is the MacroBiotech project of Ocean Rainforest, which is a company located in the Faroe Islands. Ocean Rainforest has 1200 meter of seaweed seed lines in the Faroe Islands, where continuous current and stable sea temperature provide suitable conditions for seaweed farming. This project is well documented via (Rainforest) and (Gregersen, 2015).

5.5 Harvesting technologies

Several ways and techniques of harvesting are described in the rapport (NetAlgae, 2012), which is one of the results of the EU project NetAlgae. The commercial value of the different seaweed species can be illustrated by the harvesting technique that is deployed. Most species are harvested manually. Species that are harvested by boat and mechanical tools are *Laminaria digitata, Laminaria hyperborea, Saccharina latissima* and *Ascophyllum nodosum.* These boats and tools are straight forward and have been developed by local industry in France or Norway. This is confirmed by expertise from IHC MTI (MTI, 2015). This interview also indicates that only research on this topic is executed on a low profile.

(NetAlgae, 2012) further explains that (…) mechanical harvesting is undertaken by boats and is mainly practiced in Norway (Rogaland to Sør-Trøndelag), France (Brittany), Spain (Galicia and Asturias) and to a lesser degree in the Basque country (France) and Ireland. In Norway, *Laminaria hyperborea* and *Ascophyllum nodosum* are harvested by boats using respectively a seaweed trawl (a), a paddle wheel cutter (c) or a vaccum-sucker (d). In France, *Laminaria digitata* is harvested by a boat using a gear called “scoubidou” which looks like a hook that turns around itself and turns out (b). More recently, *Laminaria hyperborea* is harvested by boat using similar gear as in Norway. (…)


a) Vessel with seaweed trawl, used to harvest Laminaria hyperborean in Norway © FMC biopolymer Corp.


b) Vessel with a « scoubidou », used to harvest Laminaria digitata on the coasts of Brittany (France) © Maguire


c) Vessel with a paddle wheel cutter, used to harvest Ascophyllum nodosum in Norway © Sander.


d) Vessel with a vaccum-sucker, used to harvest Ascophyllum nodosum in Norway © Rebours.

Figure 5-5: Examples of Mechanical harvesting (NetAlgae, 2012)

5.6 Conclusions

From the literature survey and interviews it is concluded that worldwide large quantities of seaweed are being produced. The main contribution comes from natural grown seaweed that is being harvested by hand, and from artisanal small scale production units. No information is found on large scale offshore seaweed production facilities, in which during a longer period seaweed is grown and harvested in a successful way. This also means that no examples are available for successful mechanical harvesting, nor for large scale bioprocessing for human consumption or for other (intermediate) products.

The only detailed source of information on cost, based on mid-scale development in the Faeroes region, comes from (Gregersen, 2015). This is a recent development called the MacroBiotech project of developer Ocean Rainforest.

On the other side, there has been a lot of European (research) effort on the development of a seaweed value chain during the past 10 years. Examples are found on low TRL projects like (Buck, 2007), (European project AT~SEA) and the (European project Mermaid). Examples of local Dutch initiatives are (NoordzeeBoerderij), (ZeeWaar) and the (Wierderij).

6. Physiology of Seaweed

6.1 Introduction

The purpose of the work package (WP) Physiology of Seaweed was to study the growing conditions of selected seaweed species and to provide material for WP Processing and data for WP Spatial Aspects. Two seaweed species were selected based on their ability to grow in different seasons (summer and winter) and their valuable constituents. The green alga *Ulva* sp has its main growing season in summer and contains relatively high levels of proteins, while the brown alga *Saccharina* sp. grows in winter and has relatively high levels of carbohydrates. A number of growth experiments were carried out with *Ulva lactuca* to determine production rates and to study effects of harvesting frequency on production rate and chemical composition. The first steps were taken in determination of the lowest possible harvesting frequency that will not compromise production rate or content of valuable constituents. Knowledge on the frequency is needed for development of an economically feasible production system. Less frequent harvest means less trips with the harvesting vessel. In addition, the experiments provided data for validation of the model developed to estimate spatial aspects. This included production rates and nutrient uptake rates. With these data the model can predict production rates for different locations in the North Sea. Furthermore, it can be calculated at which size of the farm local nutrient depletion will occur. And finally, the experiments provided data on chemical content of the cultured seaweeds.

6.2 Seaweed

6.2.1 *Ulva*

Classification

Kingdom:	Plantae
Phylum :	Chlorophyta
Class:	Ulvophyceae
Order:	Ulvales
Family:	Ulvaceae
Genus:	Ulva

Ulva lactuca belongs to the green macroalgae (Chlorophyta), also known by the common name sea lettuce. *Ulva lactuca* is a thin flat green algae. It can easily reach a diameter up to 30cm (Wald 2010). The membrane is two cells thick, soft en translucent. *Ulva* is very common at littoral and sublittoral shores. It is attached to rocks, shells or sand by a disc-shaped holdfast. In a later developmental stage the holdfast disappears and *Ulva lactuca* becomes a floating seaweed. *Ulva* propagation takes place by spores, but it can also propagate vegetative (Kamermans et al, 1998). The seaweed needs a lot of sunlight. In the Netherlands, *Ulva lactuca* is growing during summertime, mostly located at the water surface. *Ulva lactuca* is a seaweed which occurs worldwide where it is adapted to the local environment.

6.2.2 Saccharina

Saccharina latissima belongs to the brown macroalgaes (Phaeophyceae). It is also known by the common name sugar kelp. The seaweed occurs in intertidal pools and occasionally in the shallow subtidal, becoming more abundant at low water in sheltered areas with fast-moving water. *Saccharina latissima* propagates by sporophytes and can grow from 4mm up to 3m in length within one growing season. It consists of a claw-like holdfast, a small, smooth, flexible stipe, and an undivided laminate blade up to 3 m long with parallel, ruffled sides and an elongated, tongue-like appearance. *Saccharina latissima* prefers low light intensities and cold temperatures. Therefore, in the Dutch region, the main growing season is during wintertime. Depending on the light availability *Saccharina latissima* can grow in deeper water layers.

<u>Classification</u>

Kingdom:	Chromista
Phylum :	Ochrophyta
Class:	Phaeophyceae
Order:	Laminaiales
Family:	Laminariaceae
Genus:	Saccharina
Species:	S. latissima

6.3 Growing conditions

6.3.1 Ulva

Ulva lactuca growing conditions have been studied in outdoor raceways and tanks at the research facilities of IMARES/Yerseke (Fig. 1). *Ulva lactuca* was cultivated using raceways in spring 2015. However, cultivation did not succeed very well in the raceways. The paddle wheel disturbed the seaweed material. By changing the system from raceways to flow-through tanks during the summer experiment we succeeded to produce *Ulva* biomass. Therefore, only the summer experiment is used for production rates in this report.

The growth of *Ulva lactuca* is mainly influenced by light, temperature and nutrient availability. Average amounts of photosynthetic active radiation (PAR-light) in July and August were 33.89 mol $m^{-2}d^{-1}$. *Ulva lactuca* uses the pigments chlorophyll a and b to absorb light in the range of 400-500nm and 600-700nm. Another important factor is water temperature. *Ulva lactuca* is growing optimally during the summer season with an average temperature of 20°C. *Ulva lactuca* growth is limited at a temperature bellow 15°C. *Ulva lactuca* can grow from brackish to salt water. Therefore, salinity is less important growth condition for this seaweed. The optimum salinity for *Ulva lactuca* has been found at 30 ‰ (Malta et al, 1999). Furthermore, in several studies an average biomass production of 10 t dw ha^{-1} could be established. For the experiments performed in this project values were found between 6- 14 t dw ha^{-1} (Table 1). No significant differences between harvesting once every week or once every three weeks were found (Fig. 2, ANOVA $p>0.05$). Biomass production of *Ulva lactuca* can vary a lot (Fig. 2). A significant relation was found with minimum week temperature (regression analysis $p=0.006$).But also the type of reproduction can play a role (sporulation or vegetative propagation). The experiments were carried out by vegetative reproduction not by spores. Therefore, selection of fast growing individuals was not possible. More research about reproduction of *Ulva lactuca* is needed to access the potential for higher biomass production.

Nevertheless, we know from natural populations that *Ulva lactuca* can achieve very high growth rates up to 40% per day (Malta & Verschuure, 1997). Moreover, Taylor & Fletcher (2001) found the highest growth rates for *Ulva* in nutrient concentrations ranging from 10-100 µmol of PO4-P / l, 100–1000 µmol NO3 -N / l and 60-100 µmol NH4-N / l. Our nutrient concentrations were much lower, but we still managed to get relative growth rates of 23%. This suggests that absolute concentrations are much less important than the nutrient flux (concentration x current speed). Current speed was 2.5 l per min. Source of water was Oosterschelde.

Nitrogen content (a proxy for protein) of Ulva increased during the experiment in the raceways and declined during the experiment in the tanks (
Figure *6-1*). More research is necessary to optimize growing conditions and chemical composition of *Ulva lactuca* in farming systems.

Figure 6-1 Six raceways and six tanks that were continuously supplied with running Oosterschelde water (no nutrients added) were used for the Ulva experiments

	Average	Min	Max
pH	8.28	8.04	8.57
O_2 (mg/l)	11.32	8.71	13.06
Salinity (‰)	32.20	31.10	33.50
Temperature (°C)	20	15	25
PAR light (mol $m^{-2}d^{-1}$)	36.09	12.02	55.50
NH4-N (µmol l^{-1}) (May) In flow (July-Aug) Out flow (July – Aug)	3.1 6.90 2.11	2 0.83 0.23	4 36.76 6.52
NO3-N (µmol l^{-1}) (May) In flow (July-Aug) Out flow (July – Aug)	11.47 4.93 2.06	4.07 1.34 0.1	18.13 19.7 4.24
PO4 (µmol l^{-1}) (May) In flow (July – Aug) Out flow (July – Aug)	0.4 1.32 0.99	0.2 0.57 0.11	0.5 1.81 1.57
Biomass production in growing season (kg dw ha^{-1}) Weekly harvested Harvested every 3 weeks	933 993	208 19	1951 2007
Biomass production (kg dw $ha^{-1}d^{-1}$) Weekly harvested Harvested every 3 weeks	119 92	68 22	327 322
Total biomass production within 6 weeks in summer experiment (t dw ha^{-1})	10.37	6.7	14

Table 6-1 Experimental results Ulva lactuca growth (April – October 2015)

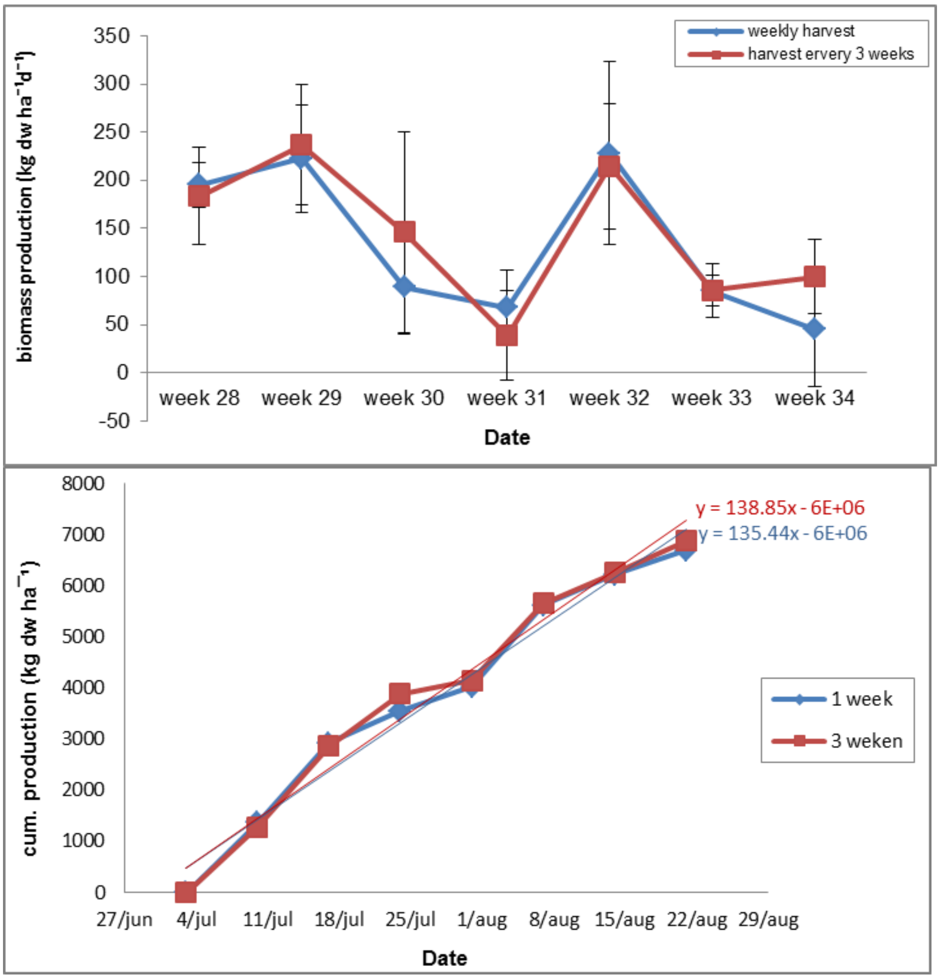


Figure 6-2 Biomass production of Ulva lactuca during the summer experiment in tanks (harvesting frequency down to 250 g once a week or once every 3 weeks). Weekly biomass production (above) and cumulative production (below).

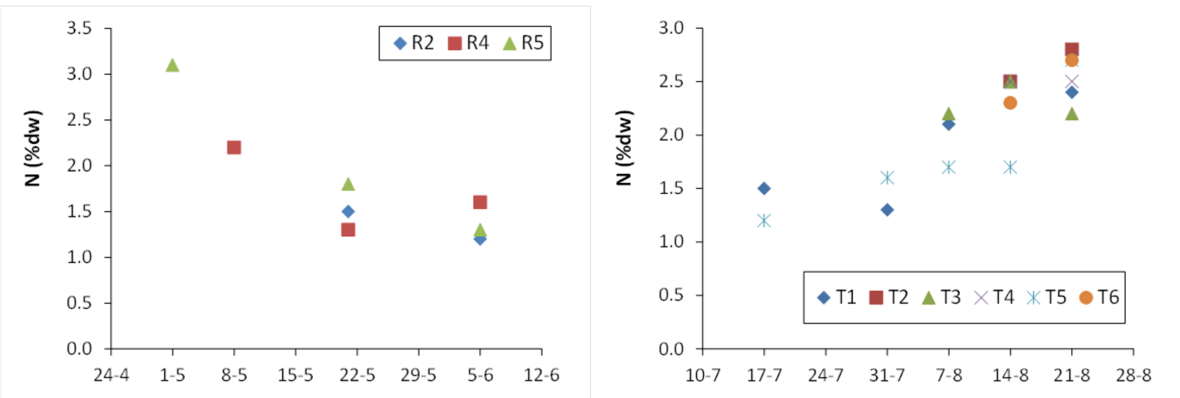


Figure 6-3 Nitrogen content of Ulva during experiments in raceways and in tanks.

6.3.2 *Saccharina*

In 2011 a seaweed test location is launched in the Oosterschelde by PRI/ Wageningen UR. On this field station, called "Wierderij", seaweed research has been taking place for several years now. One of the seaweeds that is studied is *Saccharina latissima*. Depending on the growth conditions a production between 13-21 t dw ha^{-1} can be achieved for this seaweed (Table 2).

Optimal growth conditions for *Saccharina latissima* were found at a water temperature between 5-10 °C with a salinity of 32 ‰ growing under Dutch circumstances (Table 2). Temperature range was found to be between 8-17 ° C. When the temperature rises above 17 °C, seaweed growth is limited. The seaweed will disappear by temperatures above 23 °C (Kain 1991).

Furthermore, Cesar & Freire (2015) found that the optimum light intensity for growing *Saccharina latissima* is about 16-104.3 μmol $m^{-2}s^{-1}$ (light-dark cycle 16/8h) at temperatures below 20° C. For optimal usage of light *Saccharina latissima* contains chlorophyll a and c.

Still, production of biomass can vary a lot between years, therefore more research on factors determining growth is necessary.

	Average	Min	Max
pH	8.12	8.04	8.20
Salinity (‰)	32.2	30.1	33.5
Temperature (°C)	10	4	17
Total biomass production (t dw ha^{-1}	17	13	21

Table 6-2 Saccharina latissima growth during winter growing season at the "Wierderij"

When using a year-round seaweed production system, including green and brown seaweeds, a total production of max. 35 t ds ha^{-1}can be achieved.

Note: There are opportunities to increase biomass production for *Ulva lactuca* as well as for *Saccharina latissima*. For example, selection for fast growing strains or strains that contain higher concentrations of the desired compound. Furthermore, by combining different of seaweed species in one farming area economic feasibility and risk management can be optimized. For example, when culturing *Saccharina* in winter and *Ulva* in summer in one farm area investments are used twice and risks such as crop failure are spread. Besides that, research on cultivating different seaweed species adapted to different water layers could improve economic feasibility. For instance, combining the culture of green seaweeds in the upper water column with red seaweeds in deeper water columns.

6.4 Nutrient uptake

Deltares uses a modelling package to investigate hydrodynamics and water quality (Delft3D). This is coupled to correctly parameterised growth modules for specific seaweed species (*Ulva* and *Saccharina*) to calculate yields under different environmental circumstances. Results from the Ulva growth experiments were compared to the *Ulva* model.
During unconstrained growth in the model (growth is not limited by light, temperature and nutrient availability) *Ulva* biomass can increase from 1.5 g C m^{-2} to 99 g C / m^{-2} in 3 weeks (Fig. 4), corresponding to 4.5 ton DW/ha. Average growth rate during unconstrained growth is 0.23 d^{-1} and similar growth rates are observed in the first period of the experiments (0.21 d^{-1}). The modeled N:C ratio (in mass) in *Ulva* during unconstrained growth is 0.09 and this is in the range found in the experiment. DIN uptake during unconstrained growth is 75 mmol N m^{-2} d^{-1} and PO_4 uptake is 3 mmol P m^{-2} d^{-1}.

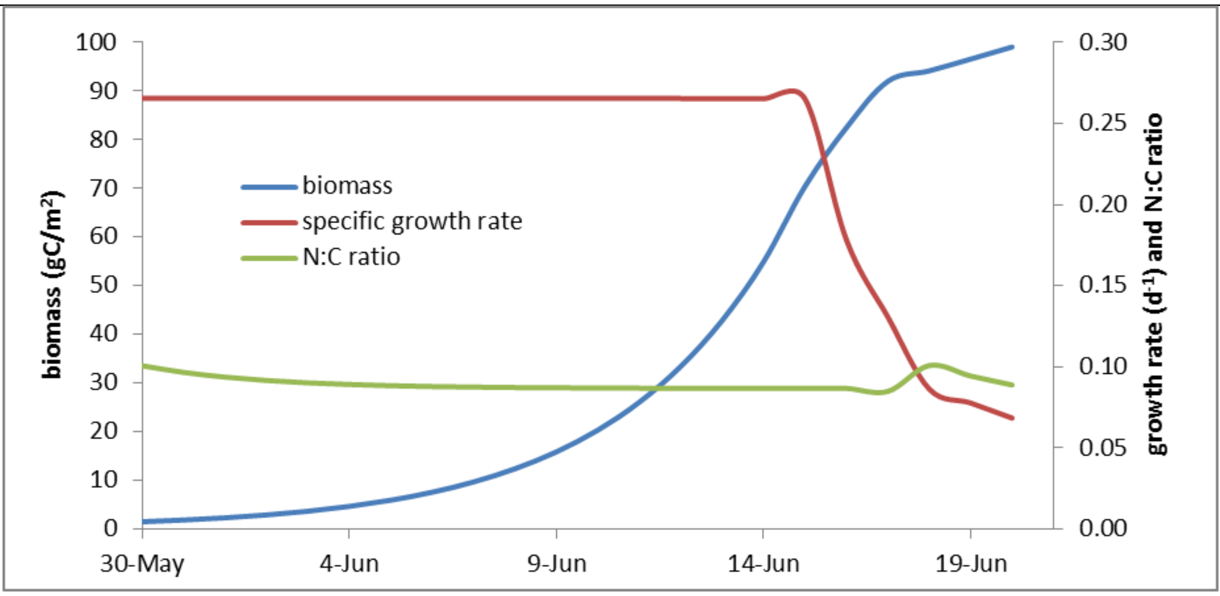


Figure 6-4 Biomass production and growth of Ulva lactuca as determined by the model.

6.5 Valuable constituents

The chemical composition of seaweed is well documented but quantitative data are difficult to report on due to large variations in seaweed type, seasonality, harvesting location and age of the plant. In general, seaweeds contain the following components (Jung, Lim et al. 2013):

- Carbohydrates (brown 30-50 wt%, green 25-50 wt% dry weight)
- Minerals such as alkali metals and chlorine (10-50 wt% dry weight)
- Proteins (7-15 wt% dry weight)
- Lipids (1-5 wt% dry weight)

Major constituents of high value in seaweeds are the carbohydrates. They can be divided in storage carbohydrates, which function as food reserve, and structural carbohydrates, which are found in the cell wall and give mechanical strength and prevent the seaweed from dehydration. In *Table 6-3* the carbohydrates present in each seaweed group is presented and the characteristics of each carbohydrate are described below. Some of these carbohydrates are also found in terrestrial plants but others are exclusively found in seaweeds.

Seaweed	Storage carbohydrates		Structural carbohydrates	
	Carbohydrate	*Building block*	*Carbohydrate*	*Building block*
Saccharina 30-50 wt%	Laminarin	Glucose	Cellulose	Glucose
	Mannitol	Mannitol	Alginate	Uronic acids (guluronic acid, mannuronic acid)
			Fucoidan	Fucose (sulphated)
Ulva 25-50 wt%	Starch	Glucose	Cellulose	Glucose
			Ulvan	Rhamnose (sulphated), xylose, glucuronic acid

Table 6-3 Carbohydrates present in Saccharina (brown) and Ulva (green) seaweed.

- Storage carbohydrates (Percival 1979, Wei, Quarterman et al. 2013)
  - Laminarin is the main storage carbohydrate in brown seaweed. It is a water-soluble polymer containing 20-25 glucose units and its content can vary from 0 to 30 % dry weight.
  - Mannitol is a water soluble sugar alcohol which functions as a food reserve. Concentrations in brown seaweed vary from 5 to 30 % dry weight.
  - Starch in green seaweed serves as a food reserve and closely resembles starches found in terrestrial plants but with lower molecular weight. It may be a linear or branched molecule of glucose units which is water soluble.

- Structural carbohydrates (Percival 1979, Wei, Quarterman et al. 2013)
  - Cellulose is the structural component of the cell wall of terrestrial plants and seaweeds (brown and green). It is a linear polysaccharide of several hundred to more than 10.000 glucose units.
  - Alginate is a linear polymer consisting of mannuronic acid (M) and guluronic acid (G) blocks in varying sequences. Alginate is present as salt of different metals, primarily sodium and calcium, and functions are principally of structural and ion exchange type. Content in brown seaweed can be as high as 30-40 % dry weight.
  - Fucoidan is a heterogeneous polysaccharide in brown seaweed consisting primarily of 1,2-linked α-l-fucose-4-sulfate units with very small amounts of d-xylose, d-galactose, d-mannose, and uronic acid.
  - Ulvan is a complex, branched sulphated polysaccharide found in green seaweed. It contains building blocks like (sulphated) rhamnose, xylose and glucuronic acid (Robic et al., 2009).

In the experiments with *Ulva* average glucose content was 9.7 % dw (4.4-22.3), rhamnose 7.5 % dw (5.4-10.) and protein 9.5 % dw (5.5-14.3) (Fig. 5). In the experiment in raceways a substantial increase in the carbohydrate glucose was observed (Fig. 5). Protein was calculated from nitrogen content using a factor 4.62 (Bikker et al., submitted).

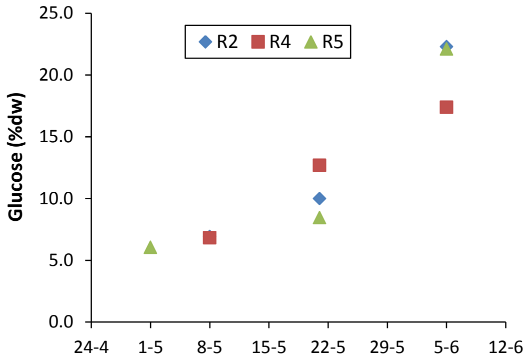


Figure 6-5 Development of glucose content during Ulva growth experiment in raceways. (R2 harvest in week 3 and week 5, R4 in week 3 and week 5, R5 in week 2 and week 5).

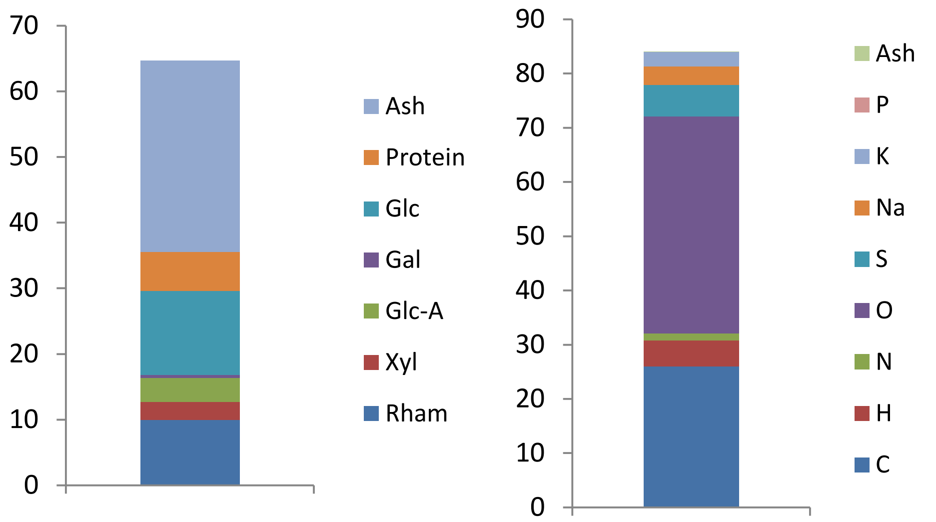


Figure 6-6 *Chemical content of Ulva during experiment in raceways. Left panel: example composition of Ulva harvested from R4 in week 4, Right panel: example elemental composition of the same sample.*

6.6 Conclusions

A number of growth experiments were carried out to determine production rates and to study effects of harvesting frequency on production rate and chemical composition of *Ulva lactuca*. The first steps were taken in determination of the lowest possible harvesting frequency that will not compromise production rate or content of valuable constituents. Knowledge on the frequency is needed for development of an economically feasible production system. No significant differences between harvesting *Ulva* once every week or once every three weeks were found. Less frequent harvest means less trips with the harvesting vessel. When using a year-round seaweed production system, including the green seaweed *Ulva lactuca* and the brown seaweed *Saccharina latissima*, a total production of max. 35 t ds ha^{-1} can be achieved.
In the experiments with *Ulva* average glucose content was 9.7 % dw, rhamnose 7.5 % dw and protein 9.5 % dw. There are indications that the culture system has an effect on the nitrogen and glucose content of *Ulva*.

In addition, the experiments provided data on production rates and nutrient uptake rates for validation of the model developed to estimate spatial aspects. With these data the model can predict production rates for different locations in the North Sea. Furthermore, it can be calculated at which size of the farm local nutrient depletion will occur. And finally, results of the experiments indicate that the culture system has an effect on the nitrogen and glucose content of *Ulva*.

6.7 Conclusions and future prospects

- Culturing a summer species (the green seaweed *Ulva lactuca*) and a winter species (the brown seaweed *Saccharina latissima*) will optimise year production.
- More tests are needed to determine if the harvesting frequency can be further reduced.
- Designing a culture system that provides a high production rate and a high content of a desired compound (e.g. protein or carbohydrates) needs to be further studied.
- The model developed for *Ulva* production is used in Chapter 6 to predict production rates and environmental impact for different locations in the North Sea.

7. Site description and spatial aspects

7.1 Spatial planning of seaweed aquaculture

As land, inland and near-shore waters are becoming very crowded, while the human population keeps increasing, investigating the possibilities of offshore cultivation sites is a logical step. One of the most essential things to assess, when considering a business case for seaweed cultures is the production carrying capacity of potential sites. In other words: how much seaweed biomass can sustainably be produced per unit surface area per year? This depends on one hand on the amount of light and nutrients available and on the other hand on the type of seaweed. Some species can cope very well with relatively low levels of phosphate but need a lot of light; others can deal with low nitrogen availability but need a larger amount of phosphate. The optimal site may therefore differ per species.
The availability of nutrients depends partly on the concentration of nutrients in the water, but also on the residence time of water in an area, i.e. on the current speeds. An area with a relatively high concentration of nutrients, but hardly any flow, may be less productive than an area with an intermediate nutrient concentration and a high exchange rate. Per unit time, the latter may have more nutrients available for growth.

The fact that seaweed cultures take up nutrients and also reduce light levels lower down in the water column, means that these cultures have an impact on their environment. We need to be able to quantify these impacts in order to avoid unacceptable damage to the system. The uptake of nutrients by seaweed is certainly not always a negative or undesired effect. Many coastal areas still experience effects of eutrophication. Seaweed cultures can potentially be used as measures to mitigate eutrophication or to minimize the impact of certain nutrient sources, such as fish farms or point discharges.

In order to assess potential production rates and potential environmental impacts detailed spatial information is needed regarding the interaction between seaweed cultures, currents, nutrients and light availability. Ultimately, for optimal site selection, also other factors need to be taken into account, such as e.g. wave conditions that may set limits to the construction, other demands on marine space, and economic factors such as transport costs.

Models to calculate potential yields as well as the “nutrient and light footprint” of seaweed cultivation facilities are important tools to facilitate site selection. Within this project we have made the first steps towards a species-specific modeling tool, that should be part of the various decision-support instruments to aid site selection, as well as optimally combine seaweed farming with other ecosystem services.

7.2 Location and Bathymetry of the southern North Sea

The Southern North Sea is relatively shallow. Most areas in the Dutch continental shelf are less than 50 metres deep (Figure 7-1).

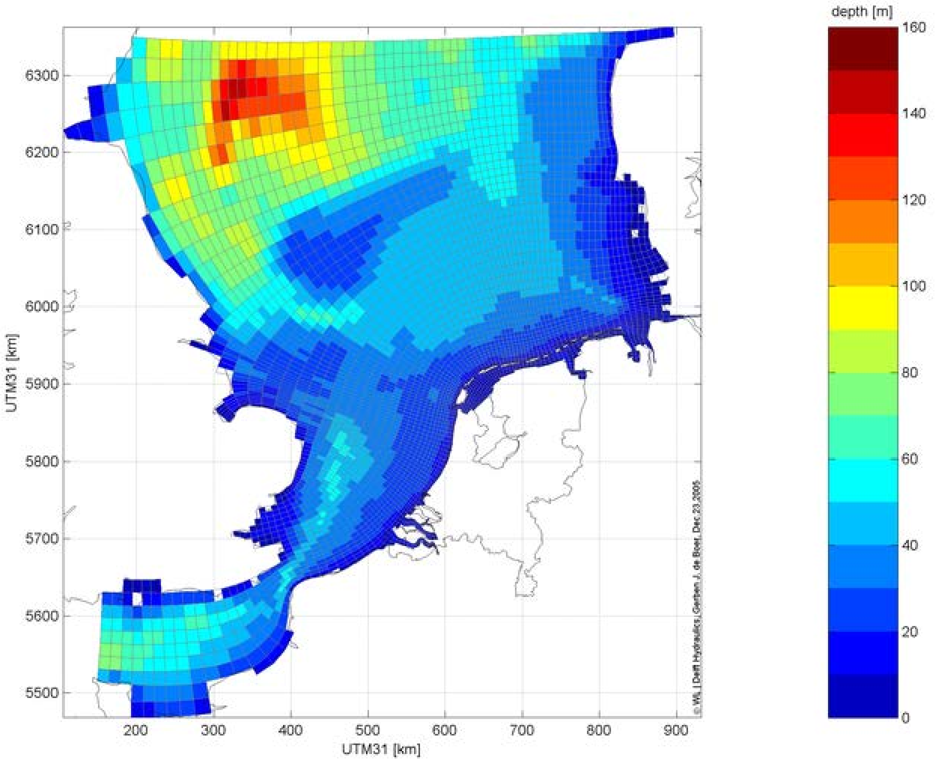


Figure 7-1: Bathymetry of the southern North Sea (the actual grid for flow calculations is on a slightly finer scale than plotted here

The Delft3D package is an open source modeling suite to investigate hydrodynamics, sediment transport and morphology as well as water quality for fluvial, estuarine and coastal environments. http://oss.deltares.nl/web/delft3d. This package has been used to characterise the current speeds in the North Sea. This is essential input for the carrying capacity model (section 6.3).

7.3 Water quality and seaweed growth model

The potential productivity (the production carrying capacity) of a seaweed farm depends primarily on nutrient availability and light availability and to a lesser extent on other environmental parameters such as temperature. By ensuring that the cultures are located at the surface, light availability is maximized. The availability of nutrients depends on: 1) nutrient concentrations in the water and 2) the transport rates of nutrients through the cultures, i.e. the current speeds.

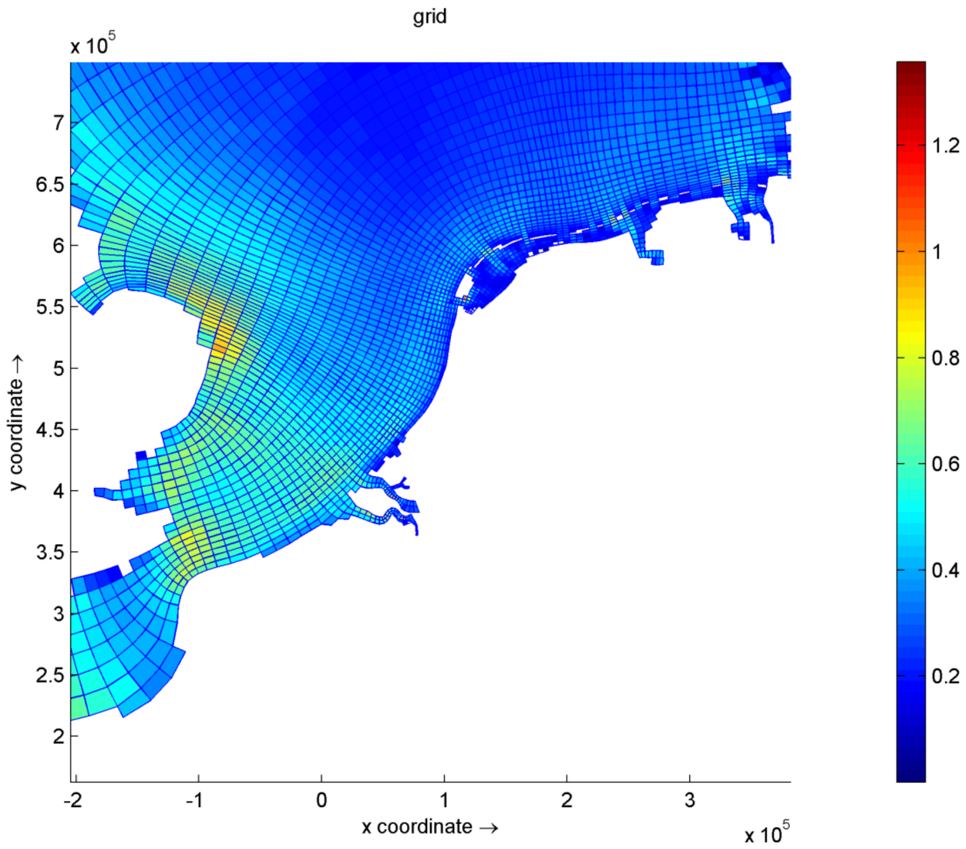


Figure 7-2 Section of the D3D North Sea hydrodynamic model with in colour coding the average velocity magnitude.

The Delft 3D water quality module (D-WAQ) calculates all these relevant components in space and time, based on the underlying hydrodynamic model (Figure 7-2). Coupling these water quality and other environmental parameters to correctly parameterised growth modules for specific seaweed species allows calculations of potential yield as well as optimal site selection for seaweed farms. These models can also indicate the best periods for stocking and harvesting.

Currently this modeling suite offers two distinct options to model macroalgal growth:

1 similar to microalgae, using a modified phytoplankton module (BLOOM)
2 as a macrophyte (plant) using an adaptation of the vegetation module (SAV)

Within this project the macrophyte module was adapted to simulate the growth of the green macroalga *Ulva lactica*. The advantage of this module over the BLOOM option is that this allows long term storage (of carbohydrates). Previous attempts to model *Saccharina latissima and Laminaria digitata* using BLOOM resulted in unrealistic growth dynamics over time. This module has not yet been incorporated in the full 3D version of D-WAQ, but the growth dynamics of *Ulva* fit measured dynamics.

Within the EU project MERMAID, the growth of two brown macroalgae *Saccharina latissima* and *Laminaria digitata* were modelled using BLOOM in the North Sea D-WAQ model. Due to the fact that it is not possible to model storage of compounds with this module, the absolute values of biomass production are not yet reliable. However, the levels of productivity and therefore the indication of profitable and less profitable locations depend primarily on the nutrient dynamics. These are well represented by the model, therefore the relative levels of productivity are shown here as an example of the potential use of such models for site selection.

7.3.1 *Ulva* model results and comparison with experimental data

The parameter settings in the vegetation module were based on an older model study (Kamermans 1996). The vegetation module was initially set to run in a 1D-setup, calculating the growth of *Ulva*. The model results were compared to the experimental results (Chapter 5) for net growth as well as N:C ratios. The model and experimental results are reasonably consistent, despite some discrepancies in modelled and experimental conditions. Results of this model were presented and discussed together with the experimental data in Chapter 5.

7.4 Spatially explicit model (example *Laminaria* and *Saccharina*)

Production of *Laminaria* and *Saccharina* was tested on 8 locations in the North Sea, using a spatial ecosystem model (ZUNO-2D) (McCulla et al. 2013). Parametrisation of the 2 seaweeds in BLOOM was based on literature. The selected locations were a test site for seaweed aquaculture near Texel, wind farm Gemini and wind farm Borssele. In addition, 5 Dutch monitoring locations, varying in environmental conditions were included in the model analysis.

Results are shown in Figure 7-3Figure 7-3 where the height of the bars present maximum produced biomass (starting from 0, without harvesting) and this is indicative for production. *Laminaria* reached higher biomass than *Saccharina* at all sites. Locations with high biomass production for both species are Borssele (best), Texel, Gemini, and Schouwen. High production in the model occurs at sites with high current velocity, i.e. with relatively large nutrient supply (See e.g. Figure 7-2)Figure 7-2.

7.5 Discussion and outlook

The vegetation module appears to offer good prospects for modelling macroalgae.. Currently Deltares is busy incorporating this module into the D3D-DWAQ suite. The vegetation module is more suitable for other species, such as the brown seaweeds *Laminaria* and *Saccharina*. These species rely stronger than *Ulva* on storage of carbohydrates.

Clearly for optimal site selection, productivity is an important issue and models such as these can help assess potential suitability and potential revenue from sites. This ought to be combined with information regarding suitability of sites regarding wave exposure, constructional constraints as well as operational constraints. Sites that are potentially very productive, but are at risk of structural damage due to wave action are likely to be less desirable. Also distance to shore will generally be a strong financial constraint as longer distances to processing plants require more transport costs.

Generally speaking, sites closer to shore, which are more influenced by nutrient input from rivers, tend to be more productive than locations further offshore. However closer to shore, pressures from other human use tend to be more intensive. Production carrying capacity is only one of the issues to be taken into consideration.

Models such as the D3D suite can also be used to assess the footprint of aquaculture sites on nutrient dynamics. These models allow assessing the impact that cultivation sites have on nutrient removal from the environment. On one hand they allow assessment of competition with phytoplankton and the productivity of other components of the North Sea ecosystem. On the other hand this can also allow optimal spacing of seaweed farms to sources of nutrients (e.g. fish farms or discharge locations) in order to use these seaweed farms to mitigate eutrophication and optimally combine ecosystem services of these businesses.

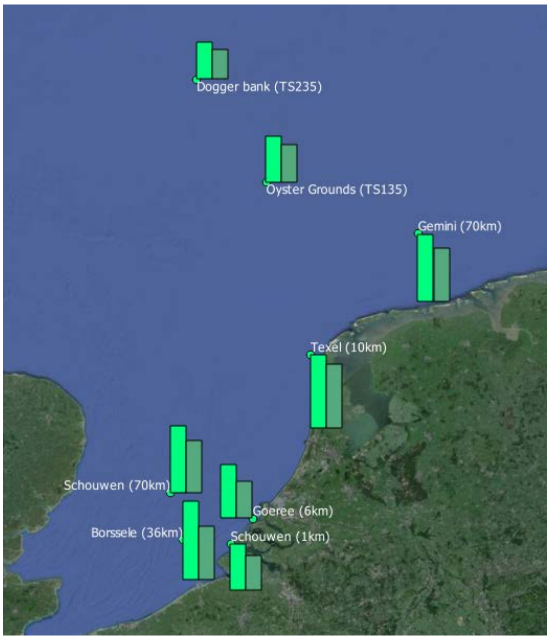


Figure 7-3 Maximum produced biomass of Laminara (light green) en Saccharina (dark green) on different locations in the North Sea.

8. Seaweed farm design

8.1 Introduction

It is evident that the development of the technology required for safe and reliable seaweed farms is still in its early days. Experience until today has been gained via small scale experimental projects or via small scale pilot projects mainly outside the Netherlands. Those experiences have delivered understanding on a number of aspects, but have not resulted in a final and optimal seaweed farm design ready to apply offshore at any type of environmental conditions. A large number of uncertainties and risks are still to be quantified, like the response of the seaweed farm support structure on extreme wave loading.

In this section the contribution of Deltares, MARIN and TNO on the seaweed farm design is presented. The three parties worked closely together in a study on the behaviour and integrity of a typical support structure in waves and current. The objective is to gain better insight in the technical suitability and capabilities of a typical support structure, which is the key component in the seaweed farm design. Deltares, MARIN and TNO delivered detailed technical reports on the work performed under this project. This Chapter 6 summarizes the work in a relatively non-technical manner. For more technical background details reference is made to (Deltares, 2015), (MARIN, 2015) and (TNO, 2015).

8.2 Study approach

The joint effort of MARIN, Deltares and TNO in in this study is a technical analysis in order to come to a seaweed farm design, which is cost effective and reliable. The focus in the design is the support structure. This component is considered the key component of the seaweed farm. Because of the limited time for this project a support structure type is selected from a literature review. This selection is adapted to the project requirements and is baptized as the TO2 concept. This is described in 8.3.

Next, the selected TO2 concept is assessed in a qualitative way that results in a description of the concept components. This assessment is done based on technical expertise from generic offshore applications. Section 8.4 summarizes the results. Subsequently a series of three initial technical assessments are performed to better understand the behaviour and integrity of the TO2 concept. A summary of the results of this assessment is presented in 8.5. Finally section 8.6 summarizes the main conclusions from the seaweed farm design study.

8.3 Seaweed farm support structure concept

8.3.1 Main requirements of the seaweed farm design

For the current project the challenge is to design an optimal seaweed farm for a realistic future wind farm site located 25 km offshore of Egmond that meets the following requirements:

- the seaweed farm should stay afloat supporting a large cultivated seaweed population;
- the seaweed farm should stay in place during all types of weather conditions; and
- the seaweed farm should facilitate the growth of *Laminaria digitata*, *Saccharina latissima* or *Ulva lactuca*. In more detail this means that:
    - the algae should grow between 0 and 3 meters below water level.
    - the density of the algae in the water should not exceed a certain value to make sure there is enough light and nutrient supply for all of the algae.
    - there should be a flow of nutrient rich water past the algae to provide nutrients.

8.3.2 Selection of seaweed support structure concept

A series of five concepts have been proposed. These concepts are not only based on the main requirements from the previous section, but also on a more technical design basis, a literature study and interviews with experts. These schematic concepts have been compared with previous studies, see for example the studies of (Buck, 2007) and (Roesijadi, 2007). A short description of the proposed concepts is given below.

Concept 1
Square structure which supports and tensions seaweed growth lines, see Figure 8-1. On each corner of this structure a buoy is mounted. The structure is fully submerged and moored on one single point.

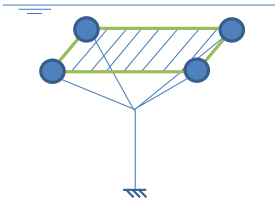


Figure 8-1: Concept 1

Concept 2
Square structure which supports and tensions seaweed growth lines, see Figure 8-2. Four lines connect the structure with one buoy that is floating on the water surface. The structure is moored on one single point.

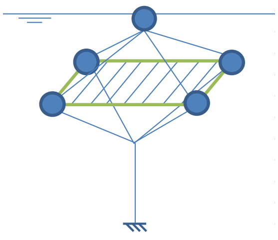


Figure 8-2: Concept 2

Concept 3
Structure fully build of lines and buoys, see Figure 8-3. The connecting lines between the buoys are also growth lines of seaweed. Growth lines of seaweed are near the water surface.

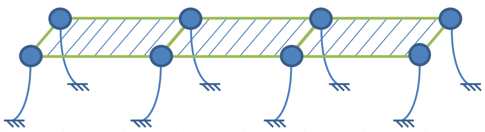


Figure 8-3: Concept 3

Concept 4
Line structure build out of lines and buoys, see Figure 8-4. The connecting lines between the buoys are also growth lines of seaweed. Growth lines of seaweed are near the water surface (e.g. H-profile).

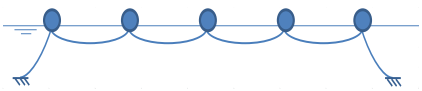


Figure 8-4: Concept 4

Concept 5
Line structure build out of lines and buoys, see Figure 8-5. Growth lines of seaweed are below the water surface.

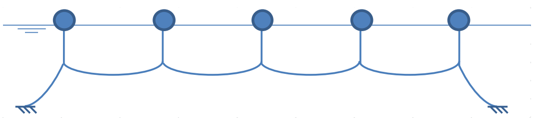


Figure 8-5: Concept 5

Based on a multi-criteria analysis these concepts are evaluated. This results in a selected design concept, to be applied for further assessment. The concepts are checked against the criteria by giving a value between 1 (negative impact) and 3 (positive impact). By adding a weight value the mutual influence of the requirements are set. The concept with the highest summed value is most suitable for seaweed cultivation in a near coast location. Requirements as well as the assigned values are shown in *Table 8-1*.

Requirement	Weight	Concept				
		1	2	3	4	5
Environmental						
Wave resistance	3	2	2	1	1	2
Current resistance	3	1	1	2	3	3
Multi-direction of wave and current	3	1	1	3	3	3
Method of growth and harvesting						
Removal of structure before harvesting	1	2	3	2	2	2
Applicability of automated harvesting	2	1	2	1	3	3
Removal of the crop from the matrix	3	2	1	1	3	3
Plant of new crop on matrix	2	2	1	1	3	2
Reinstallation of the structure in sea	1	3	3	1	3	2
Structural						
Minimal amount of parts and connections	3	2	1	1	2	2
Sea weed interaction with structure	2	1	1	2	3	3
	Total score	37	32	35	59	59

Table 8-1 Multi-criteria matrix of concepts against the criteria in order to select the most suitable concept

8.4 TO2 support structure concept description

Deltares, MARIN and TNO jointly selected concept 4 as the basis for the assessments in the TO2 project. This TO2 concept is applied for the tests and simulations described further on in this report. A design process is iterative by nature, with as a first step the selection of geometry and materials. In general and also in this project the selection of the geometry and materials are based on generic offshore engineering judgement. The chosen concept, including the initial dimensions, is shown in the figure below.

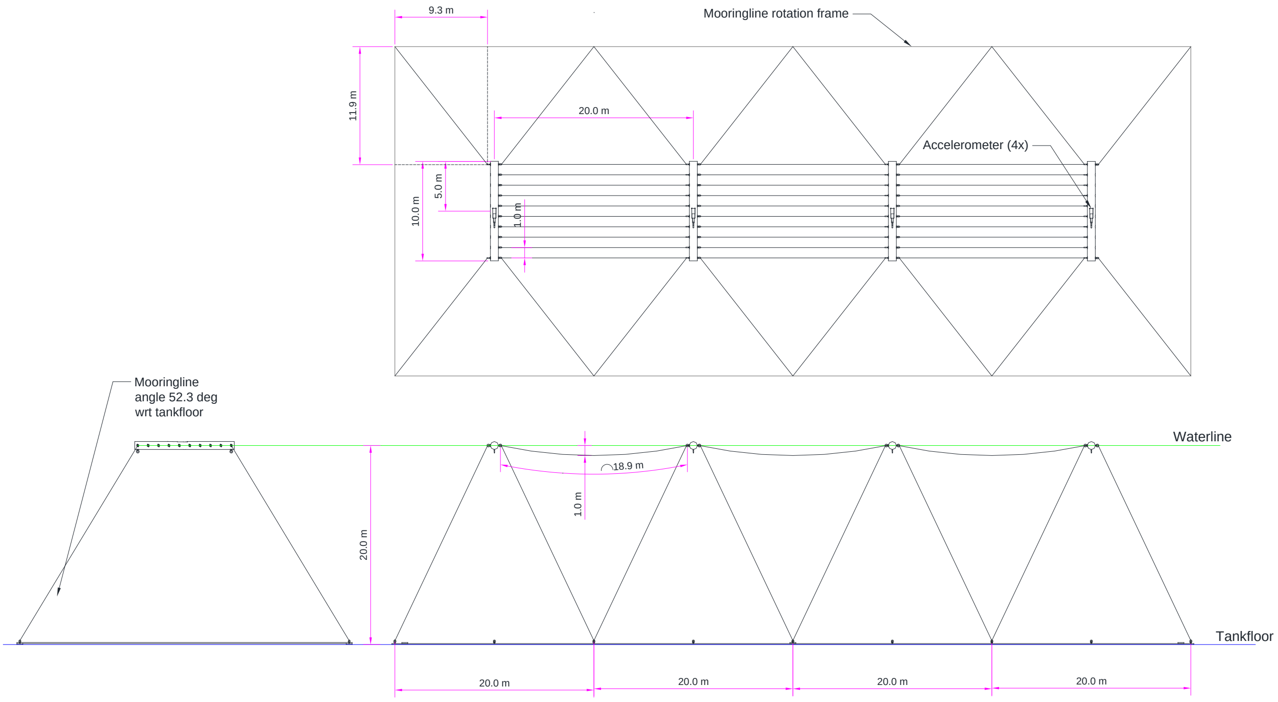


Figure 8-6 Tested seaweed support system in the MARIN Shallow Water Basin

8.4.1 Floater Design

The TO2 concept is a multiline concept type, which is similar to a concept that has been operated in the North Sea under a pilot program of a Dutch seaweed company. A typical design comprises multiple floaters with interconnected parallel seaweed lines. The TO2 concept floater design is similar to the common floater designs to grow shellfish. It is decided that 2 x 10 lines will be supported by each buoy. Both the buoy and the mooring system are designed to withstand the North Sea metocean conditions.

8.4.2 Mooring system

It is known from experience that seaweed lines are exposed to snap loads. Therefore it has been decided to moor each floater with a taut mooring system. The mooring system consists of 4 lines per floater, in which the mooring lines are attached to with a design angle of 37 degrees with the waterline in both the xz-plane and the yz-plane. This creates stiffness for both roll and pitch rotation. The mooring lines have their anchor point at a water depth of 20 m.

8.4.3 Seaweed line design

For the cases selected in this study, two different types of seaweed have been selected. Both types require a different line support. *Saccharina* grows directly on the seaweed lines, whereas *Ulva* requires a system that can contain the *Ulva* in a confined space (e.g. a cage). On the basis of this knowledge the following designs are proposed:

- *Saccharina* – A line which allows for easy growth of seaweed and has a Maximum Breaking Load beyond the maximum line loading expected in the severe metocean conditions.
- *Ulva* – A line with a cage containing the *Ulva*. The cage should not lead to high loadings as this will impact the structural design and cost of the system.

8.5 Results of the technical assessment

Three model studies are performed in order to get an understanding of the dimensions of the TO2 concept support structure. These studies lead to information regarding the behaviour of the TO2 concept in the North Sea conditions at the selected location. Being the first step in a design process the result of these three studies is whether the selected geometry and dimensions fulfil the maximum accepted stress levels of the selected materials. The three model studies are:

1. Shallow water basin model tests: Scale model of subsections of the selected model in a wave and current tank at MARIN that results in the a good understanding of the hydrodynamic behavior of the seaweed support structure,
2. Computational Fluid Dynamics model simulations to understand fluid flow around the seaweed support structure that results in the resistance of the seaweed and subsequent loading on the structure, and
3. Finite Element model simulations of the structure in order to calculate the limit states that results in the structural behavior of the seaweed support structure and the maximum stress levels that occur.

The hydrodynamic behavior of the support structure is tested via small scale model tests in the MARIN facilities to get a first impression of the interaction between the different components. During this test the structure is tested on a 1:20 scale in the Shallow Water Basin. To simulate the depicted North Sea location a JONSWAP spectrum is used with different significant wave heights from different directions, followed by a series of current only tests. The data and information gathered during the tests comprise general hydrodynamic behavior (qualitative), floater motions, mooring forces, and some of the forces in the seaweed lines.

The resistance of the seaweed and subsequent loading by the seaweed on the support structures is investigated by Deltares by setting up a Computational Fluid Dynamics (CFD) model. More detailed information on movements and loading can be retrieved in every location in the computational domain. For instance, it is useful to study the (vertical) mixing of seawater around the mooring lines and aquaculture, to understand the exchange of nutrients to the vegetation. Other important parameters are forcing in the lines and wave attenuation due to the presence of the seaweed and its support structure.

The structural behavior of the seaweed support structure is investigated by TNO. When the loads are identified, which is done by MARIN experimentally and by Deltares numerically, a structural model can be developed to evaluate the structural integrity of the system. The three parts of the system; floater, mooring and seaweed ropes can be evaluated separately. All of them should survive their lifetime both the ultimate limit state and the fatigue limit state.

8.5.1 Shallow water basin model tests

8.5.1.1 Description of performed model tests

The purpose of the model tests is to understand the hydrodynamic performance of the TO2 seaweed support structure. Measurements of motions, accelerations and loads on a scale model provide the required hydrodynamic insight to improve the design to cope with the extreme North Sea environment. Two types of model tests have been performed in the Shallow Water Basin at MARIN:

- Current load tests of *Laminaria/Saccharina* type of seaweed and *Ulva* – to understand the drag loading (due to wave and current) on the seaweed growth lines (with a length of 6 m). Tests have been performed at a scale 1:1 to understand drag loads on both the seaweed blades and lines in case of the *Saccharina/Laminaria* type *and* the *Ulva* cage under influence of waves and current.
- Mooring model tests of TO2 seaweed support structure to understand the motion behaviour of a full mooring support structure including floaters, seaweed lines and mooring lines. Model tests have been performed at scale 1:20.

8.5.1.2 Current load tests of *Laminaria/Saccharina* type of seaweed and *Ulva*

Several relative headings with respect to the incoming current have been tested (0, 45 and 90 degrees). The maximum forces measured on the seaweed blades correspond to an equivalent weight of approximately 1.4 kg, which is considered to be low. Despite the fact no in-depth research has been applied on the ultimate/fatigue loading seaweed can bear it is known from experience that seaweed can deal with large loadings when attached to hard substrate/lines. Bela Buck (Buck et al., 2007) determined the drag on different size of blades. In this research for each blade size a different loading has been determined. The loads as measured in the TO2 research as a function of current velocity have been plotted against the results of Bela Buck. By comparing this relation with the relation of Bela Buck a close match has been achieved indicating that seaweed has been correctly modelled.

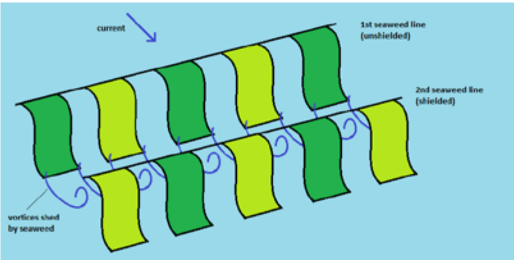


Figure 8-7: Shielding effect with two lines of seaweed

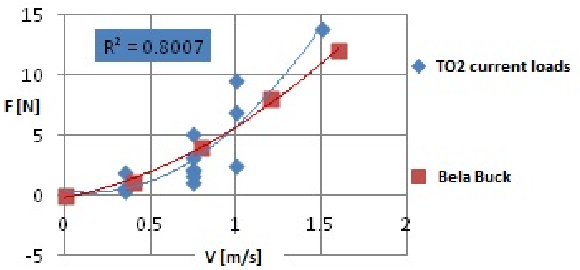


Figure 8-8: Comparison drag force by Bela Buck (Buck, 2007) and drag measurements Saccharina model MARIN

Knowing that the drag for individual seaweed blades has been modelled correctly the integrated load on the line with 13 seaweed flaps can be determined. This leads to the following conclusions:

- Considering a line of seaweed the direction of the incoming metocean conditions shows a significant effect on the loading on the line.
- In heading 0 degrees (parallel with current direction) the projected area of the seaweed line is low compared to the other (non zero) headings reaching around 3 kg of force in wave and current (0.2 m/s and H=0.3m/T=2.4s). For 45 and 90 degrees heading (oblique and perpendicular with respect to current direction) the maximum loading found is respectively 10 kg and 15 kg of loading (at current velocity of 1 m/s).
- For the cage containing *Ulva* (see Figure 8-11) for heading 0 degrees loads up to 6 kg have been recorded (at current velocity of 0.35 m/s). For heading 45 and 90 degrees the largest loads are measured reaching almost 30 kg and 45 kg of force at a relatively low current speed of 0.35 m/s.
- Cultivating *Ulva* will result in a loading a factor 25 higher than cultivating *Laminaria/Saccharina* (taking the difference of the current velocity into account).

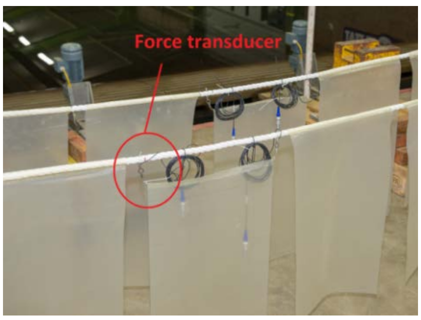


Figure 8-9: Impression of Saccharina modelled seaweed. The seaweed has been modelled by plastic flaps of 0.7 x 0.4 m.

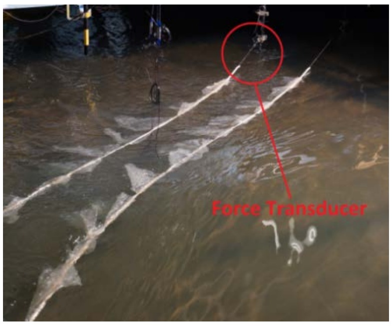


Figure 8-10: Impression of Saccharina modelled seaweed in the basin, where the load on the line is measured.

Figure 8-11: Impression of model test of the Ulva Cage. The Ulva is contained within the cage of 4.8 x D0.3 m.

In addition measurements have been performed to understand the difference of loading for the two lines in the vicinity of each other (see Figure 8-10). It is expected that the upstream line will shield the downstream line. This mechanism is important to understand so the cultivation of seaweed can be optimized growing the young vulnerable seaweed plants on the shielded lines. On basis of these results it is understood that cultivation of *Ulva* in a cage type structure shows a significant higher loading than cultivating the *Saccharina/Laminaria* type on a line. The consequence of this finding is that stronger support systems are necessary to allow cultivation of *Ulva* with such a type of structure. In the following set of experiments the *Laminaria/Saccharina* type has been used in a full mooring setup at model scale 1:20.

8.5.1.3 Mooring model tests of TO2 support structure

In the following figures an impression is given on the moored seaweed support structure, where the different floaters are interconnected by multiple seaweed lines and the seaweed is modelled similar to the current load tests at a smaller scale (1:20). The performance of the small scale TO2 design has been evaluated for both realistic current and wave conditions.

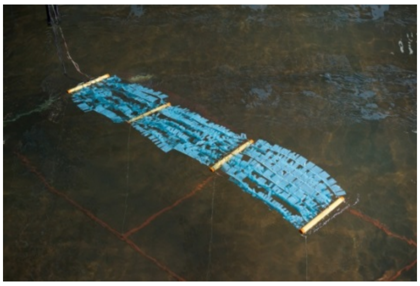


Figure 8-12: Impression of four interconnected seaweed support buoys with interconnected seaweed lines.

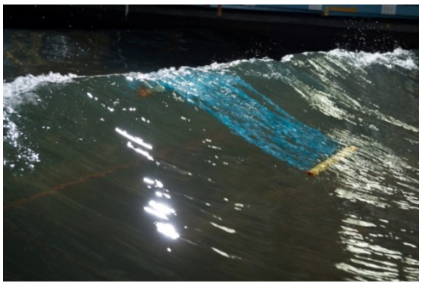


Figure 8-13: Impression of TO2 seaweed support design in extreme conditions

Figure 8-14: Impression of flexible TO2 seaweed support structure “bending” with the wave

For design purposes it is crucial to know the maximum accelerations experienced by the structure. The statistics of the accelerations are determined for each test. The most severe heave accelerations (upward motion) have been measured in the test with the highest significant wave height (H_s) H_s=4.2m with an extreme of almost 2g in heave. Large accelerations will have an influence on the integrity of the structure and mooring line, hence it is important to reduce these accelerations as much as possible. From the experiment it shows that the loading in the seaweed lines is relatively low due to the fact that the mooring lines take a significant part of the loading. The most severe loading in the mooring lines appeared in the 0 degrees heading case for a sea state with a significant wave height of 4.2m, where 94% of the allowable load in the line has been reached. The maximum load measured in the seaweed lines reaches 97% of the allowable load for the highest sea state tested (H_s=4.2m).

On basis of the findings as described above the main conclusions is that the current system is able to handle waves up to H_s 4.2m. However, the metocean conditions of the selected site show that sea states larger than H_s 4.2m will occur. These are likely to cause loadings above the load allowance of the current design. By selecting stronger seaweed/mooring lines the loading as a result of more severe conditions can be dealt with. This subsequently results in higher design cost for the seaweed support structure for Saccharina/Laminaria and even larger costs to support the Ulva cages as described in the previous section. A summary of the specifications on basis of the model test is given in *Table 8-2*.

Technical Specification	
Floater Concept	
Type	Cylindrical multi-line floater
Design and Certification	TO2 design (not certified)
Capacity	10 lines * 20 meter per module
Design water depth	Approximately 20 m
Floater	
Length	10 m
Weight	1947 kg
Displacement	3323 kg
Mooring system	
Type	Taut mooring nylon rope
Number of mooring lines per floater	4
Maximum Breaking Load	72.6 kN
Fairlead departure angle	37 degrees
Ulva line support system	
Length lines	20 m
Maximum Breaking Load	30.7 kN
Ulva support system	Ulva cages
Length cages	2/4/6/8 m
Saccharina/Laminaria line support system	
Length lines	20 m
Maximum Breaking Load	30.7 kN
Operating Data	
Maximum H_s at initial growth phase	4.2 m
Maximum H_s at final growth phase	< 4.2 m
Design life	15 years

Table 8-2 Seaweed Floater Design

8.5.2 Computational Fluid Dynamics model simulations

8.5.2.1 Description of performed study

By means of the scale experiments conducted at MARIN’s shallow water basin, information on the movements of the floating seaweed structure is obtained. However, more detailed information is required to explore the properties of the design. Therefore, a Computational Fluid Dynamics (CFD) model has been set up by Deltares. The added value of this model is amongst others:

- More detailed information can be retrieved in every location in the computational domain. For instance, it is useful to study the (vertical) mixing of seawater around the mooring lines and aquaculture, to understand the exchange of nutrients to the vegetation. Other important parameters are forcing in the lines and wave attenuation due to the presence of the seaweed and its support structure;
- The geometry of the structure can be altered rather easily. For example, simulations can be performed with a smaller number of mooring lines, or with other mass distributions.
- Studying more complex situations, a.o. like extreme wave impacts, the effect of currents on the support structure, the interaction with waves and currents simultaneously with the support structure, or the situation of two seaweed support structures aside each other etc..

The extent of this project only allowed for the setup of the model and validation of the scale modelling results at the shallow water basin.

The simulation model is verified (validated) by comparing the model results to the experiment results. For the modelling, the open-source software package OpenFOAM is applied. The wave modelling in OpenFOAM is already existing and available (Jacobsen et al., 2012) and there has already been carried out work with floating structures in OpenFOAM, see e.g. Rafiee and Fievez (2015), with simple mooring lines.

The main challenge in this work was to make a system of interconnected floating structures that are moving due to the wave forces and the forces from the interconnecting lines. This has not been performed so far with OpenFOAM. The interconnections are given as simple analytical catenary mooring lines. More detailed description of the software developments, model setup as well as the modelling results can be found in Deltares' report (Deltares, 2015).

The setup is depicted in Figure 8-15 where it is seen that four cylinders are connected by three catenary lines (black lines). All cylinders are anchored with mooring lines to the sea bottom. The initial system is symmetric. The cylinders have a radius of 0.4 m and the cylinders are approximately 20 m apart. The water depth is 20 m and the included layer of air above the water surface has a height of 10 m. The dimension in the z-direction comprises a single cell width of 2 cm, which makes the model essentially two-dimensional. A detailed view of the meshing around one of the floating cylinders is displayed in Figure 8-16.

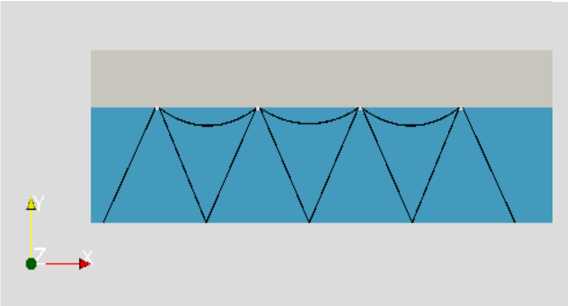


Figure 8-15 Model setup for initial time

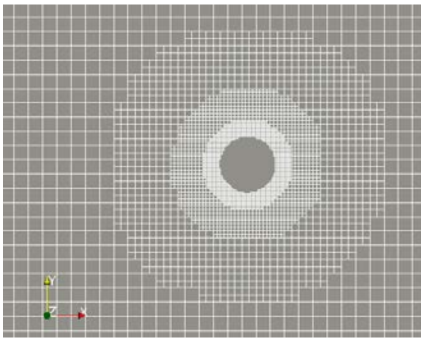


Figure 8-16 Detailed meshing around one of the floating cylinders.

In this study, three experiments of MARIN's test were simulated, representing the experiments without currents. The wave parameters varied from low to relative high waves H_s (1.8 m, 3.55 m, 4.20 m) and associated variation in peak wave period T_p (6.6 s , 8.4 s , 8.8 s respectively).

The results of the simulations were subsequently compared to the experimental results. It is generally seen that the movement of the cylinders are of the same order of magnitude, but there are differences in e.g. the horizontal and vertical displacements. This is thought to be caused by differences in the representation of the mooring system in the physical and numerical experiments. The scope of the project did not allow for a sensitivity analysis on the numerical design of the mooring system, consequently the results are preliminary in nature and recommendations are listed for future improvement.

The two figures below provide an artist impression of the water level displacements at the seaweed support structures caused by the wave propagation through the model domain resulting from the numerical computation.

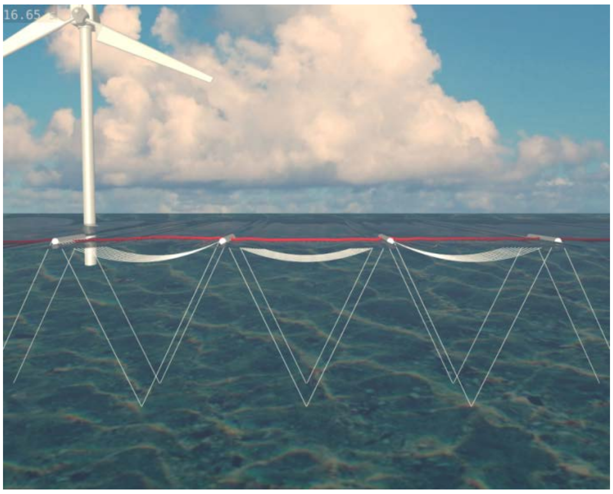


Figure 8-17 Situation when waves start to clearly appear at the floating structure.

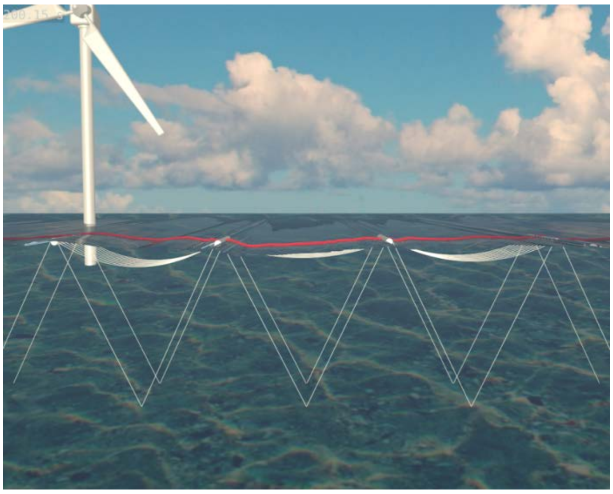


Figure 8-18 Situation when waves are developed.

8.5.2.2 CFD study conclusions

Based on the numerical modelling results it was concluded that a numerical model for multiple interconnected floating structures is presented. The model has been developed within the numerical framework foam-extend-3.1 and it is to the authors' knowledge the first time that interconnected, floating bodies have been modelled with OpenFOAM.

The numerical results were compared to data from the laboratory campaign at MARIN. There were some differences between the physical and numerical results, but these were mainly attributed to the representation of the mooring system in the numerical model.

The scope of the project did not allow for a sensitivity analysis on the numerical design of the mooring system, consequently the results are preliminary in nature. Nevertheless, it is expected that this modelling development is a tool to further study the optimization of the design by better understanding the loading and response of the structure.

8.5.3 Finite Element model simulations

8.5.3.1 Approach FE study

The structural analyses performed by TNO focus on the integrity of the seaweed lines, the mooring lines and the floaters of the concept. The design has been executed through a design method by which the target safety level is obtained as closely as possible. This is achieved by analysing the loads acting on the structure on the one side and the resistance of the structure on the other. Safety factors are applied to the characteristic reference values of these basic load and resistance variables.

The situations that are used to analyse the design are so-called limit states. These limit states are the conditions beyond which the structure fails to fulfil the design requirements. The number of limit states that are considered relevant in performance evaluation are:

- Ultimate limit states corresponding to the ultimate resistance for carrying loads.
- Fatigue limit states related to the possibility of failure due to the effect of cyclic loading.

8.5.3.2 Ultimate limit state results

The preliminary results of the model tests performed by MARIN are used to determine the maximum loading in the mooring lines. Although the tests are based on representative conditions, an actual ultimate limit state design assessment should be made with a wave that has a return period of 10 years (H_s ~ 6.5 meter NW). The test series with a heading of 0 degrees and a significant wave height of H_s = 4.2 meter result in the worst case scenario for the mooring line loading. This signal gives a maximum loading of 70 kN in the starboard mooring lines, and a maximum load of 10 kN in the seaweed lines.

An Ansys FE model is set up to determine the stresses in the cylindrical floater introduced by the lines attached to the floater. The geometry and structural aspects are based on the TO2 concept, while the material characteristics have been selected using standard available material, steel S355 in this case. The cylinder is closed at the ends and all areas are modelled with shell elements with steel properties. To model the vertical component of the mooring lines a distributed load is applied, together they sum up to the vertical component of the mooring forces. The horizontal mooring forces are applied on the corners. The seaweed lines are applied as point forces on their attached locations. To get the resultant force right the model is restricted in the four corner points in vertical direction.

Dimension	(m)
Length	10
Radius	0.8
Wall thickness	0.01

Table 8-3 Model dimensional properties

The eventual dimensions are listed in Table 8-3. An overview of the model and the resulting equivalent stress contour plots can be found in Figure 8-19: *Finite Element Model used for the ULS calculations* en Figure 8-20.

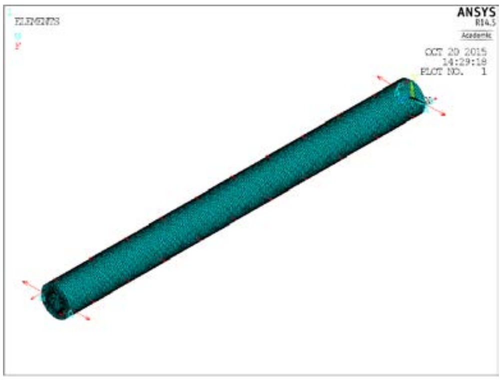


Figure 8-19: Finite Element Model used for the ULS calculations

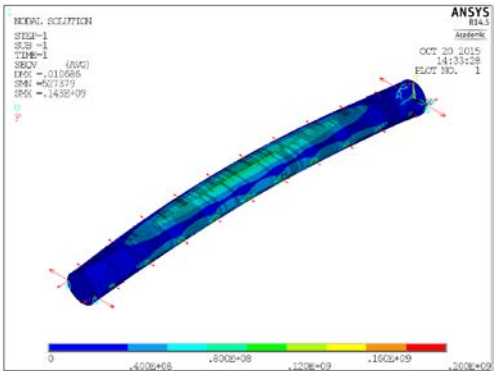


Figure 8-20: Equivalent stress overview

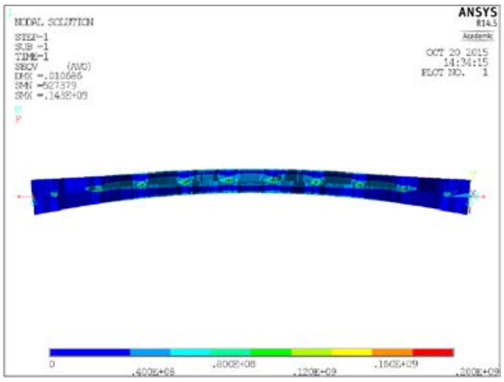


Figure 8-21: Equivalent stress side view

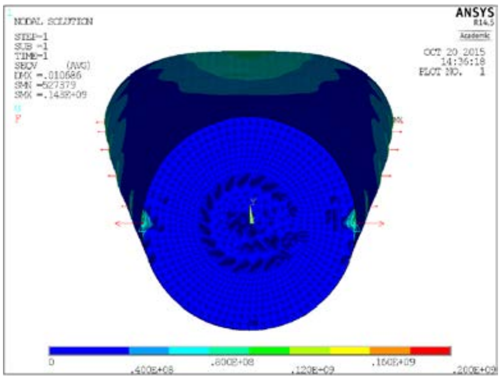


Figure 8-22: Equivalent stress cross section

From these results it can be concluded that with the eventual model dimensions the accepted stress level is not exceeded in the structure. The highest loads are found around the applied load of the middle seaweed line. The exact design of the attachment of these lines is has to be elaborated in a detailed design phase. This means that the final value of the stress will differ from the calculated value, and can be optimized to come to a more optimal design. The loads implied by larger significant wave heights are not known yet, but will be relatively easy to calculate now that the Deltares hydronamic model and the FE model are available.

Mooring lines and seaweed lines are considered to be made of HMPE or equivalent material. For both lines a maximum loading of 70 kN applies. Synthetic fibre mooring lines require a significant safety margin (factor 7), which leads to a typical 24 mm diameter line (synthetic fibre HMPE) with a breaking strength of 49,000 kg for this concept. It can be argued that the seaweed lines do not need such stringent safety margin, since seaweed line failure does not lead to loss of the seaweed support structure as a whole. Again, an actual ultimate limit state design assessment should be made with a wave that has a return period of 10 years, which will lead to higher but more representative loading. When these loads are known, a new mooring line can be selected.

8.5.3.3 Fatigue limit state results

A fatigue check of the floater can be performed with standard SN-curves when the life time equivalent loading is known. The stress fluctuations over a period of 10 years can be calculated with the MARIN test results extended by the Deltares simulations, the depicted offshore site wave and current properties and the Ansys FE model. It is expected that the fatigue life will not be the design driver. The reasons for this expectation are that the design life is relatively short, the extreme condition in the North Sea is relatively severe, and that the design fatigue factor will be 1 because the floater is accessible for regular inspection and can be repaired in dry and clean conditions.

It is possible that the structure will vibrate due to the snapping loads in the mooring lines and seaweed lines. To find out the Eigen modes and frequencies also a modal analysis is performed in Ansys. The floater is modelled as a beam with circular tube sections. The beam is mounted on springs to simulate the restoring moment of the floater. Next, an added mass factor is added to the system to simulate the water moving with the floater. The results can be found in *Table 8-4*. The first two rigid body modes are not taken into account since only the bending modes are of importance in this case. The bending will only become a problem in case of excitation in the Eigen frequency. From these results it can be concluded that there will be no excitation by waves. Only 5% of the waves at the offshore site have a period below 3s and those have an amplitude that will not affect the fatigue life.

Mode	Frequency (Hz)	Period (s)
3	0.35	2.82
4	0.93	1.08
5	1.71	0.58
6	2.63	0.38
7	3.65	0.27

Table 8-4 Eigen frequencies

The fatigue performance of HMPE mooring and seaweed lines in a novel application is in general verified via long-term fatigue testing of a test specimen with subsequent examinations and tests. Frequent failure mechanisms are the failure of the splices and creep, which both can lead to changing system properties and eventual breakage. However, in case of HMPE lines an extensive track record exists on past performance in the oil and gas industry. This history makes prove testing redundant, and a safety margin of factor 7 will suffice when authorities agree.

8.6 Seaweed farm design conclusions

In the TO2 work package “Technical Feasibility” a design has been selected according to different selection criteria. The design has been based on the current state-of-the-art experience from small scale (pilot) projects. Deltares, TNO and MARIN contributed to the technical evaluation of the design. Via this study a number of knowledge gaps, like the understanding of the response of the structure on extreme wave loading, have been filled.
From the analyses it is found that for the current TO2 design the loading on each individual seaweed blade (Laminaria/Saccharina) is limited for currents up to 1.5 m/s irrespective of direction. However, the line loading is significant and strongly dependent on current direction. This information provides insight in how to select an optimal orientation of the support structure with respect to the metocean conditions. Furthermore a good understanding of the motions for significant wave heights up to 4.2m is found, which is concluded to be the maximum sea state at which the structure can be in operation while keeping the mooring and seaweed lines intact.

The ultimate load and fatigue analyses show that both limit states will not be exceeded based on the loads derived from the model tests. However, at the selected operating site the sea state can be more severe than simulated. In order to select appropriate mooring and seaweed lines more research has to be performed with wave conditions with a return period of 10 years (Hs ~ 6.5 meter NW).

The research performed shows that the current structure is not able to cope with the severe conditions of the selected site. As a first step in a design process this is a probable outcome and the basis for further optimizing a design. Next, the research performed has been valuable in understanding the physical mechanisms in order to develop a more robust design that is cost efficient and applicable for large scale seaweed exploitation.

Part of the literature study has focussed on some general cultivation issues in seaweed cultivation. A common problem with the small scale offshore seaweed farms is the loss of seaweed in the harsh conditions. A main reason is the damaging of seaweed due to interaction with the structure. Bela Buck conducted research to investigate the strength of the seaweed as well as the influence of the environment on the seaweed (Buck B. , 2007). The most important conclusions on seaweed survival that can be used in offshore seaweed farming are the following:

- Offshore grown (brown) seaweed is strong enough to withstand the current and wave loads.
- The hydrodynamic and structural properties of (brown) seaweed change when it grows in harsh offshore environments.
- The drag on (a bunch of) Laminaria is relatively small.

9. Seaweed processing and plant design

9.1 Summary

Value chains for two different seaweed species were selected for technical demonstration. One value chain was based on brown seaweeds, the other one on the green seaweed Ulva. The brown seaweeds contain mannitol, laminaran and alginates as well as proteins. The value chain was based on a cascading valorisation concept with high value applications for all streams. The variation in chemical composition for different cultivation locations for two types of brown seaweeds (Sugar Kelp and Oarweed) were determined as input in our economic model.

Pure mannitol (>98%) has been successfully extracted from fresh and stored seaweed. Mannitol is a food ingredient and high value chemical intermediate. It can also serve as a raw material for other high value intermediates, which has been demonstrated in the past using seaweed derived mannitol. A novel intermediate was selected, but the target molecule (a plasticiser) proved to be elusive. Alginates on the other hand were successfully extracted as the last step of the cascading valorisation scheme. This concept can be applied to fresh and stored seaweed, a significant finding as the cost of storing is significant in our economic model.

The green seaweed Ulva was used to produce a novel furan based chemical building block (5-methyl furfural), thus demonstrating that the unique raw materials for chemical building block can be used to obtain intermediates which are otherwise difficult to isolate from more traditional terrestrial sources. Extracting the proteins anywhere in the cascading value chain proved to be challenging, or with other words, we have not yet successful. The residues from the various routes proved to be less digestible than whole seaweed, but still usable.

9.2 Introduction

In this WP, we aim to isolate several high value products from fresh seaweed. For these processes, we have selected *Saccharina latissima* (also known as: *Laminaria saccharina*) and *Ulva* as the two target seaweeds. The two species with the selected value chains are depicted below.

The product spectrum for *Saccharina latissima* encompasses a food and pharmaceutical ingredient, mannitol, which is also a high value chemical intermediate for further conversion to other high value chemical intermediates. One such intermediate is isomannide, an isomer of isosorbide which is among others used by Sharp for the production of the screens of smart-phones. Another mannitol-derived building block is 2,4:3,5-dimethylenemannitol, a product with two primary hydroxyl groups that may give special properties to e.g. polycarbonates.

From the residue, one can isolate alginate to further develop the biorefinery concept. In parallel, the isolation of protein in the chain at various places is evaluated to assess the most optimal protocol in conjunction with the other high value products.

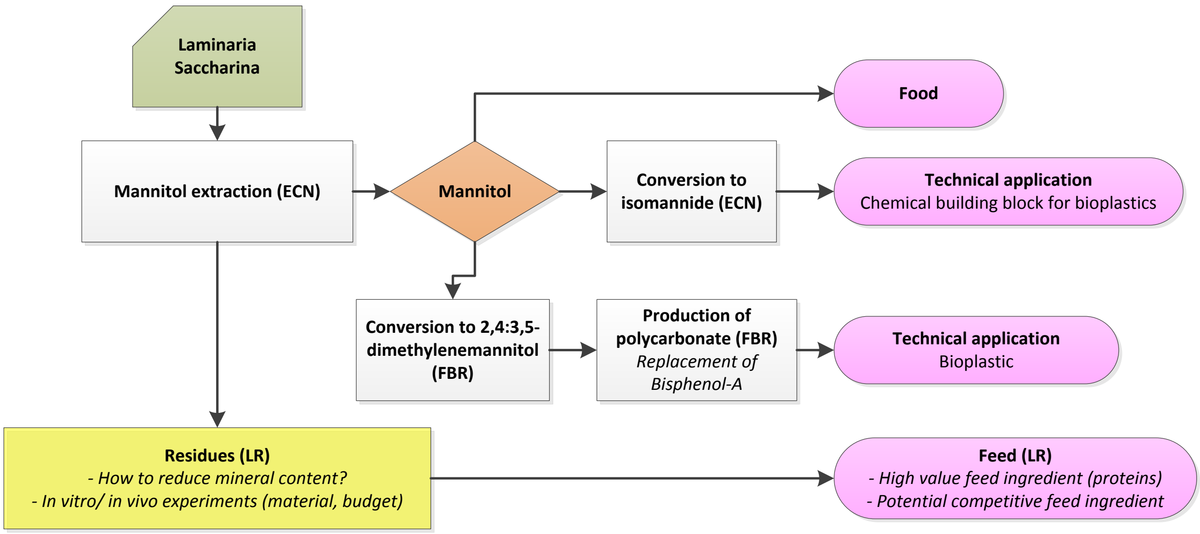


Figure 9-1: Value chain of Saccharina latissima

Seaweed is highly perishable. Thus, storage concepts are being developed. One such storage concept is silage. The effect of silage on the composition is experimentally determined, followed by the effect on the efficacy of the mannitol extraction of ensiling the seaweed.

For *Ulva*, rhamnose was selected as high value compound, as this is both a valuable food compound (regarded as healthy carb) (Holdt and Kraan, 2011) and an intermediate for furanics building blocks which are difficult to produce from more traditional carbohydrate precursors. Two parallel protein extraction schemes were selected, one prior to carbohydrate extraction and one post.

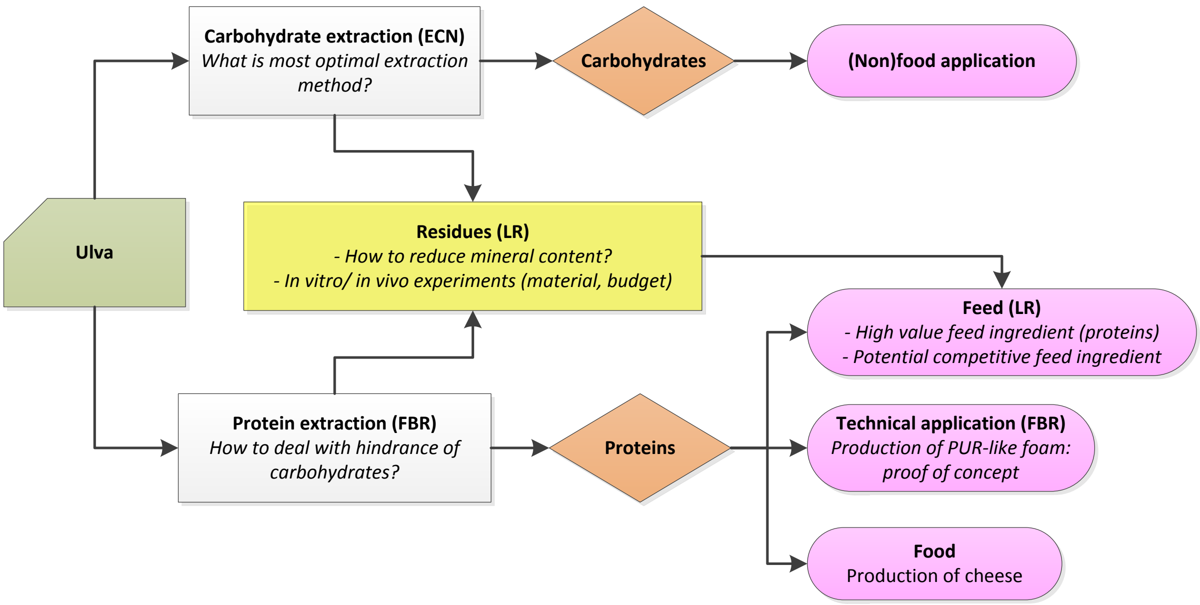


Figure 9-2: Value chain of Ulva sp.

9.3 Description of processes

9.3.1 Effect of silage on the composition of *Saccharina latissima* (ECN)

Various samples of Kelps (brown macroalgae) were supplied by Hortimare (cultivated in Norway, from the EU-FP7 @Sea project), OceanHarvest (Ireland) and NoordZeeBoerderij ('North Sea Farm', The Netherlands). Samples of both *Saccharina latissima* and *Laminaria digitata* were received. The composition of the Kelps was determined and is given in Figure 9-3. Large differences in the protein content (about factor 2) and alginate content (about factor 3) were found. These differences are probably due to growing conditions and maturity of the plants.

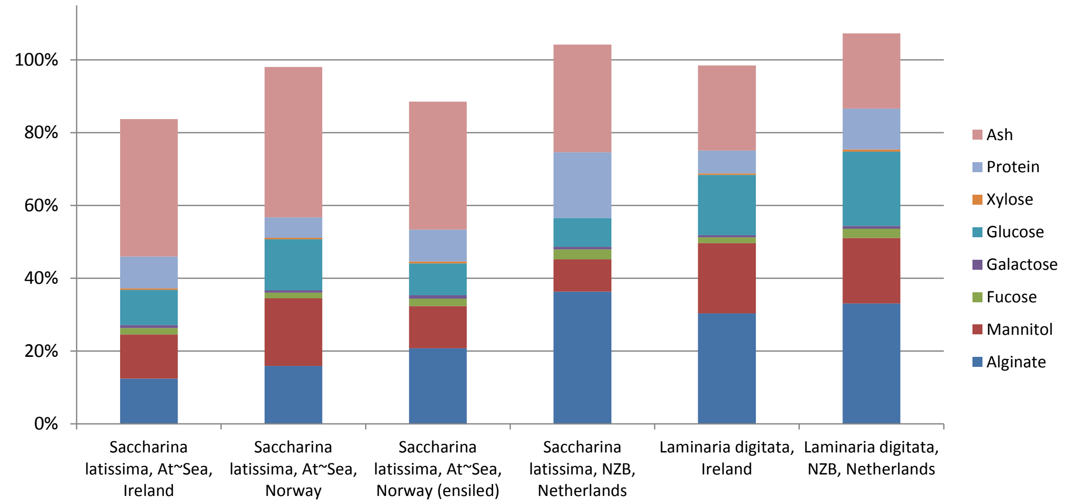


Figure 9-3: Composition (% dw) of various Kelps tested within the project.

The *Saccharina latissima* cultivated within the EU-FP7 @Sea project was ensilaged by Hortimare and a large batch of the ensilaged seaweed was provided to the TO2 seaweed project. Ensiling was performed by covering fresh wet seaweed with plastic, putting water on top and storing the seaweed for weeks at room temperature (Figure 9-4). The effect of ensiling was assessed by comparing the composition of the ensilaged material with that of the fresh material directly after harvest (Figure 9-5). Ensiling was found to result in a lower content of minerals, mannitol and glucose and enrichment in protein and alginate. The structure of the ensilaged seaweed was still relatively intact. The lower content of mannitol is partly due to extraction of mannitol into the process liquor that is formed during ensiling as well as possible consumption of mannitol by lactic acid bacteria grown during storage. The quality of the protein and alginate present in the ensiled seaweed needs to be verified, but ensiling seems an effective way to preserve the major structural components of *Saccharina latissima*.

Figure 9-4: From left to right: Cultivation system of EU-FP7 @Sea, Harvest of Kelps, Ensiling container and Ensilaged Seaweed.

9.3.2 Isolate mannitol from *Saccharina latissima* by ECN

Mannitol was isolated following a cascading biorefinery approach (van Hal et al., 2014) from two batches of Kelps: (a) the ensilaged *Saccharina latissima* and (b) fresh *Laminaria digitata* from Ireland. The latter was included for comparison since fresh Kelps seem a better source for mannitol. Mannitol isolation was performed using the following steps: (a) extraction with fresh water[2], (b) separation of mannitol from high-molecular weight components such as laminarin by membrane-filtration of the extracted liquor, (c) rota-evaporation of the obtained permeate and (d) purification of the obtained crude mannitol. The solid residue obtained from step (a) contained most of the protein and alginate. This residue was supplied to WUR-LR as well as used for alginate extraction (Figure 9-5).

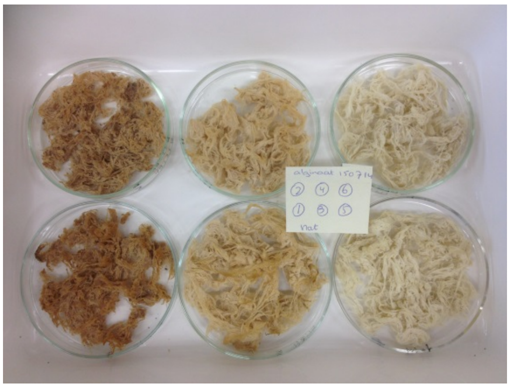


Figure 9-5: Alginate isolated from process residues. Quality of alginate to be determined in follow-up project.

Treatment of ensilaged *Saccharina* was found to result in isolation of 71-86% of the mannitol present in the feedstock. However, also ~60% of the minerals, ~40% of the protein fraction and 25-30% of other carbohydrates including laminarin and alginate were co-extracted due to washing and cell disruption caused by osmotic shock. In other words, aqueous extraction is an effective, but not a selective, process for mannitol isolation and purification of the extract is required. The same holds for mannitol isolation from fresh *Laminaria digitata*, although the extraction process was found to be more selective in that case, most probably because the structure of the seaweed feedstock was more intact.

[2] For process details see J. van Hal & W.J.J. Huijgen (2012), Process for mannitol extraction from seaweed, patent NL 2009482.

The process liquors were first centrifuged to remove any solid particles present. Subsequently, the liquors were successfully subjected to ultrafiltration in two steps: (a) 30 kDa and (b) 1kDa to remove high-molecular weight impurities. Finally, the permeates were rota-evaporated to obtain a crude mannitol powder. From fresh *Laminaria digitata*, a crude with a 45% mannitol purity was obtained. The remainder consisted of 4% ash and the rest were probably oligomeric carbohydrates (with Mw <1kDa). Continuation of the membrane-filtration over longer times in order to produce a larger batch of mannitol showed a reduction of the selectivity of the membrane resulting in a crude with a 28% mannitol purity. The crude mannitol was purified using methanol extraction in a Soxhlet set-up and subsequent crystallisation of mannitol. This purification procedure was found to be very effective resulting in virtually pure mannitol with only traces of impurities. The melting point of the purified mannitol was 166 °C compared to 168 °C of commercial mannitol. In summary, the total process of isolating pure mannitol from fresh and ensilaged brown seaweeds was successfully demonstrated within this project.

Figure 9-6: From left to right: Laminaria digitata, Crude extract, Purified mannitol.

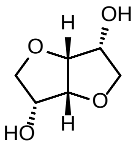
9.3.3 Conversion of mannitol (WUR/ECN)

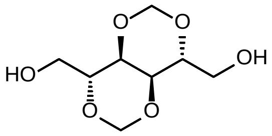
No activities were performed on the conversion of mannitol by ECN within this project. Generally, ECN is interested in conversion of mannitol into isomannide (Figure 9-7) that can potentially be applied into biobased plastics.

WUR-FBR have pursued the preparation of 2,4:3,5-dimethylene-D-mannitol (Figure 9-6Figure 9-7). Its synthesis by a multi-step procedure has been described in literature, (Haskins and Hudson, 1943; Haworth and Wiggins, 1944; Lavilla et al. 2012) and starts by ‘protecting’ the 1- and 6-positions of mannitol by reaction with benzoyl chloride. The obtained 1,6-dibenzoyl-D-mannitol is then reacted with paraformaldehyde to give the 1,6-dibenzoyl-2,4:3,5-dimethylene derivative. In the final step, the benzoyl groups are removed to give the desired product.

This published procedure is not economical, and not green. WUR-FBR therefore tried to simplify the procedure by reacting mannitol directly with paraformaldehyde in an attempt to obtain the targeted building block in one step. The method was based on a published procedure for the preparation of 1,3:4,6-dimethylenegalactitol (Hann et. Al, 1942), and involves the slow spontaneous formation of crystals of the dimethylene derivative from a mixture of the sugar alcohol in formaldehyde / concentrated hydrochloric acid solution which is put in a desiccator containing anhydrous calcium chloride, sodium hydroxide pellets and several small beakers of concentrated sulfuric acid. Instead of calcium chloride, sodium hydroxide and sulfuric acid, we used only phosphorus pentoxide (P_2O_5) in the desiccator. Crystals formed much earlier (after three days) in the case of mannitol compared to galactitol (after seven days). After about one month, the crystals were isolated according to the published method, and characterised by NMR spectroscopy.

It was found that, instead of the desired dimethylene derivative, a trimethylene-D-mannitol had formed. The exact structure of the triacetal could not be determined. Due to a lack of time, no further attempts could be made to prepare the dimethylene-D-mannitol and use it for polymerisations.





isomannide 2,4:3,5-dimethylene-D-mannitol

Figure 9-7; Structures of mannitol-derived isomannide and 2,4:3,5-dimethylene-D-mannitol.

9.3.4 Isolation of Rhamnose (and conversion) from *Ulva* by ECN

Fresh *Ulva* was supplied by WUR-IMARES from the cultivation tests performed in Yerseke. Two runs were performed with the received feedstock: (1) aimed at hydrolysis of polysaccharides into monomeric carbohydrates, including rhamnose, and (2) aimed at hydrolysis of polysaccharides into soluble oligomeric carbohydrates and simultaneous preservation of the protein fraction. Both runs were performed in a 20L autoclave set-up at 140 °C and 100 °C, respectively. The residue from run 2 was sent to WUR-LR and WUR-FBR for further tests.

Sample (% dw)	Ash	N	Rhamnose	Galactose	Glucose	Xylose	Glucuronic acid
Ulva feedstock June 2015	34.3	1.6	7.8	0.5	13.7	1.8	3.7
Residue run 1 @140 °C	21.9	2.0	2.8	<DTL	6.4	0.6	0.8
Residue run 2 @100 °C	ND	3.8	1.5	0.7	16.7	3.5	1.1

Table 9-1 Composition of Ulva feedstock and process residues

The composition of the *Ulva* feedstock and the solid process residues is given in Table 9-1. The Ulva feedstock supplied turned out to contain low amounts of rhamnose and protein relative to Ulva batches processed in earlier projects (Bikker et. Al, 2015)[3]. The residue resulting from mild hydrolysis at 100 °C was enriched in N, glucose and xylose due to partial solubilisation of rhamnose, glucuronic acid (both part of ulvans) as well as ash. The residue from severe hydrolysis at 140 °C (Figure 9-8) was depleted in carbohydrates and probably consisted of humins / other condensation products.

[3] The Ulva used in that study has a total N content of 4.9 %dw and rhamnose content of 9.0 %dw.

Figure 9-8 Ulva feedstock (left) and process product from hydrolysis at 140 °C (run 1, right).

The first run at 140 °C showed very good mass balances and yields of monomeric glucose and rhamnose. The carbohydrates were almost entirely present in their monomeric form. The second run at 100 °C showed a poor mass balance, probably due to handling losses (data not shown). The resulting carbohydrates in the process liquor were predominantly present in the oligomeric form.

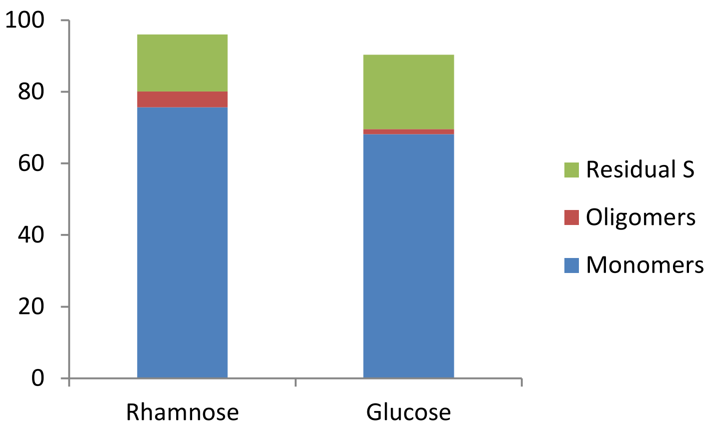


Figure 9-9; Yields and mass balance of rhamnose and glucose (% based on composition feedstock) from hydrolysis at 140 °C.

In summary, it was demonstrated that monomeric carbohydrates can be obtained in high yields directly from fresh *Ulva sp.* and that *Ulva sp.* is thus a valuable source for both specialty (rhamnose, glucuronic acid) and standard carbohydrates (glucose, xylose) that can e.g. be converted into biofuels by fermentation. In a follow-up project, the optimum route for combined carbohydrate and protein isolation from *Ulva sp.* should be studied.

9.3.5 Isolation of protein from *Ulva lactuca* by WUR

Isolation of protein for the production of cheese calls for delicate extraction procedures, where the extraction temperature does not exceed 50 °C, in order to prevent protein denaturation. This limits the number of possibilities of selective protein extraction or carbohydrate extraction for the production of protein-enriched fractions.

Proteins are part of the cell wall and are closely associated with the carbohydrates. Extraction of proteins from seaweed is difficult due to the presence of these carbohydrates as they increase viscosity and limit access to the proteins. In this project we followed two lines, *i.e.* alkaline extraction of proteins followed by isoelectric precipitation, and carbohydrate/ulvan hydrolysis for the production of protein-enriched fractions.

1. During the first experiment freeze dried *Ulva* was placed in deionized water to cause cell disruption by osmotic shock, followed by an alkaline extraction at pH 8.5 to bring the protein into solution, and isoelectric precipitation at pH 4 to isolate the protein. Analysis of the protein content of the samples revealed that protein was not extracted from the seaweed.
2. In the second experiment the alkaline extraction was done at higher pH, but this had no positive effect on the protein yield.
3. In the third experiment focus was on cell disruption of fresh *Ulva*, where osmotic shock (see experiment 1) was compared with enzymatic degradation of carbohydrates to open the cell walls. Enzymatic treatment resulted in partial disintegration of the seaweed structure as reduction of viscosity was observed.
4. Enzymatic hydrolysis of *Ulva* (freeze dried and fresh) was further studied by measuring released sugars and protein,

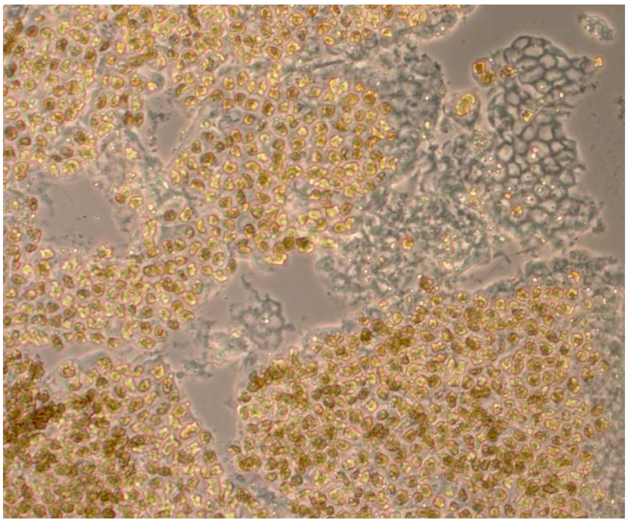


Figure 9-10 Light microscopy image of Ulva lactuca after mechanical and enzymatic treatment. Intact cells are shown in green, while cell walls of empty cells show as gray lines

To summarize, alkaline extraction followed by isoelectric precipitation did not work, as proteins were not released from the seaweed biomass. Production of protein-enriched fractions by hydrolysis of the carbohydrates was more successful, as sugar release was observed. Large differences were detected between freeze dried seaweed and fresh biomass; release of sugars from fresh seaweed is much higher than from freeze dried material. Membrane filtration proved to be an interesting technique for desalination and purification of samples.

Further work needs to focus on cell disruption of seaweed, comparable to work done on microalgae. Microscopic analysis showed that most of the cells were still intact (Figure 9-10), even after washing, homogenisation and enzymatic hydrolysis during few days.

9.3.6 Evaluation of the residues as feed (WUR-LR)

The residue of seaweed after extraction of specific components, e.g. mannitol, as described in previous paragraphs, may be used as a feed ingredient in the diet of farm animals. This application would contribute to the development and (economic) feasibility of a seaweed chain. Therefore we determined the in vitro digestibility of residual fractions of mannitol extraction from *Saccharina* latissima and *Laminaria* digitata (chapter 9.2.3) and of rhamnose extraction from *Ulva* lactuca (chapter 9.2.5) to evaluate the nutritive value of these seaweed residues. In addition, a sample of each of the three intact seaweeds prior to extraction was included in this study to determine the effect of the extraction process on the in vitro digestibility (Boisen and Fernandez, 1995 and 1997).

Briefly, determination of the in vitro digestibility includes incubation of the substrate in two steps with the addition of pepsine-HCl and pancreatine in the required conditions (e.g. temperature, pH) to reflect the digestion in the stomach and small intestine of monogastrics. Filtration was used to separate potentially degradable and undegradable fractions after 2, 4 and 6 hours of incubation. The results in Figure 11 and 12 indicate that the in vitro dry matter digestibility of the intact seaweed was approximately 15-20% lower than soya bean meal. Furthermore, digestibility of the residues was substantially lower than the digestibility of the intact seaweed. For *Saccharina* and *Laminaria* the overall difference was approximately 20 percentage points whereas in *Ulva* the difference was close to 30 percentage points. The most likely main reason is that the fresh water extraction not only removes the carbohydrate fraction of interest (mannitol, rhamnose) but also co-extracts a large proportion of the minerals (~60%), protein (~40%) and other carbohydrates (25-30%) (chapter 9.2.3). Presumably this extractable fraction is highly digestible and contributed to the higher digestibility of the intact seaweed. Hence, after extraction of this fraction, the remaining residue comprised the components with lower digestibility, e.g. complex carbohydrates with a low solubility and a low digestibility because of lack of digestive enzymes for these specific carbohydrates. The reduction in digestibility due to the washing of intact *Saccharina* l*atissima* (Figure 9-11) confirms that the washing removes highly soluble and digestible components, presumably minerals. It is not quite clear why the in vitro digestibility of some of the fractions in Figure 9-11decreased between 4 and 6 hours of incubation. This would be an unlikely physiological effect in the digestive tract unless certain components coagulate and precipitate during the incubation process. The latter effect may indeed reduce their digestibility.

The digestibility of *Ulva* residue showed the biggest reduction compared to the intact seaweed. This may be related to the autoclaving process used to extract rhamnose. As indicated above, this extraction may have removed the readily soluble components, thus increasing the relative amount of components with lower solubility and digestibility in the residue. Moreover, it cannot be excluded that the conditions of the autoclaving process, i.e. high temperature en pressure, influenced the digestibility of the residue fractions.

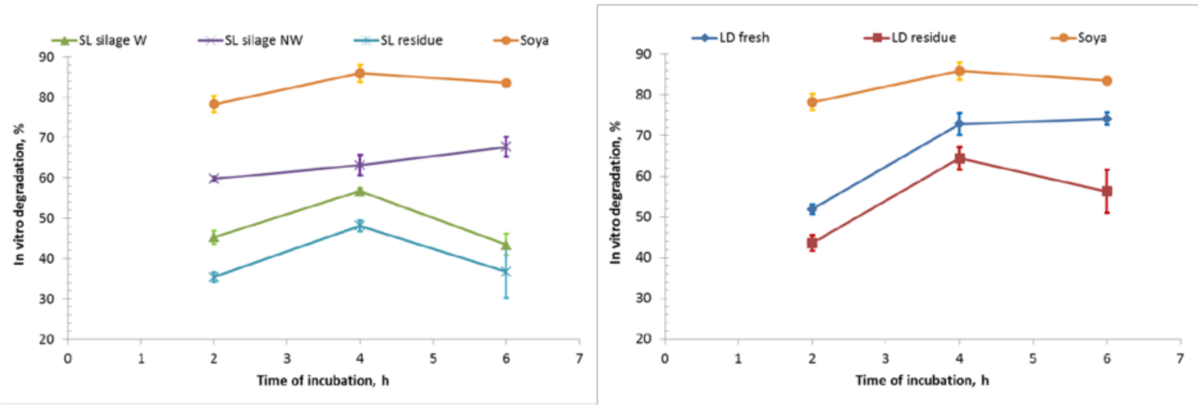


Figure 9-11 In vitro dry matter degradation of washed (W) and non-washed (NW) Saccharina latissima (SL) silage and residue of NW SL extraction and fresh and extracted Laminaria digitata (LD) compared to soya bean meal.

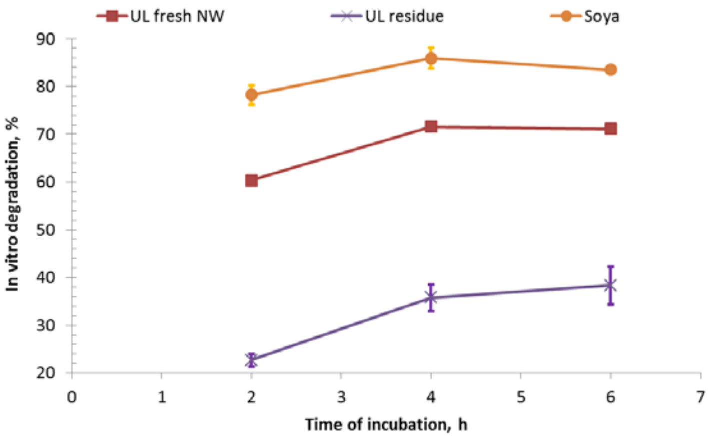


Figure 9-12 In vitro dry matter degradation of fresh and extracted Ulva lactuca (UL) compared to soya bean

9.3.7 Conclusions

We have observed a large effect of ensiling on the composition of Kelps. The storage sugars are preferentially extracted or metabolised during the storage process. However, the structural components are largely intact. We have also observed differences of factors in the composition of the kelps as functions of their locations.

Mannitol and alginic acid were successfully extracted and purified from fresh and ensiled kelps. The conversion of mannitol to a high value intermediate yielded unexpectedly a different derivative of the mannitol.

We were successful in producing a rhamnose containing syrup. Extracting protein from Ulva using alkaline extraction was not successful.Ulva protein extraction needs further investigation and remains challenging. . The in vitro digestibility of the residues was substantially lower than digestibility of intact seaweed, presumably because of the removal of a relatively large part of the soluble and digestible minerals, proteins and carbohydrates by the extraction process and possibly because of an influence of the extraction process. Presumably, the lack of digestive enzymes to degrade the complex carbohydrates in seaweed is a major physiological cause of the relatively low digestibility of seaweed and residues.

We conclude that the three seaweed species used in this study had a moderate in vitro digestibility as compared to soya bean meal. The digestibility of the organic matter may be somewhat overestimated by the high solubility and digestibility of minerals as suggested by the difference between washed and unwashed seaweed. The digestibility of the residue is substantially lower, presumably because of the removal of a relatively large part of the soluble and digestible minerals, proteins and carbohydrates by the extraction process and possibly because of an influence of the extraction process. Presumably, the lack of digestive enzymes to degrade the complex carbohydrates in seaweed is a major physiological cause of the relatively low digestibility of seaweed and residues. The use of further processing, e.g. using exogenous enzymes may be rewarded to improve the digestibility. This requires further investigation.

10. Environmental and Governance challenges

10.1 Introduction

Given the fact that culturing of seaweeds does not require extra input of energy, nutrients, or other additives, it may form a sustainable alternative for other sources of energy, such as fossil fuels, for other types of biomass such as corn, meat and fish, and for chemically produced or otherwise harvested substances and products.

The North Sea is a highly productive sea, loaded with nutrients from land-based sources, both from natural and anthropogenic origin. Therefore, it has a high potential for the production of biomass, including seaweeds (van den Burg et al, 2013). In order to explore the possible environmental benefits of seaweed culturing in the North Sea, assessments are needed as proof of evidence. Paragraph 10.2. will provide a start in this environmental assessment.

The North Sea is also a highly crowded sea. Therefore culturing of seaweeds in the North Sea faces various challenges, including social, economic and legal challenges (Stuiver et al, 2016). In paragraph 10.3 we examine these governance challenges and give some recommendations how to deal with these challenges in the future.

10.2 Environmental challenges

10.2.1 Introduction

The whole seaweed value chain needs to be considered for the assessment of environmental impacts as illustrated in Figure 10-1. Whereas the installation, production and harvesting take place at sea, further processing is foreseen to be mainly land-based. Consequently, the interaction with the environment/ecosystem should be evaluated at different spatial levels, i.e. local and global.

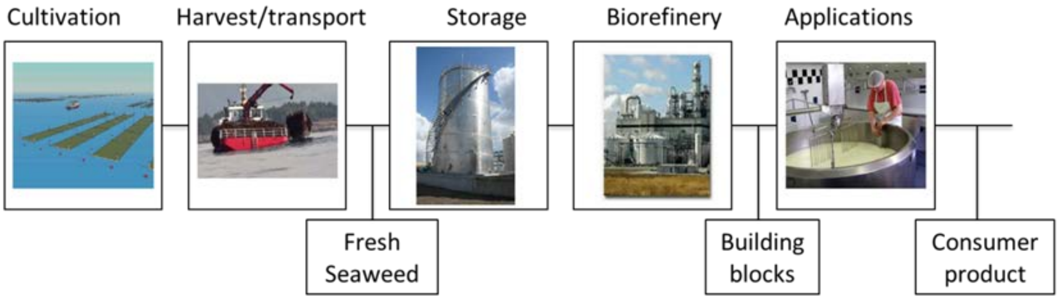


Figure 10-1 Seaweed value chain for the assessment of environmental impacts.

An assessment framework should be created including assessment criteria that can answer the following questions :

- How can we compare the culturing of seaweed in different areas on the basis of environmental criteria? What criteria could be used, and how should these be assessed?
- How can we compare the production of products derived from sea weeds with comparable products from other sources?

This latter question is particularly of interest for industries in order to assess the economic and ecological benefits of products derived from sea weeds in comparison to those derived from traditional sources. E.g. mannitol, a potential building block for bioplastics, is now mainly derived from corn. A comparison should therefore also include issues of concern for land based production (such as the use of fresh water resources) and those specific for marine production (such as transport at sea).

In order to answer the abovementioned questions, an assessment framework has to be developed, and relevant assessment criteria need to be selected and applied. For the assessment of environmental effects on specific ecosystems, such as the North Sea, methodologies for an Environmental Impact Assessment (EIA) can be applied (Tamis et al., 2015), while for the evaluation of products a Life-Cycle Assessment (LCA) approach seems most appropriate (ISO 14044, 2006). Not all impacts of seaweed culture on the ecosystem may be classified as negative, since seaweeds may provide various goods and services as well (Vásquez et al., 2014; Helmes et al., 2015). Ecosystem services provided by seaweed culturing should also be considered when assessing its environmental performance.

Environmental Impact Assessment (EIA) can be defined as the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made (IAIA, 1999). It is an important policy instrument for environmental management to regulate human activities with regard to their environmental and human impacts. In general, effects on the ecosystem from human activities are caused as a result of various pressures. Since various pressures, arising from different (sub)activities, affect ecosystem components (e.g. species, habitats) at the same time and space, effects may cumulate.

In a Cumulative Effect Assessment (CEA) approach, these environmental changes caused by a range of pressures are analysed in a systematic way (Tamis et al., in press). Effects occur when there is a spatial and temporal overlap in the occurrence of pressures and (potentially) affected ecosystem components. Therefore, a CEA applies to local situations, and for a defined period of time, whereas in an LCA approach the effects are formulated at a ‘global’ level (Figure 10-2).

Ecosystem components considered in risk assessment studies usually consist of species, although also habitats, ecological processes or ecosystem services may be taken into account. Whereas risk assessments and LCA mainly focus on the negative ecological aspects of human activities, an approach focusing on ecosystem services may also reveal positive ecological aspects related to the same human activities (see e.g. van den Burg et al., 2016).

Ecosystem services comprise various types (Millennium Ecosystem Assessment, 2005) including: production services, e.g. for seaweed as a source of food, feed or building component for other products; regulating services, such as targeting ocean acidification and carbon sequestration; cultural services, such as tourism and health; and supporting services like nutrient cycling and primary production.

When considering the effects of a seaweed production chain on the level of the (local) ecosystem an EIA / CEA approach seems most relevant in combination with ecosystem components that take into account both species (groups) and ecosystems services.

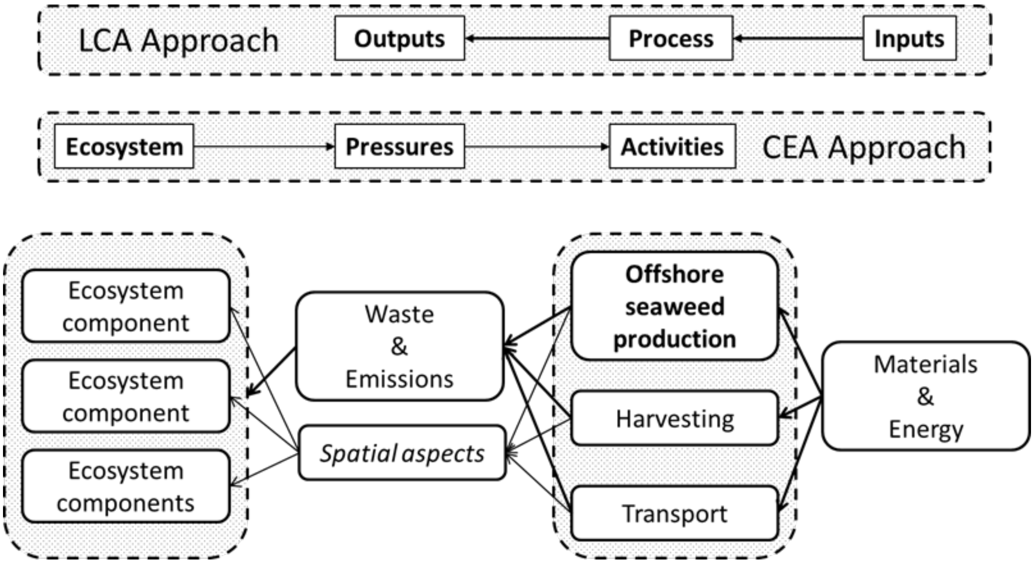


Figure 10-2 An integration of ecological impact assessments by a Life-Cycle Assessment (LCA) approach and a Cumulative Effect Assessment (CEA) approach. Spatial aspects refers to pressures at a local scale.

10.2.2 Seaweed as a sustainable alternative to other sources

Building blocks may be derived from seaweed that may serve as an alternative to those derived from agricultural products. This could potentially prevent environmental drawbacks related to land-based production. Land-cultured crops may cause ecological and environmental problems such as deforestation, eutrophication (Geist & Lambin, 2002; Daniel et al., 1994) and desertification (Danfeng et al., 2006). Since seaweed can be cultured in natural sea water, no addition of nutrients would be needed, and irrigation with fresh water can be excluded. Seaweed proteins may alleviate a growing demand of protein. It can be used as fish feed and further form an alternative to fish and meat, lowering the risk of overfishing and feed demand. Oils or biomass from seaweed could potentially replace fossil fuels in energy production (Demirbas & Fatih Demirbas, 2011). The comparison of these types of impacts can be performed by a Life-Cylce Analysis approach, taking into account resources of materials and energy, and outputs of energy and waste.

10.2.3 Environmental challenges of offshore constructions

Any structure placed in the sea will become colonised by marine organisms (Firth et al., 2014). Since the bottom of the Dutch North Sea consists mainly of soft sediments (EMODnet, 2015), constructions for sea weed production will provide an addition to the sparsely available hard-substrate and its specific flora and fauna (Zintzen, 2007; Coolen et al., 2015). This newly created substrate may be similar to shipwrecks and offshore energy devices, offering a habitat to similar fouling communities as those found on natural reefs. These communities also attract species of higher trophic levels, such as fish, birds and sea mammals. Van Hal et al. (2012) found higher densities of a.o. horse-mackerel and cod in the surroundings of monopiles of windturbines, while lower abundances were observed of flatfish and whiting. Constructions could also provide a habitat for unwanted exotic species. However, the contribution of added constructions to the total amount of hard substrate is small. Artificial substrates could also facilitate source populations and stepping stones for opportunistic or even invasive species to spread and enter seaweed communities on natural substrates (McKindsey et al., 2011).

Other impacts of the presence of constructions at sea are the reduction of current speed and dampening of waves. It is yet unclear what kind of ecological effects these changes may cause directly, but indirectly habitat characteristics may be affected, including sedimentation rates, sediment grain size composition, and light penetration. These types of ecological impacts will strongly depend on local environmental and ecological conditions and the dimension and configuration of culture sites. Effects are considered to be small, because they are very localised.

Depending on the type of structure used, additional piling are other kind of anchoring may be needed. This activity may cause temporal and reversible short term pressures and their effects, including noise disturbance to marine mammals and fish, displacement of mammals and seabirds and damage to seabed communities (Lindeboom et al., 2011, Degraer et al., 2012).

10.2.4 Environmental challenges of offshore seaweed production, harvest and transport

As primary producers, seaweeds compete for nutrient resources with naturally present producers, such as micro-algae, seagrass and natural seaweed communities (Furuya, 2004). In cases where nutrients are limiting growth of primary producers, seaweed production may reduce the carrying capacity of the (local) ecosystem. In North Sea coastal waters however, nutrients are available in excess, even causing eutrophication problems (Troost et al., 2014). This especially relates to the formation of spring blooms of micro-algae that profit from high winter nutrient concentrations. Therefore seaweeds produced during winter could benefit from these high nutrient concentrations and mitigate the problems caused by these (van den Burg et al., 2016).

As primary producers, seaweeds take up carbon dioxide (CO_2), and convert it to biomass and oxygen. The uptake of CO_2 lowers CO_2 concentrations in water, which also results in enhanced pH level (Chung et al, 2011). Seaweeds could thus contribute to a reduction of the risk of elevated global CO_2 levels, and reduce the risk of acidification in local water bodies. Drawbacks of high biomass levels is the oxygen consumption rate during night time, which could result in oxygen stress to local (benthic) communities, especially where water exchange rates are low. In addition, where seaweeds are lost from the production site, they may settle to the sea floor causing organic enrichment of the sediment and resulting in changes to the benthic community (Rossi et al., 2013).

Natural seaweed communities can support high biodiversity through structuring complex habitats for associated species, including invertebrates and (juvenile) fish that may find their food and refuge and vertebrate predators, including large fish, birds and sea mammals that are attracted by increased food levels.

Harvesting and transport involves the presence of boats and people, the generation of noise, and potentially the production of waste material (litter). Boats further emit greenhouse gasses to the atmosphere, but these are unlikely to cause impacts at a local scale. Studies on offshore mussel cultures have demonstrated that effects of boat activities are minor or absent (Cheney et al., 2010), but depend on the type of boats used and on the production system applied.

10.3 Governance challenges

10.3.1 Introduction

As there are different competing claims on the space in the North sea by other marine activities and infrastructures in the so-called Blue Growth agenda, (European Commission, 2016) a series of governance challenges for the development of seaweed activities can be identified in The North Sea; the social challenges, economic challenges, and legal challenges.

10.3.2 Social challenges

Seaweed farming in the North Sea started in the beginning of the 20th century with a network of entrepreneurs that aimed to explore the potential of sea weed for different purposes. With the development of offshore wind energy farms in the North Sea the stakeholders felt the momentum had arisen to bring their wishes forward to the policy domains and proposed to combine seaweed with other functions such as wind energy in the form of multi-use combinations at sea (Stuiver et al, 2012, Rockmann et al, 2015a). The wind energy platforms could be ideal for seaweed farming. The EU started subsiding several research projects such as Mermaid, Tropos and H2Ocean (Mermaid 2015) and the Dutch Ministry started a programme called KB Triple P at Sea (van den Burg et al, 2013). There was ten years ago still a lot of knowledge lacking, such as optimal growth conditions and what varieties would be most competitive. This implied that the development and implementation of the potential of seaweed farming in the growing network went hand in hand with the development of the research and innovation network over the years (Gerritsen et al, 2016).

For the future actors should make use and take advantage of the knowledge and experience gained in these different projects. These projects have conducted research, involving different stakeholders, sharing and increasing their knowledge as well as expressing their views regarding the difficulties with the development and implementation of seaweed production, fish farming, wind farming on multi-use platforms (Rockmann et al, 2015b). It is recommended to get familiar with this knowledge. This helps taking into account a variety of institutional, technical, environmental, financial and socio-economic aspects in maritime spatial planning and for developing policy instruments that can support the development, implementation and running of new economic activities at sea (Stuiver et al, 2016).

One of the challenges of these different projects is to engage different stakeholders in the process. Diverse knowledge and competences, as well as different responsibilities are spread out by several stakeholders capable of affecting the policy making process that is required for planning and developing future activities. Important stakeholders are business partners and the potential future developers, environmental authorities, local or regional administration, relevant professional associations, local NGOs, and research institutes (Van den Burg et al, 2016). Stakeholders can provide the process with crucial information for its success: “Transparency, clear and close communication with stakeholders and promotion of good governance practices are essential”. The involvement of stakeholders in this policy making process will contribute to the project’s societal legitimacy. Shared knowledge and experience can contribute to the design of more efficient, reasonable and sustainable policies for the new activities (van den Burg, 2015b).

10.3.3 Economic challenges

In the Netherlands there are already several examples of market parties taking initiatives to develop seaweed production (Van den Burg et al, 2014). For example, the Dutch offshore aquaculture sector is in the beginning of a new development. A transition phase to more offshore cultures has started, probably triggered by indications that the market potential for mussels might be twice the current market. The potential for seaweed cultivation, not only for food and health care products, but also for plastic products, indicate an increasing need for large quantities However, the financial and economic feasibility of large scale Dutch offshore seaweed production is unclear and is dependent on the future development of demand and the potential of co-use synergies (ibid).
However, stakeholders show scepticism against the financial feasibility of combining offshore mussel and seaweed farming with wind energy (Rasenberg et al, 2014), in particular because wind energy operators are presently reluctant to share their allotted space with other operators due to the risks associated with multiple use, which could have an influence on insurance premiums. The uncertainty of a business case is illustrated by the negative profitability of seaweed cultivation and the uncertain profitability of mussel farming at The North Sea case study. However, especially the case for mussels could become financially feasible if reductions on operational and maintenance expenditures can be obtained, e.g. through substantial synergies with other uses (Jansen et al, 2016).
A major concern in the market is reliability and normalization of products and production processes. Standardization of products is required to ease market transactions as it helps to align sellers and buyers of seaweed products. In the European context, normalization of seaweed is developed in the CEN working group BT/WG 218. The co-use of offshore wind parks by seaweed growing companies will require an assessment of risk and development of safe operating practices to make sure that insurance companies can insure businesses.
It is recommended to create mechanisms for financial support to make the investments attractive to developers. Similarly to what generally occurs in land-based innovative technological projects, the start-up of

seaweed farming comes with substantially higher investment costs and risks compared with business-as-usual projects. Under current conditions, governments should "use subsidy only as a means to start activity, not to maintain activity (Van den Burg, 2015b). There must be a long term business case without subsidy".

Recommendations include the development of financial mechanisms to support the start-up of offshore multi-use platforms that combine seaweed production with other functions such as windfarms, to avoid the "Valley of Death". Financial support should benefit pilot projects on the short and medium term to enable investments in the long term. It is advised to avoid subsidies in the long-term, as multi-use platforms should be economically viable in the long-term. Additionally, multi-use platforms should be able to compete with "conventional" producers if site conditions are good enough (ibid).

10.3.4 Legal challenges

Legal challenges are that at present there is no clear regulatory framework in the Netherlands although the Dutch government is taking the lead in a reconsideration of regulations (Ministry of Infrastructure and Environment, 2015, Noordzeeloket, 2015). Energy companies have and will build various offshore windfarms but an offshore aquaculture sector is still in its infancy. Consequently, policy-makers and regulators have not yet been substantially challenged to handle requests for permits, and subsidies and a regulatory framework are missing. Also, there is no area designated for aquaculture in the Dutch spatial plans for The North Sea. Current practice for offshore windfarms is to forbid other vessels to enter the designated parks, thereby avoiding question about risks and responsibilities, though the Dutch government is currently investigating the risks of opening up the windfarms to free passage and shared use (van den Burg, 2015b).

The recommendation is to assure protection of the marine ecosystem by licensing procedure based on site-specific environmental studies and guaranteeing the implementation of an environmental monitoring system in the designated areas. In order to understand if and how the environment is being affected by the project, and to avoid, minimize and eventually offset the adverse significant negative impacts, an environmental monitoring program is necessary (van den Burg, 2015b). Since the North sea is an intensely used sea, aquaculture activities should fit with other user functions (Jansen et al, 2016.). A feasibility assessment therefore not only requires an environmental assessment, but also a governance approach, led by the responsible authority for spatial management. A feasibility study for sea weed culturing for different locations in the North Sea, has to include other user functions and environmental considerations.
The environmental monitoring system could focus on issues such as e.g. spreading of invasive species, biodiversity, underwater noise and electromagnetic radiation, water pollution, along the lifetime of the project, preceded by environmental baseline studies. Minimizing environmental impact and continued monitoring should not be seen as burden, instead, they contribute to the social license to operate (van den Burg et al, 2015).

10.4 Concluding words

Natural seaweed has various ecosystem services; enhancing biodiversity, fixation of CO_2, reduction of nutrients, production of oxygen and sheltering for organisms. Seaweed production by cultivation plants has the potential to solve public problems such as the transitions to sustainable protein and non fossil energy and commodities for a biobased economy. For a successful development of a seaweed value chain a strong cooperation is needed between various entrepreneurs and stakeholders. There is also a role for governments to play; to select the right mix of legal, environmental, social and economic incentives to encourage businesses to take up the initiative, as the example of the EU financed project Maribe shows. MARIBE is a HORIZON 2020 project exploring cooperation opportunities for companies that combine different Blue Growth and Blue Economy sectors. (Maribe, 2016). Government can furthermore facilitate the development of seaweed production by overcoming obstacles in legislation (Stuiver et al, 2016) and enhancing the sustainable exploitation of the sea by environmental legislation (ibid). The key question is if governments give sufficient weight to global concerns such as food security and global warming to justify a greater role of public authorities in the development of these type of activities (Van den Burg, 2015a).

We end this part by six recommendations:

- Standardization of products is required to ease market transactions as it helps to align sellers and buyers of seaweed products. In the European context, normalization of seaweed is developed in the CEN working group BT/WG 218.
- The co-use of offshore wind parks by seaweed growing companies will require an assessment of risk and development of safe operating practices to make sure that insurance companies can insure businesses.
- Create mechanisms for financial support to make the investments attractive to developers. Under current conditions, governments should "use subsidy only as a means to start activity, not to maintain activity. There must be a long term business case without subsidy".
- Include the development of financial mechanisms to support the start-up of offshore multi-use platforms that combine seaweed production with other functions such as windfarms, to avoid the "Valley of Death".
- Financial support should benefit pilot projects on the short and medium term to enable investments in the long term. It is advised to avoid subsidies in the long-term, as multi-use platforms should be economically viable in the long-term. Additionally, multi-use platforms should be able to compete with "conventional" producers if site conditions are good enough (ibid).
- The last but not least recommendation is to assure protection of the marine ecosystem by licensing procedure based on site-specific environmental studies and guaranteeing the implementation of an environmental monitoring system in the designated areas.

11. Economic Feasibility

11.1 Introduction

This chapter presents the results of the study into the economic feasibility of the production and processing of seaweed. This study was done in two steps. The first step assessed the costs of seaweed cultivation on the North Sea. An economic model was built able to estimate current production costs and calculate the economic consequences of several different methods of seaweed cultivation. This economic model includes all activities required until the seaweed is unloaded onto the harbour quay, as shown in *Figure 11-1*.

In the second step, the market value of the seaweed was calculated. A lot of interest goes out to the possibilities to increase the market value of seaweed by fractionating the raw materials into the valuable chemicals in a bio refinery. The sum of values of these products, minus the costs of the chemical process, is an indication of the maximum price to be paid for the raw seaweed.

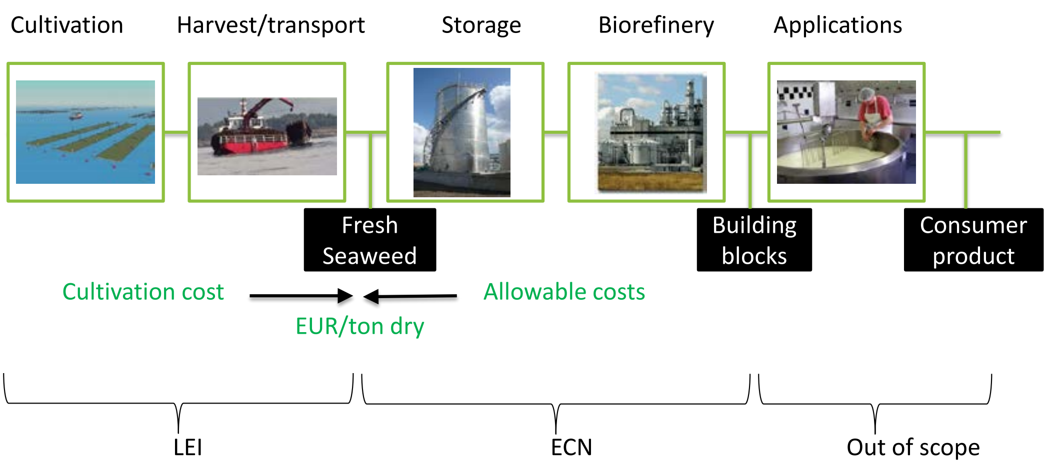


Figure 11-1 the seaweed chain studied

11.2 Seaweed production costs

11.2.1 Introduction

Seaweed aquaculture is common practice in many parts of the world and more than 90% of seaweed used comes from aquaculture[4]. Contrary to this, European seaweed is heavily based on the collection of natural seaweeds, either through active harvesting or collection of seaweeds washed ashore.

In recent years, various initiatives have emerged to cultivate seaweeds in the European waters. These can be seen along the entire Atlantic coast, including North Sea, with examples in Norway, Denmark, Germany, Netherlands, France and Portugal. In the United Kingdom and Ireland, initiatives to cultivate seaweeds are also witnessed.

[4] See FAO Fishstat at http://www.fao.org/fishery/statistics/software/fishstat/en (last accessed 25-11-2015)

Various production systems can be identified, from tanks and ponds to the near-shore aquaculture in combination with fish farming – the so-called IMTA system (Integrated Multi Trophic Aquaculture; Troell et al. 2009; Abreu et al. 2011). This study is focussed on stand-alone offshore aquaculture of seaweeds and does not focus on combinations with for example fish farming or offshore wind energy (for more information on this combination see for example (Buck and Buchholz 2004; Lagerveld et al. 2014),.

11.2.2 Conceptual system design

In the model three different production systems are taken into consideration.

1. The longline system as described by van den Burg et al (2013, 2015). It consists of floating longlines with growth lines hanging down. In this system very high yields per ha of sea can be reached, as the longlines and growth lines can be situated quite close to each other.
2. The MACR system, which is currently used near the Faroes Islands and described by Gregersen (2015) and uses floating longlines below sea level. The growth lines are fixed on the long lines, hold up by small buoys. This is an extensive system. The mutual distance between the longlines is dozens of meters, simplifying crop care and harvesting.
3. A third system resembles the longline system, but is more suited for growing *Ulva Lactuca*. Instead of growth lines in this system bags or cages are used in order to protect the Ulva against the influences of rough seas.

11.2.3 Model description

A model was built to estimate the production costs of seaweed. The objective of the model is to gather and structure the available information, to calculate the production costs per ton seaweed and to assess the contribution of the several cost items to the cost price, depending on different input parameters.

The model includes the next items:

- Main farm characteristics, where a choice can be made between several farm sizes, locations, installation systems and seaweed species.
- Seaweed production data: the most important data of the weeds are put in, e.g. yield, dependences of the circumstances during the growing cycle and the costs of the seed lines.
- The installation for seaweed production. For each production system, the model aims to present the total investment in anchors, buoys, long lines, growth lines and installation costs. The costs depend on the farm size.
- The machinery data: The most important machines are combined planting and harvesting machines, passenger boats and passenger cars. The size and amount of the machines are related to the size of the total system.
- Location: two locations are defined. One location is assumed to be situated in open sea and the other one near-shore.
- Transport, which describes the costs from the harvest up to the quay including harbour fees, transhipment costs. It is assumed transport ships and cranes are rented.
- Other cost, like labour, administration, accountancy, any duties, assurances, crop protection and interest.

11.2.4 Input parameters

Appropriate data for the model input parameters is scarce for several reasons. There are hardly any practical experiences with seaweed cultivation in open sea, beyond experiments. From the few commercial production plants, details on the technologies and on costs are not public. Available information relates to relatively small seaweed production facilities. Table 11-1 shows the main data sources for the input parameters.

Part of the model	Items	Source
Seaweed data	Yields, expressed in kg fresh weight (FW) per m growth line Costs of seed lines	Brandenbrug (2015, Pers. comm.) Chapter 4 of this report. Gregersen (2015) Gregersen (2015)
Seaweed installation	Longline system Longline system MACR system Cage system	Van den Burg et al (2013) Brandenbrug (2015, Pers. comm.) Ólavur Gregersen (2015) Brandenbrug (2015, Pers. comm.)
Machinery data	Equipment for planting and harvesting	Gonzales, MTI (2015, pers. Info)
Transport	Costs for ship rentals, fuel etc Costs for harbour duties Costs for transhipment	Amasus Shipping (pers. Info) Rotterdams havenbedrijf Europees Massagoed Overslag
Labour costs	Labour costs Required number of workers for planting and harvesting Required number of workers for other activities	Intermediair, Loonwijzer Gonzales, MTI (2015, pers. comm.) Own calculation
Other costs	Crop protection, any duties	Own estimates

Table 11-1 Sources of information used to collect input parameters

The life-span of the systems is initially set at 6 years. In the base scenario, it is assumed there is one harvest per year.

11.2.5 Output and scenario analysis

The costs of production are calculated for different scenarios. The base scenario comprises a production size of 200 kton fresh weight per year on a fictitious open sea location situated 50 km from the transhipment harbour.

For the production of *Saccharina latissima* five scenarios are analysed:

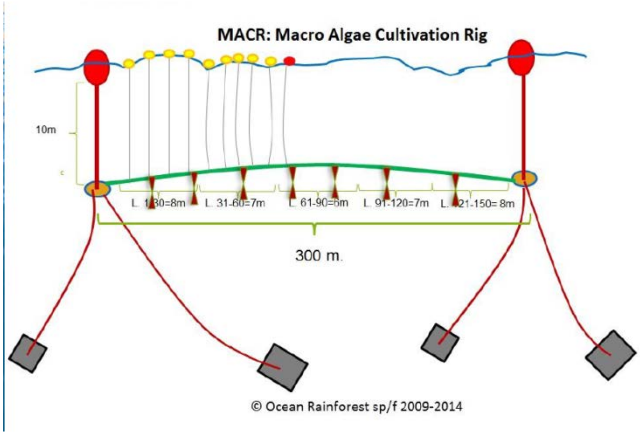


Figure 11-2 A construction as used by Ocean Rainforest on the Faroer Islands

S.1. We started with a relatively simple case, in which *Saccharina latissima* is cultivated by the MACR system, with longlines situated 50 m from each other. On every two meters of the longlines 10 meter growth lines are connected. In spring the seed lines are (See Figure 11-2) connected to the growth lines and in the autumn the complete growth lines are harvested. In wintertime the system is not in production. Figure 11-3 shows that the total costs are calculated at €1.230 /ton FW (= €9.400 /ton DW[5]). The system is extensive; a plot area of 25,000 ha is needed for the production of 200 kton FW.

S.2. In this scenario, the longline system is used, with distance between of the longlines reduced to 1 meter. In order to prevent the growth lines from entwining the length of the growth lines is reduced to 3 meters. In this scenario only 1,900 ha plot area is used. The cost price is slightly higher than in scenario 1. The biggest cost items are the seed lines (50% of the costs) and the installation (42% of the costs).

S.3 . In scenarios (1) and (2), the life span of the installation is assumed to be six years, in accordance to the calculations of Gregersen (2015). In order to reduce the installation cost the total life span of the installation described in scenario 2 is extended to fifteen years, according to the figures given in Table 8-2. The model calculates a cost price of €1.050/ton FW (= €8.000 /ton DW).

S.4. This scenario seeks to reduce the costs for the seed lines. In the MACR system, there is experience with 'mowing' the *Saccharina latissima* rather than 'cutting' in. This has two benefits: (1) the seed line can be used for three years instead of one and (2) the average yearly yield turns out to be higher. We assumed this practise can be copied to the longline system without any problems. The cost price is significantly reduced to €320/ton FW (= €2.500 /ton DW).

S.5. It is expected that in the seed line production can be done more efficiency (Brandenburg, pers. communication, 2015). If the costs of seed lines are reduced by 50%, the calculated cost price will drop to €270/ton FW (= €2.050 /ton DW).

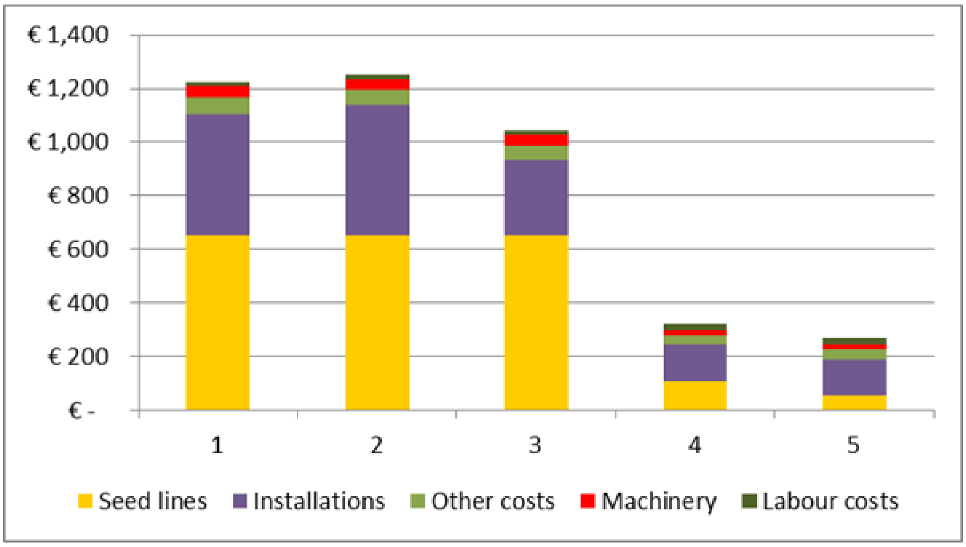


Figure 11-3 Cost structure of large scale Saccharina latissama production in five different scenarios (in €/ton$_{FW}$)

[5] Based on %dm in table 12.2

For the production of *Ulva sp.* three scenarios are calculated and summarized in Figure 11-4 :

U.1. The base scenario is based on the cage system, with a life span of the installation of six years and a price of €3.80 per meter seed line. Like *Saccharina latissima* the most important cost items are the installation costs and the costs for the seed lines. The total costs for the production of Ulva in this scenario add up to € 920/ton FW (= €4.400 /ton DW).

U.2. Extending the installation life span to twelve years, would reduce the cost price to € 800/ ton FW (= €3.800 /ton DW).

U.3. Halving the price of the seed lines has a significant positive effect on the cost price of Ulva sp. production. It is reduced to € 570/ton FW(= €2.700 /ton DW).

11.3 Seaweed valorization

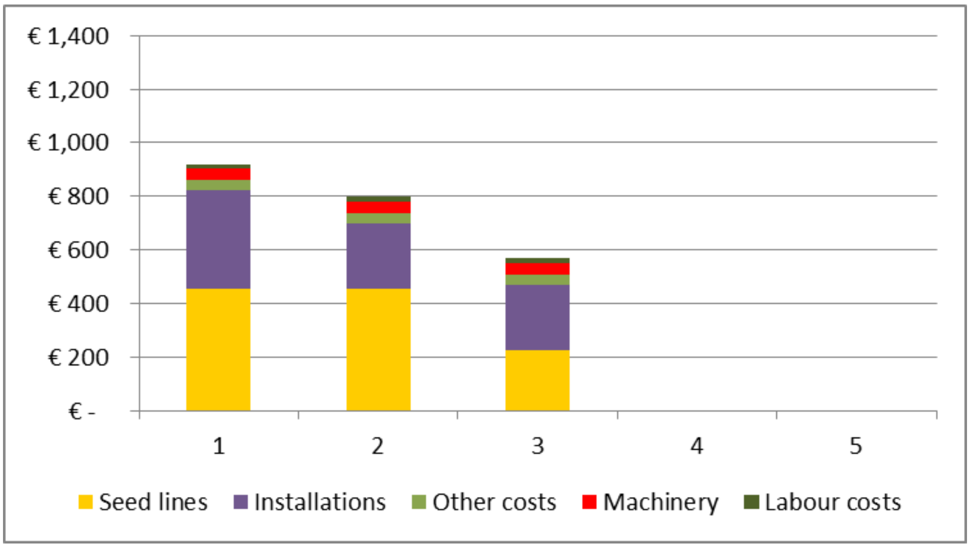


Figure 11-4 Cost structure of large scaled Ulva sp. production in four different scenarios (in €/ton$_{FW}$)

11.3.1 Introduction

Seaweed is valorized into marketable streams of building blocks that can be used for a large variety of applications in the consumer and industrial markets. For this the seaweed is fractionated into its main constituents in a biorefinery following a cascading biorefinery approach (Van Hal et al., 2014). Such biorefineries make for the large part use of conventional operations currently used in the chemical and food industry, yet the design of the configuration and unit operations themselves is novel. The overall block scheme of a seaweed biorefinery will depend on the seaweed type targeted products. The work done here aimed to get insight in economically promising combinations of target products and seaweed type. A high-level approach was applied, looking at the potential value from product streams and at the cost structure of seaweed processing. This can then serve as a basis for selecting cases for a more detailed design and evaluation of seaweed biorefinery schemes.

The focus is on two seaweed types: *Saccharina latissima* as an example of brown seaweed and *Ulva sp.* as an example of green seaweed. For both types potential products are selected, and a conceptual process design was made for a biorefinery plant for two sizes a small plant at 2 $kton_{dw}$/yr (dw=dry weight basis) and a large industrial scale plant of 200 $kton_{dw}$/yr. Based on a mass balance the value of products, the economics of the seaweed processing are evaluated. The results are presented in terms of allowed costs for seaweed feedstock for a biorefinery to be economically feasible. Special attention is paid to the impact of seaweed storage on economic feasibility.

11.3.2 Conceptual process design

The sugars, organics and inorganics in seaweed can be used for a variety of products for application in the chemical industry, food industry, energy applications and for minerals production. For this project a selection was made focussing on the main constituents of seaweed.

For both seaweed types, products targeted are:

- Proteins for application in human or animal food applications
- Fertilizer, making use of the nutritive value of mostly potassium and phosphate present in the seaweed

Specifically for *Saccharina latissima* the following products are targeted additionally:

- Alginate, a thickener that has a wide variety of applications in the food industry, paint industry and chemical industry.
- Laminarin, a polysaccharide of glucose that, after hydrolysis can be used as a replacement for sugars for fermentation processes.
- Mannitol is a sugar alcohol that is commercially used in the production of polyols, or as sweetener in food applications
- Biogas from fermentation, which can be used as a fuel for heat of power applications

Specifically for *Ulva sp.* the products targeted additionally are:

- Rhamnose, a specialty sugar that is used in functional foods
- ABE, a biofuel mixture of acetone, butanol and ethanol.

The conceptual process scheme for processing for the processing of *Saccharina latissima* is depicted in Figure 11-5. Wet seaweed from the storage is fed to a size reduction unit and the extractable sugars (mannitol and laminarin) are removed by hot water extraction. The solids fraction goes to a black-box protein removal process. The alginates are obtained as sodium alginate through reaction with sodium carbonate. A second protein fraction is removed through filtration. From the sugar stream laminarin is removed by membrane filtration. Mannitol is obtained through crystallization. The remaining constituents are sent to a digester for production of biogas and the inorganics are concentrated by a reverse osmosis membrane to obtain a liquid fertilizer feedstock stream.

Some uncertainties in the process design remain. The feasibility of protein separation is unsure and is modelled by a black-box approach. For the mannitol separation, now an evaporative crystallizer is foreseen, but the energy demand might call for an alternative solution.

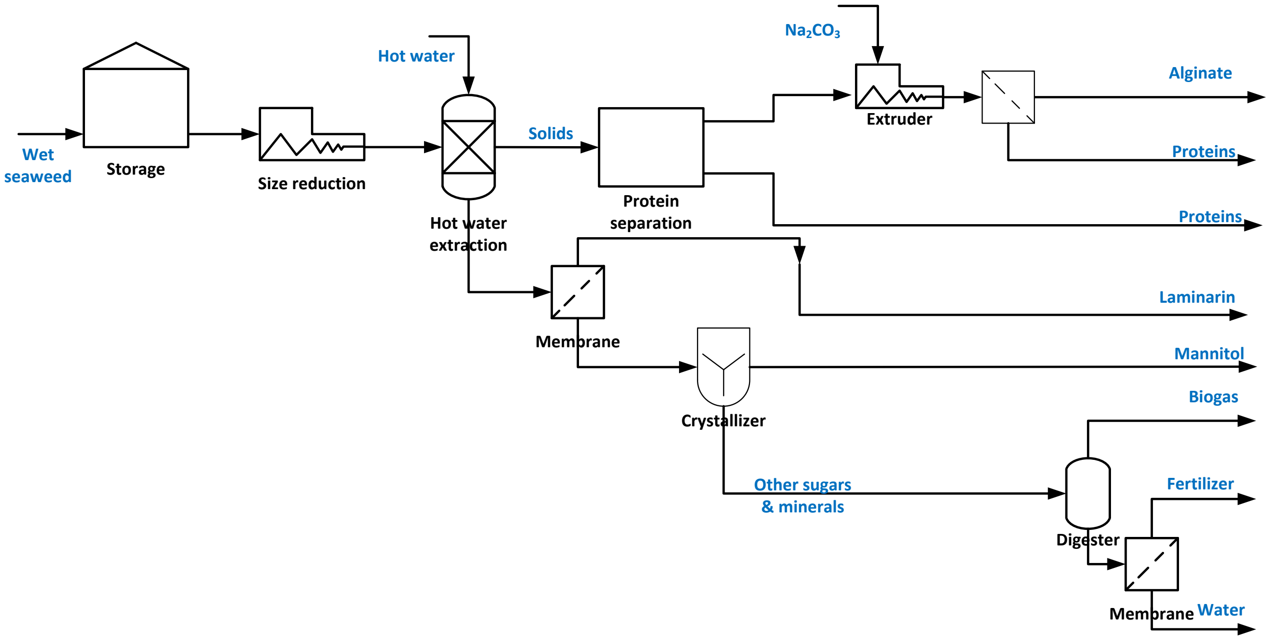


Figure 11-5 Process scheme Saccharina latissima

Figure 11-6 *Process scheme Ulva sp.*Figure 11-6 depicts the conceptual process scheme for processing of Ulva sp. After size reduction the first step is protein separation. The sugars are hydrolysed by acid, here hydrochloric acid is selected but sulphuric acid might be an alternative. After neutralization with sodium hydroxide, the rhamnose is removed by a simulated moving bed reactor (SMB). The organics are then used for the production of ABE by fermentation. ABE is concentrated by distillation and fertilizer feedstock is produced by reverse osmosis.

Uncertainties in this process are again the feasibility of protein removal. The SMB is existing technology but is known to have high investments.

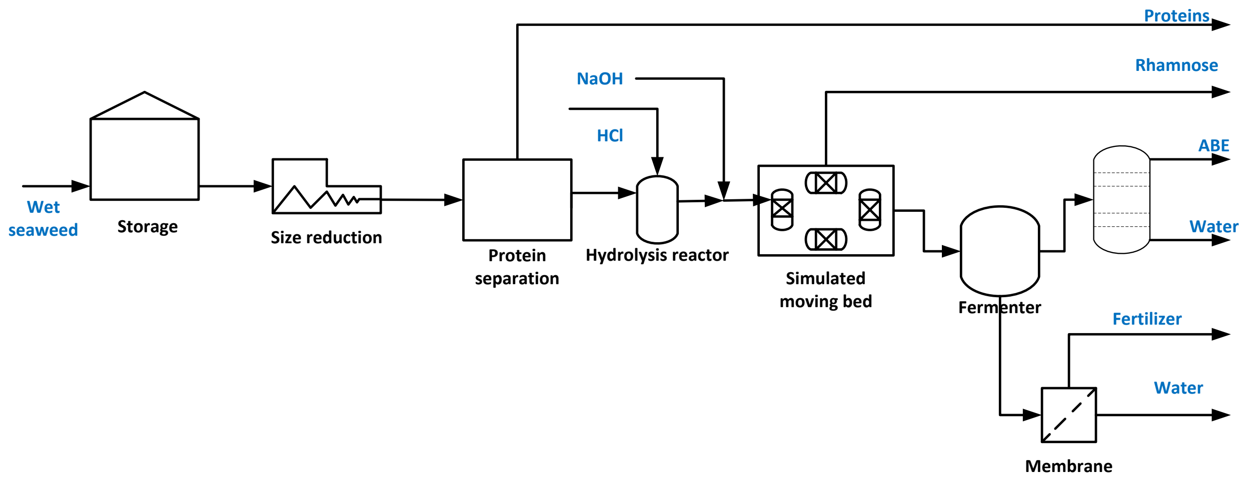


Figure 11-6 Process scheme Ulva sp.

11.3.3 Model description

Based on the conceptual process designs a process economic model has been developed. The model calculates the costs of seaweed production from the sales benefits and production costs. The model makes use of a standardized method for assessment of economics of chemical processes (Seider, 2004). Elements of the model are the following;

- Seaweed compositions taken from literature. If multiple literature sources were available, the average value was taken. Seasonable variations, which can have a large impact on composition, have been disregarded.
- A mass balance based on assumed yields from the fractionation process. The heat use of the process has been simplified into a 10% demand for total utilities in the process, which needs to be verified with a detailed process design.
- Market values for pure product streams and consumables, taken from literature and from an ECN in-house database.
- An estimation of the capital investments of the process based on the conceptual process designs discussed above. The sizing of the main equipment is done using feed/product mass flow rates. The bare equipment costs are calculated using literature and in-house data, and applying a Williams-rule for power law for scaling. The total plant capital investments are obtained applying cost factors for direct costs per unit operation and overall cost factors for indirect costs to arrive at the total capital investments of the biorefinery. The factors used are for the most taken from (Seider, 2004).
- Calculation of the capital cost (CAPEX) and operational costs (OPEX) based on standard financial parameters.

The model calculates the allowed seaweed cultivation costs, targeting the break-even point benefits for sales of products and all costs of processing including tax and a target Return on Investments.

11.3.4 Input parameters

The main input parameters to the model are listed in Table 12.2. In general the parameters can be considered realistic (seaweed composition, costs of bare equipment, financial parameters, market values) or optimistic (product yields, operating costs, surcharges for total capital investment, unlisted equipment, contingency, Return on investment target). Since the process design has little details and many unknowns and is likely to be more complex in reality, an unlisted equipment entry has been added, estimated at additional 20% on process equipment (excluding storage and protein separation). The protein separation has been modelled by a black-box which has very uncertain investment costs.

	Composition Saccharina lat. (% mass$_{dw}$)	Composition Ulva sp. (% mass$_{dw}$)	Yield (% mass$_{dw}$)	Sales value (EUR/ton$_{dw}$)
Proteins	12%	24%	90%	800
Alginate (to sodium alginate)	22%	0%	91%	3000
Mannitol	12%	0%	95%	1750
Laminarin	16%	0%	95%	650
Rhamnose (precursor)	0%	10%	95%	550
Minerals (to fertilizer)	32%	30%	95%	100
Residual organics (to methane)	40%		21%	416
Organics (to ABE)		60%	35%	1000
Dry weight content (%mass)	13%	21%		

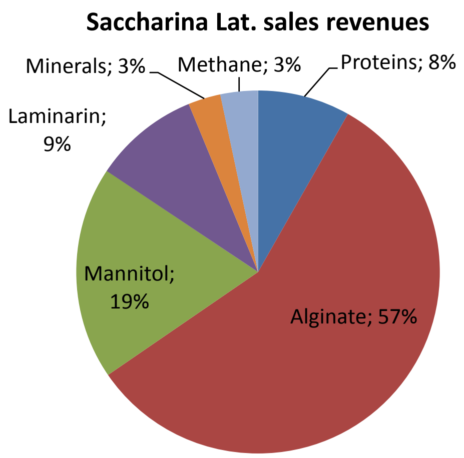
Table 11-2 Model input parameters: All input parameters are based on literature data (Holdt & Kraan, 2011; van den Burg et al, 2013) and can differ from experimental findings reported in Chapter 4.

Financial parameters include a 15 year depreciation period, 25% tax and 10% return on investment (ROI). Operating and utility costs are assumed 10% of the total feedstock costs.

11.3.5 Output and sensitivity analysis

Figure 11-7 depicts the distribution of sales revenues from the targeted products, which is valid for both the 2 $kton_{dw}$/yr and 200 $kton_{dw}$/yr cases. The main contribution in *Saccharina latissima* is from alginate and mannitol. The price of alginates is known to be very dependent on quality and thereby application of the alginates. For this analysis the price of 3000 EUR/ton is for sodium alginate for medium quality applications.

For the Ulva case, ABE has the highest contribution. Proteins have a higher relative contribution than in *Saccharina latissima*. both because the protein content is double that of *Saccharina latissima*, but also because the total sales of *Ulva sp*. are around 50% lower than those of *Saccharina latissima*. (See table 12.2).



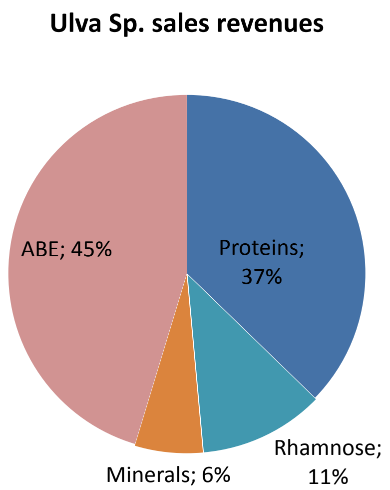


Figure 11-7 Distribution of sales revenues processing of Saccharina latissima. (left) and Ulva sp. (right).

For determining the capital investments one very important aspect addressed is the storage period for seaweed. Assuming that there are no technical limitations to storage of seaweed, the objective here is finding a balance between costs for storage costs versus plant investments. From figure 12.7 it is seen that increasing the period over which seaweed is stored, the storage costs increase but the plant size significantly decreases because the same yearly harvest can be processed over a longer time. The optimum is dependent on the relative share between storage and plant costs, and on the scaling factors for both. For *Saccharina latissima* the optimum found is at 7.0 months, whereas for *Ulva sp*., which has relatively lower plant investments the optimum is at approximately 3.9 months of storage time.

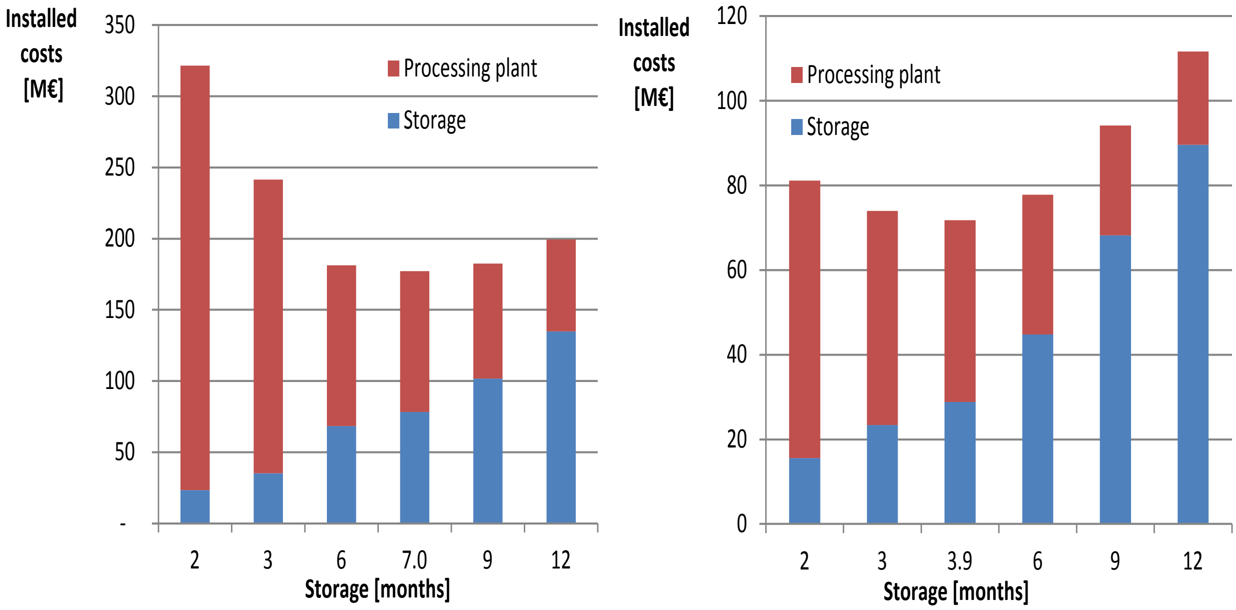


Figure 11-8 Impact of seaweed storage period, 200 kton$_{dw}$/year feed plant size

A breakdown of the total installed costs for both plants at the optimal storage size as presented in Figure 11-9 shows that the share of conventional equipment such as grinders, extruders, reaction vessels is relatively low compared to those of more special equipment such as membrane units, SMB, and protein separation. The modular characteristics of membrane units make that the relative share of membrane units is larger for the large-scale case.

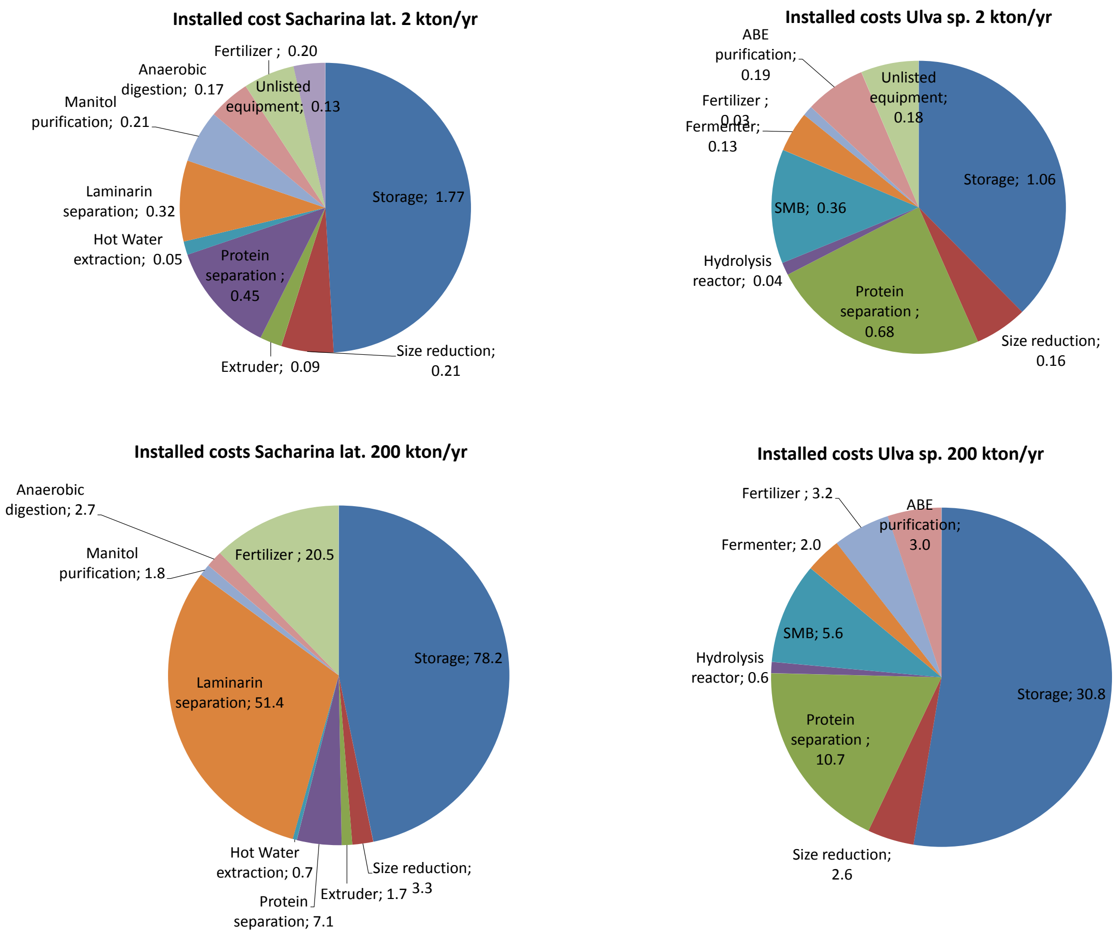


Figure 11-9 Installed costs break-down in MEUR at optimal storage time (7.0 months for Saccharina latissima, 3.9 months for Ulva sp.)

The overall financial performance of all cases is depicted in Table 12.3. For the small scale case at 2 kton$_{dw}$/yr feed the size and investments of process equipment are small, which makes that the methodology used, which is for much larger chemical plants, is less suited. For *Saccharina latissima*, product sales outweigh production cost, for *Ulva sp* this is not the case. Taking into account the depreciation and return on capital, there is no positive business case for both small scale plants, even at zero price of seaweed. For the large scale cases, the allowed seaweed costs for *Saccharina latissima* are 456 EUR/ton$_{dw}$ and for *Ulva sp* 263 EUR/ton$_{dw}$. The investments for the *Saccharina latissima* plant are over 3 times as high as for *Ulva sp.*, but higher product sales compensate for this.

		Saccharina latissima 2 kton/yr	*Ulva sp.* 2 kton/yr	*Saccharina latissima* 200 kton/yr	*Ulva sp.* 200 kton/yr
Investments					
Installed equipment cost	MEUR	3.6	2.8	177	61
Total depreciable capital	MEUR	5	4	256	90
Total capital investment	MEUR	**7.7**	**6.1**	**372**	**131**
Production costs					
Raw materials	MEUR/yr			104	53
Depreciation	MEUR/yr	0.4	0.3	20	7
O&M and plant overhead	MEUR/yr	1.3	0.7	36	15
Total production cost	MEUR/yr	**1.7**	**1.1**	**161**	**75**
Sales					
Proteins	MEUR/yr	0.17	0.35	17	35
Alginate	MEUR/yr	1.20		120	
Mannitol	MEUR/yr	0.40		40	
Laminarin	MEUR/yr	0.20		20	
Rhamnose	MEUR/yr		0.10		10
Minerals	MEUR/yr	0.06	0.06	6	6
Methane	MEUR/yr	0.07		7	0
ABE	MEUR/yr		0.42		42
Total product sales	MEUR/yr	**2.1**	**0.93**	**210**	**93**
Cash Flow	MEUR/yr			57.7	20.3
Pay out time	Year			4.4	4.4
ROI	%			10%	10%
Allowed seaweed costs	EUR/ton_{ww}	<0	<0	59	55
Allowed seaweed costs	**EUR/ton_{dw}**	**<0**	**<0**	**456**	**263**

Table 11-3 *Summary of seaweed processing financials.*

Figure 11-10 depicts the sensitivity of the allowed costs for seaweed to the starting points. An estimate has been made on the uncertainty range of input parameters, which are presented as a percentage relative to the base case value. For *Saccharina latissima* the highest impact is by feedstock sales, especially by those of alginate. Also for *Ulva sp.* the product sales values are most important, but variations are less pronounced in absolute terms. For both processes, capital related factors have a significant impact, but are less pronounced than those of the sales revenues.

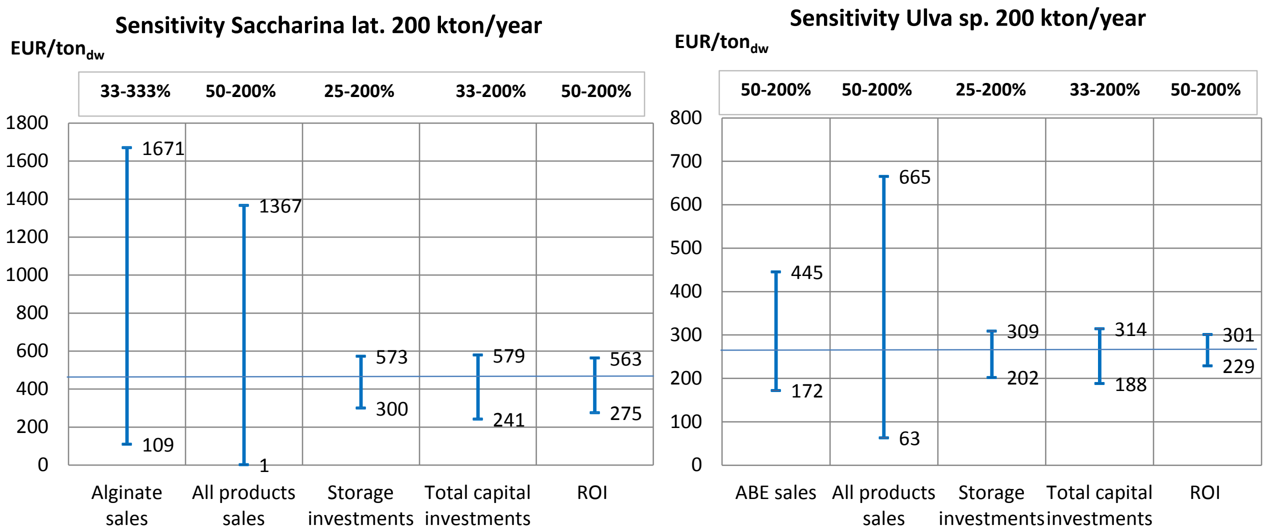


Figure 11-10 Sensitivity analysis seaweed processing. Impact of variation of starting points (% relative to base case value) on allowed dry weight seaweed costs.

11.4 Conclusion and discussion

11.4.1 Discussion

The results of the scenarios need to be interpreted with care. Little information is available about the relation between natural parameters such as water temperature and the yield and composition of seaweeds. For this reason, the results of the experiences near the Faroes Islands are copied indiscriminately to the North Sea situation. In certain aspects this is risky. The North sea temperature is higher, which could imply a higher risk for diseases. Also, the transparency of the North Sea is lower, which means that the growing conditions are less. A last comment is that some locations on the North sea are more influenced by fresh water from the rivers, which can float as a film over the salt water mass. It is yet unknown whether this has a negative effect on the yields of *Saccharina latissima*.

All results depend heavily on the starting points for the design and evaluation, as shown in the sensitivity study. Better (experimental) design data, and also an improved process design based on the outcome of the current analysis will improve both the economics, as well as lower the uncertainties. The effects of starting points can be very large and significant improvement in process economics can be envisaged with optimized process design. Finally, development of a proven method for storing seaweed without significant quality loss for multiple months is essential to arrive at acceptable plant investments. Also, combining species harvested in different seasons in one biorefinery is a possibility to improve the load factor and should be explored further.

Finally, many uncertainties and unknowns have been encountered in the evaluation; in all aspects, seaweed composition, design variables and economic parameters. Experimental process evaluation, especially focussed on seaweed feedstock, of the envisaged process steps will provide much better input for design studies. The outcome of this analysis should primarily be used to identify the major cost drivers and guide further research on cost reduction.

11.4.2 Conclusions

The allowed costs for seaweed based on sales values and processing costs in a biorefinery have been estimated at €456 /ton_{dw} for *Saccharina latissima* and at €263 /ton_{dw} for *Ulva sp*. for large-scale plants of 200 $kton_{dw}$/yr seaweed. The allowed costs for seaweed turn out to be higher than those of wood, which is typically around 100 EUR/ton_{dw}. The allowed feedstock costs might become higher as there will be higher revenues from seaweed derived third generation biofuels and chemicals combined with substantially lower processing costs.

The costs for seaweed production in the base scenario are calculated at €9.600 /ton_{dw} for *Saccharina latissima* and €4.500 /ton_{dw} for *Ulva sp.* The largest share in total costs comes from the seedlines and the installations. The effect of various scenarios to reduce cost of production was calculated. Based on these, a reduction of cost prices to €2,150 EUR/ton_{dw} *Saccharina latissima* and prices €2,700 /ton_{dw} for *Ulva sp*. seems possible.

The estimated current production costs turn out to be far higher than the allowed costs. For a small scale case where 2 kton/yr of seaweed is processed there is no profitable business case as the cost of processing exceeds the revenues. Only the development of high-value applications could create one. Based on the results of the sensitivity analysis, a profitable business-case seems possible for the large-scale scenario. This however requires developments on multiple aspects of the value-chain.

First and foremost, a reduction in the costs of seaweed production is required. The major cost drivers are the seedlines and installations. If it is possible to use the seedlines for multiple harvest, revenues would increase. The development of systems with lower annual costs is another point of concern. Development of simple and low costs but robust cultivation systems, with a high degree of standardization and industrialization in manufacturing of the components of the system could likely reduce costs.

For good process economics, a high yield of high-value products is the most important factor in seaweeds processing. For *Saccharina latissima*, alginate gives the highest sales revenues. For *Ulva sp.* this is ABE, which is a mixture of acetone, butanol and ethanol. Product sales have been demonstrated to be the most important factor in process economics. Therefore, this needs to be the primary focus in seaweed selection, process development and process design.

Focussing on high-value products will help process economics, and especially for small scale cases which have the worst process economics this needs to be the primary target. Some high-value applications are not addressed in this report. For example fucoidan present in brown seaweeds is reported to have anticoagulant properties, and rhamnose anti-inflammatory properties. Small volumes could be marketed as a pharmaceutical for very high prices. Ulvans, present in *Ulva sp.* are a potential feedstock for bioplastics.

Based on the design, several options can be identified to improve the process economics. A simplification of the process can be considered, omitting target products, but at the same time significantly reducing the capital investments.

Seaweed storage is essential for good process economics. To limit the capital investments, a good balance between storage size and plant size should be found which is dependent on the relative costs of both. Within the current design, optimal storage periods of 7 months for *Saccharina latissima* and 3.9 months for *Ulva sp.* were determined. Reducing the costs of storage, e.g. by dewatering or pre-processing of seaweed could improve the process economics. The capacity factor of processing plants can also be improved by multi-processing of several seaweeds from various seasons.

12. Conclusions

Background
Worldwide, large quantities of seaweed are being produced. The main contribution comes from seaweed growing naturally, that is being harvested by hand, and from artisanal small-scale production units, generally located near shore or in coastal inlets. No information is found on large-scale offshore seaweed production facilities and successful mechanical harvesting techniques. The only detailed source of information on cost, based on mid-scale development in the Faroese region, comes from Gregersen (2015).
However, there has been a lot of European (research) effort on the development of a seaweed value chain over the past 10 years. This project has assessed the feasibility of developing offshore seaweed aquaculture at offshore sites in the Dutch North Sea in the near future. It has looked at the various stages of the production chain, from the physical boundary conditions at offshore site and the constraints this sets for engineering, as well as production potential at various sites, effects of harvesting frequencies on seaweed chemical composition and the extraction of valuable compounds. All links in the chain were assessed on their contribution to the costs of production and financial revenue.

Physiology of seaweed
Within this TO2 project we showed that, with a year-round seaweed production system, including the green seaweed *Ulva lactuca* and the brown seaweed *Saccharina latissima*, a total production of max. 35 t dry matter ha^{-1} can be achieved. We found out that there are no significant differences in total yield of algal biomass between harvesting *Ulva* once every week or once every three weeks. Less frequent harvest means fewer trips with a harvesting vessel. In the experiments with *Ulva* average glucose content was 9.7 % dw, rhamnose 7.5 % dw and protein 9.5 % dw. There are indications that the physical conditions within the cultivation system have an effect on the nitrogen and glucose content of *Ulva*.

Site selection
The combined use of laboratory experiments on algal physiology with numerical models resulted in a basic framework to model macroalgal productivity for specific species at specific cultivation sites. Clearly for optimal site selection, productivity is an important issue and models such as these can help assess potential suitability and potential revenue from sites. This ought to be combined with information regarding suitability of sites regarding wave exposure, constructional constraints as well as operational constraints. Sites that are potentially very productive, but are at risk of structural damage due to wave action are likely to be less desirable. Also distance to shore will generally be a strong financial constraint as longer distances to processing plants require more transport costs.
Generally speaking, sites closer to shore, which are more influenced by nutrient input from rivers, tend to be more productive than locations further offshore. However, closer to shore, pressures from other human uses tend to be more intensive. The ecological carrying capacity (how much biological production can occur) is only one of the issues to be taken into consideration.

Models such as the D3D suite can also be used to assess the footprint of aquaculture sites on nutrient dynamics. These models allow assessing the impact that cultivation sites have on nutrient removal from the environment. This is useful for various objectives: they allow assessment of competition with phytoplankton and the productivity of other components of the North Sea ecosystem. It can also allow optimal spacing of seaweed farms to sources of nutrients (e.g. fish farms or discharge locations) in order to use these seaweed farms to mitigate eutrophication and optimally combine ecosystem services of these businesses.
The models used in this project were suitable for ecosystem-scale assessments. Future developments (based on a different type of hydrodynamic model) should also allow calculations on local nutrient depletion rates, allowing optimisation at farm-scale. This will however still take some further work.

Technical Farm design
Test on the cultivation structures indicated that the line loading is significant and strongly dependent on current direction. This information provides insight in how to select an optimal orientation for the support structure with respect to the metocean conditions.
Furthermore we found that the maximum significant wave heights the support structures were able to withstand were 4.2m. Load and fatigue analyses showed that exceeding these wave conditions caused damage to moorings and seaweed lines. However, at the selected North Sea operating site, the sea state can be more severe than simulated. To realise offshore seaweed cultivation engineering solutions will have to be found to cope with wave and current conditions with a return period of 10 years (Hs ~ 6.5 meter NW). Although the current design does not meet this criterion it fulfilled the purpose of understanding the operating limits. The research performed has been valuable in understanding the physical boundary conditions and the requirements for suitable design.

With respect to the hydrodynamic loading on the seaweed itself, we found that the drag on each individual seaweed blade (*Laminaria/Saccharina*) is relatively low for currents up to 1.5 m/s irrespective of direction. The most important conclusions on seaweed survival that can be used in offshore seaweed farming are the following:

- Brown seaweed is strong enough to withstand the current and wave loads to be grown offshore.
- The hydrodynamic and structural properties of (brown) seaweed change when it grows in harsh offshore environments.
- The drag on blades of *Laminaria* is relatively small.

Processing
We have observed a large effect of ensiling on the composition of Kelps. The storage sugars, such as mannitol were preferentially extracted or metabolised during the storage process. However, the structural components remained largely intact. We also observed large differences in the composition of the kelps as function of environmental parameters (e.g. exposure to waves).
Mannitol and alginic acid were successfully extracted and purified from fresh and ensiled kelps. We were also successful in producing a rhamnose containing syrup from *Ulva*. Extracting protein from *Ulva* using alkaline extraction or enzyme aided extraction produced low yields of protein. Protein extraction from seaweed in general remains challenging and needs further investigation.
We conclude that the three seaweed species used in this study had a moderate *in vitro* digestibility compared to soya bean meal. The digestibility of the residues after extraction of mannitol or rhamnose is substantially lower, presumably because of the removal of a relatively large part of the soluble and easily digestible minerals, proteins and carbohydrates by the extraction process and possibly because of an influence of the extraction process on the digestibility of remaining nutrients. Presumably, the lack of digestive enzymes to degrade the complex carbohydrates in seaweed is a major physiological cause of the relatively low digestibility of seaweed and residues. The use of further processing, e.g. using exogenous enzymes may improve the digestibility. This requires further investigation.

Governance
Natural seaweed has various ecosystem services, such as; enhancing biodiversity, fixation of CO_2, reduction of nutrients, production of oxygen and sheltering for organisms. Seaweed production by aquaculture has the potential to solve societal problems, such as the transitions to sustainable protein, non-fossil energy and production and providing commodities for a bio-based economy. However for a successful development of a seaweed value chain in the future a strong cooperation is needed between stakeholders, such as entrepreneurs, investors, policymakers and scientists. There is also a role for (regional, national and international) governments to play; to select the right mix of legal, social and economic incentives to encourage investors and businesses to take up the initiative. Similarly, they can use such incentives to encourage other stakeholders in the North Sea (wind farms, nature conservation NGOs, fishermen) to stimulate co-use of space as well as initiate public debate, to create wide-spread acceptance of seaweed aquaculture.

Governments can for instance facilitate the development of seaweed production by overcoming obstacles in present legislation and enhancing the sustainable exploitation of the sea by environmental legislation.

Economics
The allowed costs for seaweed (i.e. the maximum costs against which a positive business case is possible) have been estimated at 456 €/ton_{dw} for *Saccharina latissima* and at 263 €/ton_{dw} for *Ulva sp*. for large-scale plants of 200 $kton_{dw}$/yr seaweed. This estimation is based on sales values and processing costs in a biorefinery. The allowed costs for seaweed turn out to be higher than those of wood, which is typically around 100 €/ton_{dw}. The allowed feedstock costs might become higher in future due to additional products and markets, combined with substantially lower processing costs. The costs for seaweed production in the base case scenario are calculated at 9.600 €/ton_{dw} for *Saccharina latissima* and 4.500 €/ton_{dw} for *Ulva sp.* The largest share in total costs comes from the seedlines and the installations. The effect of various scenarios to reduce cost of production was calculated. Based on these, a reduction of cost prices to 2,150 €/ton_{dw} *Saccharina latissima* and prices 2,700 €/ton_{dw} for *Ulva sp*. seems possible. The estimated current production costs turn out to be six times higher than the allowed costs. For a small scale case where 2 kton/yr of seaweed is processed there is no profitable business case as the cost of processing exceeds the revenues. Only the development of high-value applications could create one. Based on the results of the sensitivity analysis, a profitable business-case seems possible for the large-scale scenario. This however requires developments on multiple aspects of the value-chain (see also the next Chapter: Recommendations).

Our two main conclusions regarding the value chain of seaweed cultivation are:

1. Although there is currently still a gap between costs and benefits of offshore cultivation, this gap can be bridged in the near future given sufficient effort for innovation

2. The most promising road to bridge this gap is to increase the market value of sustainable seaweed and the development of high-value seaweed products. There are savings to be made in reducing production costs, but the scope for this is less.

13. Recommendations and future prospects

The revenues generated by product sales are an important factor in process economics. Given our conclusion that the best opportunities to achieve a viable business case for seaweed lies in increasing these revenues, the first priority for future projects is to obtain a high yield of high-value products in seaweeds processing. Currently, *Saccharina latissima*, alginate gives the highest sales revenues. For *Ulva sp.* this is ABE, which is a mixture of acetone, butanol and ethanol. Some high-value applications are not addressed in this report. For example fucoidan present in brown seaweeds is reported to have anticoagulant properties, and rhamnose anti-inflammatory properties. Small volumes could be marketed as a pharmaceutical for very high prices (Ulvans, present in *Ulva sp*.). All carbohydrates present in seaweeds are a potential feedstock for biofuels and bioplastics. Product sales have been demonstrated to be the most important factor in process economics. Therefore, this needs to be the primary focus in seaweed selection, process development and process design. Prices of protein are rising and world-wide protein can contribute to the solution of feeding the world population. While in the near future easily extractable high-value carbohydrates such as mannitol and similar compounds are important to kick-start seaweed cultivation, proteins will be key for the longer term.

A reduction in the costs of seaweed production is required. The major costs are the seed lines and installations. If it is possible to use the seed lines for multiple harvests, costs would decrease. Development of simple but robust cultivation systems, with a high degree of standardisation and industrialisation in manufacturing of the components of the system will likely reduce costs further.

In order to produce seaweed offshore, not only do the costs have to come down and the revenues go up, it needs to be physically possible. In the future more space will be required for aquaculture and going further offshore is one of the few options. The current design we tested is not able to cope with offshore conditions as found e.g. within wind farms. Technical innovations to allow this are required to allow this. It is sensible to follow two lines of research: firstly, innovations to increase the robustness of structural designs and secondly innovations in reducing wave impact on offshore structure. The latter could involve designs that are lowered out of the worst of the wave impact during storms or combining aquaculture with other offshore structures that can provide some shelter from wave action.

The physical circumstances during growth, which influence the composition of seaweed, can be optimized. Designing and positioning culture systems that provide a high production rate and a high content of a desired compound (e.g. protein or carbohydrates) require further study. This requires more insight into the relationship between algal composition and hydrodynamic conditions. Furthermore, this requires the development of coupled ecosystem-scale models to farm-scale models. For hydrodynamics this coupling is already technically possible, to integrate this with algal growth modelling is still a technical challenge.

Several options can be identified to improve the process economics. A simplification of the process can be considered, omitting target products, but at the same time significantly reducing the capital investments. Seaweed storage is an essential factor with high impact on costs. To limit capital investments, an optimum between storage size and plant size should be found. Within the current design, optimal storage periods of 7 months for *Saccharina latissima* and 4 months for *Ulva sp.* were determined. Development of seaweed storage concepts is therefore recommended. In particular reducing the costs of storage, e.g. by dewatering or pre-processing of seaweed could improve the process economics. The capacity factor of processing plants can also be improved by multi-processing of several seaweeds from various seasons.

With respect to the cultivation process more tests are needed to determine the optimum harvesting frequency.
From the environmental and governance issues we derived the following concrete recommendations from our project:
Standardization of products is required to ease market transactions as it helps to align sellers and buyers of seaweed products. In the European context, normalization of seaweed is developed in the CEN working group BT/WG 218.
The co-use of offshore wind farms by seaweed growing companies will require an assessment of safety risks and the development of safe operating standards and practices to make sure that insurance companies can insure the businesses that co-use the platforms.
Several studies and projects (e.g. Mermaid and Maribe) show that it is important to create mechanisms for financial support to make the investments attractive to developers.
Under current conditions, governments should use subsidy only as a means to start activity, not to maintain activity. However it is strongly recommended that in the long term there is a business case without subsidy".
In this respects it is important to introduce financial mechanisms that encourages entrepreneurs to combine seaweed production with other functions such as windfarms, to avoid the "Valley of Death" because of large costs in the take up of these projects.

The last but not least recommendation is to guide the protection of the marine ecosystem by developing licensing procedures that are based on location specific environmental studies. In this respect it is also important to guarantee that the areas will have an environmental monitoring system.

Because of the interdependencies between system design, production, processing, economic performance and environmental impact, it is strongly recommended to continue the cooperation between all knowledge institutes and to involve big companies in a common research and development program on seaweed.

Colofon

In this project 26 people from 5 institutes have worked together in close cooperation.

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TNO; Sjoerd van der Putten

MARIN; René Lindeboom

Deltares; Luca van Duren, Jan Joost Schouten, Tineke Troost, Anna de Kluijver, Niels Jacobsen, Bo Paulsen, Rene Joosten

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Appendix A:Literature

P. Bikker, M.M. van Krimpen, P. van Wikselaar, B. Houweling-Tan, N. Scaccia, J.W. van Hal, W.J.J. Huijgen, J.W. Cone & A.M. López-Contreras (2016) Biorefinery of the green seaweed Ulva lactuca to produce animal feed, chemicals and biofuels, Journal of Applied Phycology (in press, DOI 10.1007/s10811-016-0842-3)".

Berberovic, E., Van Hinsberg, N.P., Jakirlic, S., Roisman, I.V. and Tropea, C. (2009). Drop Impact onto a liquid layer of finite thickness: Dynamic of the cavity evolution. *Physical Review E – Statistical, Nonlinear, and Soft Matter Physics*, **79**(3), Article no. 036306.

Bevir, M. A theory of governance; Global Area, and International Archive, University of California Press, Berkely / Los Angeles / London,2013.

Boisen, S., and J. A. Fernández. 1995. Prediction of the apparent ileal digestibility of protein and amino acids in feedstuffs and feed mixtures for pigs by in vitro analyses. Anim. Feed Sci. Technol. 51:29-43.

Boisen, S., and J. A. Fernández. 1997. Prediction of the total tract digestibility of energy in feedstuffs and pig diets by in vitro analyses. Anim. Feed Sci. and Technol. 68:277-286

Buck. (2007). Experimental trials on the feasibility of offshore seed. Helgol Mar Res, 61:87–101.

Cesar P and O Freire , 2015. Biomass yield and morphological features of the seaweed Saccharina latissima cultivated at two different sites in a coastal bay in the Atlantic coast of Spain. Journal of Applied Phycology (Impact Factor: 2.56). 02/2013; 25(1):205–213. DOI: 10.1007/s10811-012-9854-9

Cheney D, R Langan, K Heasman, B Friedman, J Davis (2010) Shellfish culture in the open ocean: Lessons learned for offshore expansion. Marine Technology Society Journal 44: 55-67.

Chung IK, J Beardall, S Mehta, D Sahoo, S Stojkovic (2011) Using marine macroalgae for carbon sequestration: a critical appraisal. J. Appl. Phycol. 23: 877–886.

Coolen, J. W. P.; Bos, O. G.; Glorius, S.; Lengkeek, W.; Cuperus, J.; Van der Weide, B. E.; Agüera, A. (2015) Reefs, sand and reef-like sand: A comparison of the benthic biodiversity of habitats in the Dutch Borkum Reef Grounds. J. Sea Res. 103, 84–92.

Danfeng S, R Dawson, L Baoguo (2006) Agricultural causes of desertification risk in Minqin, China. J. Environ. Manage. 79: 348–356.

Daniel T, A Sharpley, D Edwards (1994) Minimizing surface water eutrophication from agriculture by phosphorus management. J. Soil Water Conserv. 49: 30–38.

Degraer S, R Brabant & B. Rumes (eds). (2012). Offshore wind farms in the Belgian part of the North Sea: Heading for an understanding of environmental impacts. Royal Belgian Institute of Natural sciences, Management Unit of the North Sea Mathematical Models, Marine ecosystem management unit.

Deltares, (2015). 1220015-018-HYE-0003 Internal Memo_Numerical modelling of a floating offshore seaweed support structure.docx

Demirbas A, M Fatih Demirbas (2011) Importance of algae oil as a source of biodiesel. Energy Convers. Manag. 52: 163–170.

Dixon, J.; Dogan, R. Hierarchies, networks and markets: responses to societal governance failure. Administrative Theory & Praxis.2002, 24 (1), 175-196.

EMODnet European Marine Observation Data Network (EMODnet) Seabed Habitats project http://www.emodnet-seabedhabitats.eu/ (accessed Aug 1, 2015).

Firth LB, M Schofield, FJ White, MW Skov, SJ Hawkins (2014) Biodiversity in intertidal rock pools: Informing engineering criteria for artificial habitat enhancement in the built environment. Marine Environmental Research 102: 122–130. doi:10.1016/j.marenvres.2014.03.016

Furuya, K. Environmental carrying capacity in an aquaculture ground of seaweeds and shellfish in Sanriku coast. Bull. Fish. Res. Agency 2004, Supplement, 65–69.

Geist HJ, EF Lambin (2002) Proximate Causes and Underlying Driving Forces of Tropical Deforestation. Bioscience 52: 143.

Gemini online: www.geminiwindpark.nl. (accessed on 24 Dec 2015)

Gerits, R. RWS. Personal communication, 2015.

Gerritsen, A.L., M. Stuiver, C.J.A.M. Termeer. Organising and enabling of knowledge trajectories. In: Dotti, N.F. (Ed.).Knowledge, policymaking and learning for European cities and regions. In prep.

Gerritsen, A. L.; M. Stuiver; C.J.A.M. Termeer. 2016. Knowledge governance: An exploration of principles, impact, and barriers. Science and Public Policy. 2013, Doi: 10.1093/scipol/sct012.

Glasby, T. M.; Connell, S. D.; Holloway, M. G.; Hewitt, C. L. Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Marine Biology2007, 133, 887-895.

Gregersen, Ólavur (2015), Economics in large scale cultivation based on the MacroBiotech project, presentation for the Seaweed Symposium on May 5 2015, The Nordic House –Faroe Islands

Hann RM, Haskins WT, Hudson CS, *J. Am. Chem. Soc.* **64**, 986–987 (1942).

Haskins WT, Hann RM, Hudson CS, *J. Am. Chem. Soc.* **65**, 67–70 (1943); Haworth WN, Wiggins LF, *J. Chem. Soc.*, 58–61 (1944); Lavilla C, Martínez de Ilarduya A, Alla A, García-Martín MG, Galbis JA, Muños-Guerra S, Macromolecules 45, 8257–8266 (2012).

Helmes, Roel & Sander van den Burg, 2015. Environmental Life Cycle Assessment of Plastics from Seaweed. SEABIOPLAS Deliverabe 7.1, Stichting DLO, Wageningen, the Netherlands.

Huang, X. L.;Ruangkanjanases, A.; Chen, C.. Factors influencing chinese firms' decision making in Foreign Direct Investment in Thailand. International Journal of Trade, Economics and Finance.2014, 5(6), 283–291. doi:10.7763/IJTEF.2014.V5.41722.

Hoefakker B.; Don, J.; Blomen, E.; Chivers, A.; Oppentocht, M. Common Position Paper & QRA regarding Open Offshore Wind Park Access in response to "Verslag risicosessie doorvaart en medegebruik windparken, 27 mei 2015, Stakeholder advice DM, Ontwerp beleidsnota Noordzee. 38 van 28 Rapportnummer C138/15A 2016-2021" and "Eindversie kennisdocument 'Varen en vissen in windparken". Chivers, A. (NZW), Ed., 2015.

Holdt, Susan Løvstad, and Stefan Kraan. "Bioactive compounds in seaweed: functional food applications and legislation." *Journal of Applied Phycology*23, no. 3 (2011): 543-597.

Ignacio, J.; Fernández, P.; Cala, A.S.; Domecq, C. F.. Critical external factors behind hotels' investments in innovation and technology in emerging urban destinations. Tourism Economics.2011, 17(2), 339–339. doi:10.3387/te.2011.0033

ISO 14044 (2006) 'Environmental management — Life cycle assessment— Requirements and guidelines' issued by the International Organization for Standardization (ISO).

Issa, D.T.; Chang, A.V.;Issa, D.T.. Sustainable Business Strategies and PESTEL Framework. Gstf Int. J. Comput. 2010, 1, 1–8. doi:10.3376/2010-2283_1.1.13

Jacobsen, N.G., Fuhrman, D.R., and Fredsøe, J. (2012). A Wave Generation Toolbox for the Open-Source CFD Library: OpenFOAM®. *International Journal for Numerical Methods in Fluids*, **70**(9), 1073-1088.

Jansen HM, S VanDenBurg, B Bolman, RG Jak, P Kamermans, M Poelman, M Stuiver (Submitted) The feasibility of offshore aquaculture and its potential for multi-use in the Dutch North Sea.

Jensen, B. Jacobsen, N.G. and Christensen, E.D. (2014). Investigations on the porous media equations and resistance coefficients for coastal structures. *Coastal Engineering*, **84**, 56-72.

Jongbloed, R.; van der Wal, J. T.; Machiels, M. Notitie staandwantvisserij en windparken op de Noordzee; IMARES Notitie 15.IMA0710.NSt.ro. 2015.

Jung, K. A., S.-R. Lim, Y. Kim and J. M. Park (2013). "Potentials of macroalgae as feedstocks for biorefinery." Bioresource Technology 135(0): 182-190.

Kain, J.M., 1991.Cultivation of attached seaweed. In: Seaweed resources in Europe: use and potential, Chichester: pp. 309-377

Kamermans, P. , E-j. Malta, J.M. Verschuure, L. F. Lentz & L. Schrijvers (1998). The role of cold resistance and burial for winter survival and spring initiation of an Ulva spp. (Chlorophyta) bloom in a eutrophic lagoon (Veerse Meer lagoon, The Netherlands). Mar. Biol. 131: 45-51.

Kickert, W. J. M.; Klijn, E. H.; Koppenjan, J.F.M. Managing complex networks: Strategies for the public sector. Sage: London,1997.

Klijnstra J.; Zhang, X.; Van der Putten, S.; Röckmann C. Technical risks of offshore structures. In Aquaculture perspective of multi-use sites in the open ocean.The untapped potential for marine resources in the anthropocene.In Buck, B. H.; Langan, R., Eds. Springer.In review.

Kooiman, J. Governing as Governance. London: Sage, 2003.

Koppenjan, J.F.M.; Klijn, E.H. Managing uncertainties in networks;London: Routledge,2004.

Koundouri, P., O.G. Dávila, M. Stithou, A. Xepapadeas, I. Anastasiou, A. Antypas, N. Kourogenis, A. Mousoulides, M. Mousoulidou, A. Giannouli, C. Papagianni, E. Kotroni, N. Ahrensberg, B. Zanuttigh, F. Zagonari, M.A. Lange, C. Jimenez, E. Giannakis, L. Rosen, A. Lindhe, J. Norrman, T. Norberg, J. Schouten, R. Garção, T. Söderqvist, A. Pedersen, D. Troianos, A. Frentzos, Y. Krontira, I.J. Losada, P.

Diaz-Simal, R. Guanche, M. de Bel, W. He, S. Kabdasli, N. Elginöz, E. Oguz, T. Bagci, B. Bas, M. Cantu', M. Masotti, R. Suffredini and M. Stuiver.. Socio-economic Analysis of The North Sea Site; Deliverable 8.3.MERMAID Project, 2015.
Krenk, S. (2000). *Mechanics and analysis of beams, columns and cables*. Polyteknisk Press, Copenhagen, Denmark.
Lascoumes, P.; Le Gales, P. Introduction: Understanding Public Policy through Its Instruments—From the Nature of Instruments to the Sociology of Public Policy Instrumentation. Governance: An International Journal of Policy, Administration, and Institutions. 2007,20 (1), 1–21.
Lagerveld, S.; Röckmann, C.; Scholl, M. A study on the combination of offshore wind energy with offshore aquaculture;IMARES Report C038/14. 2014. Available online: http://edepot.wur.nl/318329 (accessed 5 December 2015).
Lagerveld, S., C. Rockman, M. School, H. Bartelings, S. van den Burg, R. Jak, H. Jansen, J. Klijnstra, M. Leopold, M. Poelman, S. Smith, J. Stavenuiter, F. Veenstra, C. Veltman & C. Westra (2014). Combining offshore wind energy and large-scale mussel farming: background & technical, ecological and economic considerations. Den Helder: IMARES report C056/14
Lindeboom HJ, HJ Kouwenhoven, MJN Bergman, S Bouma, S Brasseur, R Daan, RC Fijn, D de Haan, S Dirksen, R van Hal, R Hille Ris Lambers, R ter Hofstede, KL Krijgsveld, M Leopold & M Scheidat (2011) Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. Environmental Research Letters 6, 035101.
Malta E.-j. & J.M. Verschuure, 1997. Effects of environmental variables on between-year variation of Ulva growth and biomass in a eutrophic brackish lake. J. Sea Res. 38: 71-84.
Malta E,-j., S.G.A. Draisma & P. Kamermans, 1999. Free floating Ulva in the Southwest Netherlands: species or morphotypes? A morphological, molecular and ecological comparison, Eur. J. Phycol. 34: 443-454
Marin. Risicoanalyse: varen en vissen in windparken: 26606-1-MSCN-rev. 2,2013.
MARIN, (2015). T02 Noord-Zee-Wier-Keten. Technical Report, MARIN, Report no. 28260-1-BT-Volume I.
McKindsey CW, P Archambault, MD Callier, F Olivier (2011) Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: a review. Canadian Journal of Zoology 89: 622-646.
Meuleman, L. Public Management and the Metagovernance of Hierarchies, Networks and Markets. The Feasibility of Designing and Managing Governance Style Combinations; Physica-Verlag: Heidelberg,2008.
Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-Being: Synthesis, Island Press.
Mineur F, F Arenas, J Assis, AJ Davies, AH Engelen, F Fernades E-J Malta, T Thibaut, TV Nguyen, F Vaz-Pinto, S Franken, EA Serrão & O De Clerck (2015). European seaweeds under pressure: Consequences for communities and ecosystem functioning. J Sea Res 98:91-108.
Ministerie van Infrastructuur en Milieu and Ministerie van Economische Zaken. Beleidsnota Noordzee 2016-2021. Bijlage 2 bij het Nationaal Waterplan 2016-2021. December 2014. Available online: https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2014/12/12/2-beleidsnota-noordzee-2016-2021/beleidsnota-noordzee-2016-2021.pdf (accessed 5 December 2015).
Noordzeeloket. Weighing up the interests.Article at the Noordzeeloket website. https://www.noordzeeloket.nl/en/functions-and-use/Maritime_wind_energy/Weighing_up_the_interests/index.aspx (accessed 5 December 2015).
Ostrom, E. Self-governance and forest resources. In: Terracotta Reader: A Market Approach to the Environment. Shah.P. J.; Maitra,V., Eds; New Delhi: Academic Foundation; 2005:pp. 131–136.
Ostrom, E. Coping with tragedies of the commons. Annual Review of Political Science.1999,2: 313–337.
Ostrom, E.; Gardner, R.; Walker, J. Rules, Games and Common Pool Resources; Ann Arbor, MI: University of Michigan Press,1994.
Percival, E. (1979). "The polysaccharides of green, red and brown seaweeds: Their basic structure, biosynthesis and function." British Phycological Journal 14(2): 103 - 117.
Pestel online; www.kbmanage.com/concept/pestel-analysis) (accessed on 24 Dec 2015)
Pierre, J.;G. Peters. Governance, politics and the state; New York: St. Martin's Press. 2000.
Rafiee, A. and Fievez, J. (2015). Numerical prediction of extreme loads on the CETO wave energy converter. *Proceedings for European Wave and Tidal Energy Conference*, 9 pages
Rasenberg, M.;Stuiver, M.; Van den Burg, S.; Norrman, J.; Söderqvist, T.Stakeholder Views 2; Deliverable D2.3, MERMAID project,2014.

Rasenberg, M.; Stuiver, M.; Van den Burg, S.;Veenstra, F.;Norrman, J.;Söderqvist, T.Stakeholder Views; Deliverable D2.2, MERMAID project, 2013.
Rhodes, R.A.W. Understanding Governance: Policy Networks, Governance, Flexibility and Accountability; Open University Press, Buckingham, 1997.
Robic, A., D. Bertrand, J.F. Sassi, Y. Lerat & M. Lahaye (2009) Determination of the chemical composition of ulvan, a cell wall polysaccharide from Ulva (Ulvales, Chlorophyta) by FT-IR and chemometrics, Journal of Applied Phycology, 21(4), 451-6.
Röckmann C.; Cado van der Lelij, A.; Steenbergen J.; van Duren L. VisRisc – Estimating the risks of introducing fisheries activities in offshore windparks; IMARES report C318/15 (in Dutch), 2015.
Röckmann, C.; Stuiver, M.; van den Burg, S.; Zanuttigh, B.; Zagonari, F.; Airoldi, L.; Angelelli, E; Suffredini, R.; Franceschi, G.; Bellotti, G.; Schouten, J.J.; Söderqvist, T.; Garção, R.; Guanche Garcia, R.; Sarmiento Martínez, J.; Svenstrup Petersen, O.; Aarup Ahrensberg, N. Platform Solutions; Deliverable 2.4, MERMAID project, 2015.
Roesijadi. (2007). Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products. Batelle Pacific Northwest Division.
Rossi F, B Gribsholt, F Gazeau, V Di Santo, JJ Middelburg (2013) Complex Effects of Ecosystem Engineer Loss on Benthic Ecosystem Response to Detrital Macroalgae. PLoS One 8, e66650.
Rozemeijer M.; Slijkerman, D.; Bos, O. G.; Paijmans, A. J.; Röckmann C. Bouwen met Noordzee natuur. Uitwerking Gebiedsagenda Noordzee 2032; IMARES report, forthcoming in 2015.
Rozemeijer, M.; Slijkerman, D.; Bos, O. G.; Paijmans, A. J.; Röckmann C. Bouwen met Noordzeenatuur. Uitwerking Gebiedsagenda Noordzee 2032; IMARES report, 2015.
Sacchetti, S.; Sugden, R. The Organization of Production and its Publics: Mental Proximity, Market and Hierarchies. Review of Social Economy.2009 67:3, 289-311.
Seider, W. D., Seader, J. D. & Lewin, D. R. (2004) *Product & process design principles. Synthesis, analysis and evaluation.,* 2 ed, Wiley.
Sørenson, E.; Torfing, J.. Making governance networks effective and democratic through metagovernance. Public Administration. 2009, 87(2), 234-240. doi: 10.1111/j.1287-9299.2009.01735.x
Tamis JE, P de Vries, RH Jongbloed, S Lagerveld, RG. Jak, CC Karman, JT Van der Wal, DME Slijkerman, C Klok (in press). Towards A Harmonised Approach For Environmental Assessment Of Human Activities In The Marine Environment. Integrated Environmental Assessment and Management DOI 10.1002/ieam.1736.
Taylor R. & R.L. Fletcher, 2001. Preliminary studies on the growth of selected green tide algae in laboratory culture: Effects of irradiance, temperature, salinity and nutrients on growth rate. Botanica marina 44:.327-336
TNO, (2015). TNO 2016 R10157. Offshore seaweed farming support structures; Design concepts assessment Troost T A, A de Kluijver, FJ Los (2014) Evaluation of eutrophication variables and thresholds in the Dutch North Sea in a historical context — A model analysis. J. Mar. Syst. 134: 45–56.
Troost, T. A.; de Kluijver, A.; Los, F. J., 2014. Evaluation of eutrophication variables and thresholds in the Dutch North Sea in a historical context — A model analysis. J. Mar. Syst. 134: 45–56.
Van Buuren, M. W. van; Eshuis, J. 'Knowledge governance: complementing hierarchies, networks and markets?'; In Knowledge democracy - consequences for science, politics and media; Veld, R. J., Ed; Springer: Heidelberg; 2010: 283-297.
Van den Burg S M. Stuiver, F. Veenstra, P. Bikker, A. López Contreras, A. Palstra, J. Broeze, H.Jansen, R. Jak, A. Gerritsen, P. Harmsen, J. Kals, A. Blanco, W. Brandenburg, M. van Krimpen, A-P. van Duijn, W. Mulder, L. van Raamsdonk (2013) A Triple P review of the feasibility of sustainable offshore seaweed production in the North Sea. LEI report 13-077. https://www.wageningenur.nl/upload_mm/8/a/d/d69d82b9-904f-4bf1-9844-c24bd5d39346_Rapport%2013-077%20vdBurg_DEF_WEB.pdf
Van den Burg, S.W., A-P. van Duijn, H. Bartelings, M.M. van Krimpen & M. Poelman (forthcoming) The economic feasibility of seaweed production in the North Sea. Aquaculture Economics and Management
Van den Burg, Sander, Robbert Jak, Marie-Jose Smits, Arianne de Blaeij, Trudy Rood, Harm Blanken & Susan Martens, 2016. *Zeewier en natuurlijk kapitaal; Kansen voor een biobased economy.* Wageningen, LEI Wageningen UR (University & Research centre), LEI Rapport 2016-049. 36 blz.;
5 fig.; 5 tab.; 48 ref.

Van Hal, J.W. & W.J.J. Huijgen (2012), Process for mannitol extraction from seaweed, patent NL 2009482.

Van Hal, J.W., Huijgen. W.J.J. and López-Contreras, A.M. (2014) Opportunities and challenges for seaweed in the biobased economy, Trends in Biotechnology, 32(5), 231-233

Van Hal R, AS Couperus, SMM Fassler, S Gastauer, B Griffioen, NT Hintzen, LR Teal, OA van Keeken, HV Winter (2012) Monitoring- and Evaluation Program Near Shore Wind farm (MEP-NSW): Fish community. IMARES Report C059/12. p. 161.

Vasquez JA., S Zuñiga, F Tala, N Piaget, DC Rodríguez & JMA Vega (2014). Economic valuation of kelp forests in northern Chile: values of goods and services of the ecosystem. J Appl Phycol 26:1081-1088.

Verhaeghe D.; Delbare, D.; Polet, H. Haalbaarheidsstudie van geselecteerde passieve visserij – methodes en maricultuur in de omgeving van windmolenparken in de Noordzee (Maripas); Rapportnummer D/2011/10.970/99, ILVO; mededeling nr. 99; ISSN 1784-3197,2011.

Wald, 2010.Evaluatiestudie naar mogelijkheden voor grootschalige zeewierteelt in het zuidwestelijke Deltagebied, in het bijzonder de Oosterschelde. Wageningen UR rapport 341

Wei, N., J. Quarterman and Y.-S. Jin (2013). "Marine macroalgae: an untapped resource for producing fuels and chemicals." Trends in Biotechnology 31(2): 70-77.

Williamson, O. The economic institutions of capitalism; Free Press, New York,1985.

Zintzen, V. Biodiversity of shipwrecks from the Southern Bight of the North Sea, University of Louvain, 2007.

Appendix B: Key-parameters for the economic model

Investments and yearly costs of the installations

	Longline	MACR	Cage
Total investments, €/m growth line	14.5	13.50	45
Investments euro/ha	218,000	13,500	682,000
For 200 kTon installation	290,000,000	270,000,000	900,000,000
Depreciation, initial value (%)	17%	17%	17%
Maintenance and repair (%)	3%	3%	3%
Assurance (%)	2%	2%	2%

Investments and yearly costs of the machinery and equipment

	200 kton
Total replacement value	3,500,000
Depreciation (%)	10%
Maintenance and repair (%)	5%
Assurance (%)	2%

Weed characteristics

	Saccharina L.	Saccharina L.	Ulva Sp.
Number of harvests per year	1	3	1
Life span of seed lines, years	1	3	1
Yield in kg fw/m growth line/yr	7	14	10
Yield in ton fw/ha/yr	105	215	150
Yield in ton dw/ha/yr	14	28	31
Dry matter content (%)	13%	13%	21%
Seed line price, initial (euro/m)	3.80	3.80	3.80

Labour costs in euro per working hour

	Costs
Fieldwork	35
Management	63
Administration	26

Labour requirements for a 200 kTon installation, in hours/ton FW

	Scenario's S.2. & S.3.	Scenario's S.4. & S.5.	Scenario's U.1. – U.3.
Number of harvests per year	1	3	1
Life span of seed lines, years	1	3	1
Planting	130	15	130
Control, care, protection	100	100	100
Harvest	130	130	130
Miscellaneous	50	50	50
Management	32	32	32
Administration	60	60	60

Transport, transhipment and harbour dues per ton FW(on base of rentals)

	200 kTon
From harvester to transport ship	2.50
Transport to harbour	1.15
Harbour dues	0.85
Transhipment	2.50
Secondary transport	1.00
Total	8.00

Miscellaneous cost

Crop protection (euro/m growth line)	0.25
Taxes, rents and similar (€/ha)	50
Workwear (Euro/FTE)	200
Interest (%)	2,5%

Values of some key-parameters is the production model

Investments and yearly costs of the installations

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