



A Triple P review of the feasibility of sustainable offshore seaweed production in the North Sea

Sander van den Burg, Marian Stuiver, Frans Veenstra, Paul Bikker, Ana López Contreras, Arjan Palstra, Jan Broeze, Henrice Jansen, Robbert Jak, Alwin Gerritsen, Paulien Harmsen, Jeroen Kals, Ainhoa Blanco, Willem Brandenburg, Marinus van Krimpen, Arie Pieter van Duijn, Wim Mulder, Leo van Raamsdonk



WAGENINGEN UR

For quality of life

A Triple P review of the feasibility of sustainable offshore seaweed production in the North Sea

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Dit onderzoek richt zich op het potentieel van zeewier productie in de Noordzee, als een duurzaam uitgangsmateriaal voor productie van diervoeder en andere non-food toepassingen. Zeewier kan geteeld worden in zogenaamde multi-use platforms at sea (MUPS). Het onderzoek geeft een overzicht van kennis over zeewier productie en toepassingen. Resultaten laten zien dat Noordzee zeewier in potentie een duurzaam uitgangsmateriaal is. Diverse economische, ecologische en maatschappelijke uitdagingen zijn geformuleerd. Deze zullen geadresseerd moeten worden voordat het potentieel van zeewier ten volle benut kan worden.

This study focused on the potential of seaweed, cultivated in the North Sea, as a sustainable and profitable resource for feed and non-food applications. Seaweed production can take place as part of multi-use platforms at sea (MUPS). A review of the state-of-the-art in seaweed production and its applications revealed that North Sea seaweed is a potential sustainable resource for feed and non-food applications. Various economic, ecological and social challenges are identified, which need to be addressed to utilise this potential.

Keywords: seaweed, North Sea, sustainability, feed, green chemicals, risks, Multi-Use Platforms at Sea

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Preface

As the world population and consumption levels grow, efficient use of natural resources becomes more important. Feeding the world within the carrying capacity of Planet Earth requires an open eye for the sustainable food production at sea, as seas cover more than 70% of the planet. Shifting production to the domains of the sea can contribute to resolve some of the world's most important challenges, such as competition on land-use, depletion of terrestrial nutrients and loss of pristine forests. Seaweeds provide big opportunities for production at sea: a commodity that can be used as food for human consumption, livestock feed and a source of green chemicals.

The agro and food sector is not the only sector with an eye on the sea. Offshore wind energy production is expected to be important for reaching renewable energy objectives, in the Netherlands and abroad. This development can offer new possibilities for the seaweed sector as different production functions can be combined in Multi-Use Platforms.

This report describes the state-of-the-art in seaweed production, processing and application. It assesses the feasibility of seaweed production in multi-use platforms on the North Sea from a Triple P perspective: Profit, Planet and People. This report combines new research with knowledge and expertise from various research projects Wageningen UR is involved in. It is the joint result of researchers of various Wageningen UR institutes and integrates multiple scientific disciplines.

This study is part of the Wageningen UR strategic R&D programme 'TripleP@Sea: Smart use of marine ecosystem services providing sustainable Profit of the Planet for People' (2012-2015). We are thankful to the Dutch Ministry of Economic Affairs for funding the research through the KB programme 'Sustainable Development of Green and Blue Space'.



Dr. M.C.Th. (Martin) Scholten
Portofolio holder for Marine within the Board of Directors

Summary

A review of the state-of-the-art in seaweed production and its applications revealed that North Sea seaweed is a potential sustainable resource for feed and non-food applications. Various economic, ecological and social challenges are identified, which need to be addressed to utilise this potential.

Aim of the study

This study focused on the potential of seaweed, cultivated in the North Sea, as a sustainable and profitable resource for feed and non-food applications. Seaweed production can take place as part of multi-use platforms at sea (MUPS). The aim of this study is twofold. First, to present the state-of-the-art knowledge about different elements of the seaweed chain: production, either in separate production systems or in combination with fish farming, processing and use in diets for farm animals and fish. Hazards for feed and food production are presented as well as non-food applications of seaweeds. Second, to assess the feasibility of North Sea seaweed production from a Triple P perspective, addressing economic, ecological and social feasibility.

State-of-the-art

The review of scientific publications and experimental data reveals that seaweeds can be grown in the North Sea. Ongoing research examines how production in combination with mussel and fin fish aquaculture can be realised. The produced seaweed can be used as a source of proteins and polysaccharides to be used in feed and non-food applications. Research shows beneficial effects on adding seaweed components to the feed mix. Various biorefinery techniques are available to produce green chemical building blocks from seaweed.

Feasibility from a Profit perspective

Based on the review of expected production costs and revenues, an economically viable seaweed production is possible provided that high value products can be obtained. At this moment, there is no commercial seaweed production in the North Sea. There is uncertainty about future value chains of offshore production and it is uncertain how to organise offshore production and value chains. The market for seaweed products is diverse. High value products include feed additives, chemicals and alginates. Direct consumption by animals offers low value. The use of seaweeds for the production of biofuels seems unlikely due to the low prices that are paid for biofuel material. To match production costs and the value of the produce, biorefinery is necessary to make multiple products from the basic material. Technical innovation and the design of systems that enable multiple harvests per year can reduce production costs.

Feasibility from a Planet perspective

To be a sustainable resource for feed and non-food applications, seaweed production should not have negative impacts on the ecosystem. To assess eco-sustainability of marine seaweed production within MUPS, the applicability of different approaches and models is reviewed. Nutrient models provide quantitative biological information about growth and nutrient assimilation efficiencies as a function of environmental variables (nutrient availability, oxygen, temperature, light intensity). Cumulative Effect Assessment (CEA) and Eco-dynamic Development and Design (EDD) models identify the most severe risks and pressures, and thereby define the most vulnerable ecosystem components. In addition, these models may help to design effective production systems that make optimal use of ecological conditions, and minimise adverse ecosystem effects. MUPS systems are complicated since they include multiple production lines and have open connections with the surrounding aquatic system. A more advanced variant of Life Cycle Analysis will be needed to evaluate the eco-sustainability of MUPS.

Feasibility from a People perspective

At present there is no manifest interest among stakeholders to develop MUPS, due to the necessary high economic and social investment, including the legal procedures involved. The concept of MUPS

needs to mature so that it becomes possible to develop a realistic and reliable business case, attractive for the potential partners from the energy and aquaculture sector.

A successful business case requires an optimal governance and planning mix, instigated by different actors. This planning mix needs to support the development of such business cases. Legislation needs to change but this is not the most important obstacle. Bridging the worlds of different offshore business sectors (e.g. fisheries, aquaculture and wind energy) is a more challenging issue. It would be a major step if the current small-scale experiments in seaweed farming can be followed by an experimental MUPS to facilitate learning.

Methodology

This report combines new research with knowledge and expertise from various research projects Wageningen UR is involved in. It integrates various disciplines, such as plant science, chemistry, economics, animal science, process technology and social science. This integrated approach offers new insights for the specific field of marine production. The report addresses all the issues involved, providing a bird's eye view on the subject matter, combining the collective expertise and gaining synergy.

Overview of the report

A state-of-the-art overview of knowledge is provided in the first part of the report. The following issues are addressed:

- Basic information on botany and chemistry of the major groups of seaweed (marine macro algae) → [Chapter 1](#).
- Production of seaweeds in the North Sea, addressing growth potential of various species → [Chapter 2](#).
- Production of seaweeds in integrated multi-trophic aquaculture (IMTA) systems, combined with production of shellfish and fish → [Chapter 3](#).
- Processing of seaweeds using biorefinery, as a first step towards various applications → [Chapter 4](#).
- Potential of seaweeds a source of animal feed and feed additives, for both livestock and aquaculture → [Chapter 5](#).
- Relevant food and feed risk regulation that should be taken into account when utilising seaweeds → [Chapter 6](#).
- Possibilities to use seaweeds for non-food applications, in particular for production of green chemical building blocks → [Chapter 7](#).

The potential of seaweed production is then evaluated from a Triple P perspective. The development and exploitation of seaweed needs to be feasible in line with Profit, People and Planet requirements. In the [Chapter 11](#), conclusions from this research are presented and future research challenges are identified.

1 Introduction to the Feasibility Study

1.1 Introduction

Seaweeds are among the promising products to be produced from marine ecosystems. The attractiveness of seaweeds can be explained from three perspectives: Profit, Planet and People.

From a 'profit' perspective seaweeds are attractive because they can be used in a wide range of applications, for example:

- Seaweed can be used directly for human consumption. This is the dominant application worldwide, seaweed being a common ingredient in the Asian menu (the most familiar dish is sushi). In Western cuisine, direct consumption of seaweeds is generally less common, some coastal communities being the exemption to this rule (Sustainable Energy Ireland, 2009; Mesnildrey et al., 2012).
- They can be used for production of hydrocolloids. This is currently the second largest application of seaweeds. Hydrocolloids (alginate, agar, and carrageenan) are commonly used in the food industry as thickener (Bixler, 2010).
- Use of seaweed as feed has a long history. In coastal communities seaweeds were gathered onshore and fed to animals (Sustainable Energy Ireland 2009; Mesnildrey, Jacob et al., 2012). Current research focuses on the use of seaweeds as replacement for dominant feed stocks such as soy and fish meal (Wilding et al., 2006; Soler-Vila et al., 2009; Rust et al., 2011).
- The chemical and pharmaceutical industries have shown interest in seaweed as a source of chemicals and medicine. Research into the functional characteristics of seaweeds is ongoing.
- Bioactive molecules in seaweed species can be of interest for utilisation for health and functional food applications. Components of seaweed have shown positive effects in the treatment of various diseases (Holdt and Kraan 2011).
- Seaweeds are a potential source of bioenergy, with various production processes available. Interest in the use of algae as a source of biofuels has some history but ongoing technological developments render further investigation necessary (Mata et al., 2010; Borines et al., 2011).

The attractiveness of seaweeds in public opinion and for policy-makers is not only explained by its potential economic benefit. Seaweeds are also attractive because use can contribute to solving some of the major environmental and social concerns that are dominant nowadays. In the next decades, because of a growing world population and rising consumption levels, the use of marine ecosystems as a source of feed and food is expected to increase. Society demands that this is done in a sustainable way with combinations of ecosystem services smartly chosen to make them strengthen instead of hamper each other.

From a 'planet' perspective, seaweed production is attractive because it can:

- Contribute to tackling climate change through the production of biofuels as fewer fossil fuels need to be used.
- Reduce eutrophication of seas through strategic positioning of production facilities because nutrients are taken up during growth and removed by harvesting the seaweed.
- Help in combatting overfishing and subsequent decline of fish stocks as seaweeds can be used as an alternative source of marine protein in fish feed.
- Reduce dependency on soy import for feeding livestock and thereby combat deforestation in soy producing countries.
- Reduce fossil fuel use thanks to the production of chemical building blocks.

From a 'people' perspective, seaweed production and utilisation is attractive for the following reasons:

- The European Blue growth strategy recognises the potential of marine protein production for strengthening the European economy. In a recent press release EU commissioner Damanaki stated

that 'In the next decade or so, the blue biotechnology sector should become a provider of mass product markets, including cosmetics, food products, pharmaceuticals, chemicals and biofuels'.¹

- Marine protein production can be of particular relevance for coastal and fisheries communities that are under pressure due to declining fish stocks and a decline in available fishing grounds, among others as a result of the development of offshore wind parks.
- If seaweeds can be used for the production of biofuels this could reduce dependency on fossil fuels import.

1.2 Botanic classification

Because of specific characteristics of different groups, genera and species of seaweed, it is relevant to briefly address their botanical classification. All plants are classified as kingdoms in the domain of the Eukaryotes, in addition to other kingdoms such as animals, fungi, amoebzoa and some smaller groups (Adl et al., 2005; see also Palmer et al., 2004). The classification and evolutionary origin is disputed in more recent publications and other ways of classification have been introduced as well (e.g. Burki et al., 2007; 2012). The kingdom Archaeplastida consists of the vascular plants (Angiosperms) along with several groups of algae, as illustrated in Table 1.1. The Chromalveolata comprises the group of brown algae, among others.

Table 1.1

Simplified classification of seaweeds.

*Genera applicable for cultivation in the North Sea are indicated in **bold**.*

Kingdom	Division	Phylum	Common name	# of species	Example genera
Chromalveolata	Heterokontophyta	Phaeophyta	Brown algae	1,500-2,000	<i>Ascophyllum</i> <i>Ecklonia</i> : kelp <i>Eisenia</i> : kelp <i>Fucus</i> : kelp <i>Laminaria</i> : oarweed <i>Macrocystis</i> : kelp <i>Saccharina</i> : kelp <i>Sargassum</i> : hijiki a.o. <i>Undularia</i>
Archaeplastida		Glaucophyta	Blue-green algae		
		Rhodophyta	Red algae	4,000-10,000	<i>Chondrus</i> <i>Gelidium</i> : agar <i>Gracilaria</i> : agar <i>Kappaphycus</i> <i>Palmaria</i> : dulse <i>Polysiphonia</i> <i>Porphyra</i> : laver, nori
	Viridiplantae	Chlorophyta	Green algae	7,000	<i>Caulerpa</i> : sea grape <i>Codium</i> <i>Cladophora</i> <i>Ulva</i> : sea lettuce, gutweed, grass kelp
		Charophyta	Vascular plants		

The rationale to present this botanic classification of seaweeds is the differences in types of metabolic pathways (Maberly et al., 1992), and the differences among the structural polysaccharides and essential pigments (Table 1.2).

¹ http://ec.europa.eu/commission_2010-2014/damanaki/headlines/press-releases/2012/09/20120913_en.htm [15-3-2013]

Table 1.2

Differentiation of major chemical components in groups of seaweeds.

Data extracted from van den Hoek et al. (1995), Lee (2008) and Holdt and Kraan (2011). Additional sources: a: Fritsch (1945); Dawes et al. (1960); b: Takano et al. (1995); c: Raven et al. (2005); d: Woelkerlin (1990).

Group (Phylum)	Structural ^a	Polysaccharides		Pigments	
		additional		Chlorophyll ^c	other
Brown algae	Double cell wall; inner: cellulose, outer: algin ^s	Glucans (laminarin), Fucans ^s (fucoidan), mannitol	a, c		Fucoxanthin, violaxanthin
Red algae	Double cell wall; inter: cellulose, outer pectin	Glucans (floridean starch ^f), Xylans, Galactans (carrageenan ^s and other sulphated galactans), funoran ^b	a		lutein, zeaxanthin, Phycobiliproteins ^d
Green algae	Single cell wall: cellulose	Xylans, Galactans (sulphated), ulvan ^s	a, b		lutein, zeaxanthin, violaxanthin, neoxanthin

^s water-soluble sulphated polysaccharides; ^f: floridean starch consists exclusively of amylopectin, instead of the usual mix of amylose and amylopectin (BeMiller and Whistler, 2009). β -carotene is present in all seaweeds.

The differences as illustrated in Table 1.2 have long been recognised: brown algae are the basis for alginate production from algin, and red algae are used for the production of agar from pectin. These differences in composition are related to differences in the presence of secondary metabolites and to the accumulation of contaminants. The presented classification and chemistry can assist in the evaluation of hazards when applying certain seaweeds as sources for feed ingredients.

Although this report focuses primarily on genera which can be cultivated in the North Sea area (indicated in bold in Table 1.1), it is important to identify the hierarchical level which should be used as framework. Kelp is a processed product of seaweed based on brown algae from five different genera, of which one is primarily of interest for North Sea cultivation, whereas agar is usually produced from two different species (see Table 1.1 for names). Besides these examples of super-generic economic interest, a view on the generic level can be confusing for other reasons. The genus *Eucheuma* (red algae) is classified as *Kappaphycus* in modern systems, *Pterocladia* (brown algae) is included in *Fucus*, and *Hizikia* (hijiki, brown algae) is now classified as *Sargassum fusiforme*. Since the basic biochemistry is group or Phylum-specific (Table 1.2), and the classification at the level of genera and below is non-specific (e.g. kelp) or subject to change, the following overview of relevant literature on hazards of seaweeds will focus on the hierarchical level of phyla. In most cases the genera as reported in literature will be named for proper reference, but most results are indicative of the group or Phylum.

1.3 Chemistry

The moisture content of fresh seaweed (marine algae) is very high and may amount to 94% of the biomass (Holdt and Kraan, 2011). The nutritional composition of seaweeds varies, depending on strain, season and area of production (Connan et al., 2004; see Table 1.3 for an overview). The Appendix provides more detailed tables on several nutrient groups. The total crude protein content varies among different seaweed strains in North-western Europe and is rather small in brown seaweed (10-24% of dry weight (DM)), whereas higher protein contents are observed in green and red seaweed species (up to 44% of dry weight) (Holdt and Kraan, 2011). The commonly accepted factor of 6.25 in the conversion of total nitrogen to crude protein should be treated with caution as, among other factors, content of free nitrate will influence the total nitrogen level. Free nitrate is found in varying amounts both in brown and red algae (Guiry and Blunden, 1991). The ash content in seaweed is high (15-40%, with maximum values up to 55% of DM) because of the high content of macro minerals and trace elements (Holdt and Kraan, 2011). Seaweeds have relatively low energy content

due to low lipid content and a high dietary fibre content. The cell wall polysaccharides mainly consist of cellulose and hemicellulose, with specific additions depending on the cell wall structure (see Table 1.2). In vitro digestibility of DM is low (29.01 and 24.68%), probably due to the high content of inorganic matter and the presence of complex polysaccharides in seaweed. Holdt and Kraan (2011) concluded that unwashed seaweed offers opportunities for use as a supplement for animal feeding due to its high content of minerals and amino acids. In addition, the high content of polysaccharides and sugars (see Table 1.3) is a potential source for feed and non-food applications.

Table 1.3

Chemical composition of selected seaweeds, which are of interest for North Sea cultivation.

Sources: H & K (2011): Holdt and Kraan (2011); L-C et al. (2012): Lopez-Contreras et al. (2012).

	Group: Brown algae		Red algae		Green algae	
	Genera: <i>Laminaria, Saccharina</i>		<i>Palmaria</i>		<i>Ulva</i>	
	H & K (2011)	L-C et al. (2012)	H & K (2011)	L-C et al. (2012)	H & K (2011)	L-C et al. (2012)
Fresh weight (%)						
Moisture	73-94		84		78-80	
Dry matter (g/kg DM)						
Ash	150-450	270-363	120-270	190	110-550	194
Total protein ¹	30-210	108-124	80-350	178	40-440	235
Total fat	3-21	47-96	2-38	83	3-16	28
Polysaccharides	380-610		380-660		150-650	
Sugars		145-176		405		113
Dietary fibres Total	360				380	

¹) The commonly accepted factor of 6.25 in the conversion of total nitrogen to protein should be treated with caution as, among other factors, content of free nitrate will influence the total nitrogen level. Free nitrate is found in varying amounts both in brown and red algae (Guiry and Blunden, 1991).

1.3.1 Macronutrients

1.3.1.1 Polysaccharides

Seaweeds contain large amounts (15-65% of DM) of polysaccharides as structural components in the cell wall and as storage molecules (Fleury and Lahaye, 1991; Khotimchenko et al., 2001; Lahaye and Ray, 1996; Rioux et al., 2007; see Tables 1.2 and 1.3). The mean dietary fibre content varies between 30 and 60% in some major edible species. The contents and composition of polysaccharides varies considerably between species and with season during the year. The main polysaccharides for brown, green and red macro algae are given in Table 1.2 and in Appendix Table A.1. In addition, seaweed may contain considerable amounts of monosaccharides (Table A.2).

Dietary fibres can be classified as water-insoluble (e.g. cellulose, xylans) and water-soluble (e.g. agar, alginic acid, laminaram). Insoluble non-viscous fibres may increase the passage rate of food in the digestive tract and reduce nutrient digestibility in the small intestine. Soluble fibres may increase viscosity in the digestive tract and delay the nutrient passage and absorption rate, e.g. of glucose. The latter influences post-prandial glucose and insulin peaks and may therefore reduce the risk of metabolic diseases as diabetes. Characteristics of these polysaccharides in animal and human physiology are summarised in Table 1.4. Monogastric species, including humans, do not produce enzymes to digest these fibrous polysaccharides. Hence, part of these components may be fermented in the distal small and large intestine, thus influencing the microbiota composition and the production of fermentation products (Hooda et al., 2011; MacArtain et al., 2007; Brennan, 2005). The proportion of indigestible fibres seems relatively high whereas in vitro studies indicate incomplete fermentation since the amount of short chain fatty acids is less than the disappearance of fibres. This suggests the

production of intermediate components that cannot be readily fermented by the microbiota in the system (Holdt and Kraan, 2011).

Table 1.4

Key characteristics of selected seaweed polysaccharides
Based on a review of Holdt and Kraan (2011).

Polysaccharide	Characteristics
Laminarin	Not viscous, up to 30% in laminaria and saccharina, prebiotic effects, anti-coagulant, anti-tumour properties, modulates the immune system, decreased cholesterol absorption
Alginate	Water-soluble, viscous, alginic acid (polyuronic acid) or salt, 40-50% of DM in brown algae, may bind toxic components and metal ions in the digestive tract, protect mucosa, decrease cholesterol concentration and influence microbiota composition and fermentation products, anti-bacterial effects, prevention of gastric ulcers, haemostatic effects and wound healing
Carrageenan	Water-soluble, viscous, poorly fermentable, affects faecal consistency, potent anti-coagulant, anti-tumour and anti-viral properties against HIV and herpes in vitro but less effect in vivo, hypoglycaemic properties, however may induce colorectal ulceration and inflammatory reactions
Fucoidan	Water-soluble, viscous, up to 40% of DM in cell walls of brown algae, prebiotic effects, anti-coagulant, anti-tumour and anti-viral properties, many immune stimulating and modulating properties, anti-inflammatory agent, natural antioxidant
Agar	Water-soluble, up to 30% in red algae, anti-tumour activity, suppression of pro-inflammatory cytokines
Ulvan	Water-soluble, viscous, poorly fermentable, may amount 40-55% of DM in <i>Ulva</i> species, binding of heavy metals, influencing normal and tumour colonic cells, treatment of gastric ulcers, anti-influenza

Especially brown seaweed species may contain relatively high amounts of polyphenols. Holdt and Kraan (2011) discussed these with respect to their beneficial anti-oxidative properties and potential use for medical purposes. However, in animal diets polyphenols (tannins) may form indigestible complexes with endogenous and dietary proteins, thus reducing the protein digestibility (Tugwell and Branch, 1992). Tannins are considered anti-nutritional factors (see Chapter 6).

1.3.1.2 Proteins and peptides

The mean crude protein content in seaweed dry matter is within a range of 10-20% in brown seaweed, and in the range of 20-50% in red and green seaweed species (Tables 1.3 and A.6). The proportion of non-protein nitrogen may be 10-20% of total crude protein. The content of digestible amino acids determines the protein nutritional value for monogastric species. The contents of amino acids are listed in Table A.3. Compared with soybean meal, being the most important protein source in monogastric diets, seaweed protein is relatively rich in total alanine, glycine, methionine and valine, and relatively low in aspartic acid, glutamic acid, and serine.

Certain seaweed species contain bioactive lectins, a group of carbohydrate binding proteins present in many organisms. Because of protein-carbohydrate interactions with soluble and membrane-bound glycoconjugates, lectins are involved in host-pathogen interactions, induction of apoptosis, agglutination of blood cells, antibiotic effects, mitogenic and cytotoxic effects of the immune system etc. A number of these effects have been described for isolated lectins from seaweed (Verdrengh et al., 2000; Hori et al., 2000; Kawakubo et al., 1999). Despite their potential use in medicine, a high lectin content in the diet maybe harmful for the digestive tract. Further discussion is presented in Chapter 6.

A number of specific peptides have been isolated from seaweed species including decapeptide (Kalahide F) with anti-cancer and anti-tumour activity, hexapeptide (SECMA 1) with effect on cell proliferation and others with specific effects on physiological processes, generally shown in model species as rats or in vitro cell systems. In addition, specific seaweed species may serve as a source of arginine, taurine and other rare amino acids studied for their medicinal properties (Fleurence et al., 1999; Holdt and Kraan, 2011).

1.3.1.3 Lipids

The mean lipid content of seaweed is low, between 0.2 and 4% of DM and varies with environmental conditions (Patarra et al., 2012). The seasonal variation in lipid content however differs between seaweed species. It has been suggested that the ω -3 marine fatty acids, especially EPA (C20:5 n-3), are the predominant fatty acids in seaweed (Holdt and Kraan, 2011). However, a summary of data in their review indicate a large variation between seaweed species with EPA being 1-15% of total fatty acids in *Ulva* and *Laminaria* / *Saccharina* to almost 50% in *Palmaria*. Only *Palmaria* and *Sargassum* seem to contain a relevant amount of EPA, *Ulva* contains a relatively high amount of oleic acid (van Ginneken et al., 2011). In contrast to other plants, seaweeds contain a small amount of C18:4 n-3, which is said to influence the immune system. In addition, seaweeds contain a small amount of phospholipids, contributing to the emulsification and digestion of dietary fat. In conclusion, macro algae are relatively low in lipid content. Only specific species as *Palmaria* may significantly contribute to the supply of ω -3 marine fatty acids (EPA). In a small proportion of compound animal diets marine fatty acids are included because of expected benefits on the health and immune competence of (young) animals or in order to enrich the end product (eggs) with these fatty acids. We do not expect specific benefits of other components included in the lipid fraction like glycolipids and sterols.

1.3.2 Micronutrients

1.3.2.1 Vitamins

Seaweed species contain different types of pigments including chlorophylls, carotenoids (carotenes and xanthophylls) and phycobiliproteins in varying amounts for photosynthesis (Houghton and Hendry, 1995; Rasmussen et al., 2007). Some of these compounds function as vitamins in humans and animals, with β -carotene (provitamin A activity) and tocopherol (vitamin E) as the most important compounds. Several xanthophylls, e.g. lutein, and phycobiliproteins are used as colouring agents in food and feed. In addition, specific compounds from the pigment group have shown a potential application in diagnostic or clinical application (Astorg, 1997; Houghton and Hendry, 1995). The commercial application of seaweed as a source of these components will largely depend, among others, on the content and variability in seaweed, and cost of production in comparison to other potential sources of these products.

1.3.2.2 Minerals

Seaweeds are rich in minerals, with mean ash content varying between 10 and 40% or 5 to 10 times higher than in land vegetable products. Sulphate content is generally high in marine algae. In addition, seaweeds are relatively rich in iodine, potassium, sodium, calcium, magnesium, phosphorus, iron and zinc (see Table A.4). Mineral content and composition varies with seaweed species, season, length of growth period, geographical location etc. (Rupérez, 2002). Furthermore, the bioavailability of minerals is a point of concern because of their linkage with polysaccharides (alginate, agar, carrageenan). The potential fermentation of the polysaccharides in the digestive tract may largely determine the availability of bound minerals (Mabeau and Fleurence, 1993). In human nutrition, a seaweed portion of 8 g DM/d can make a relevant contribution (10-20%) to meet the daily requirements of Ca, K, Na, Cu, and Zn and up to 50% of Fe and Mg whereas this would supply 10-400 times the daily I requirement (MacArtain et al., 2007; Rupérez, 2002). In traditional animal husbandry in Nordic countries seaweed has been used to supplement the vitamin and mineral supply of farm animals. In modern intensive livestock systems, higher recommendations for requirements are used and vitamins and trace elements are largely supplied via an industrial composed standardised premix, without taking into account the contribution of the vegetable ingredients. Therefore the potential contribution of seaweed to the trace element supply of farm animals seems small, unless their content and availability is sufficiently constant to reduce the content in the premix. The contribution of seaweed to the macro mineral supply (Na, Ca, K, and P) can be taken into account in the feed optimisation program, provided that these levels are adequately known. Besides profitable minerals and trace elements, seaweeds can accumulate heavy metals. This aspect is discussed further in Chapter 6.

1.4 World seaweed market

FAO data show that the total traded volume of seaweed has increased five-fold since 1984.² The total value of seaweed increased by about 350% as the value per tonne decreased slightly. Total production in 2010 is estimated at 15m tonnes.

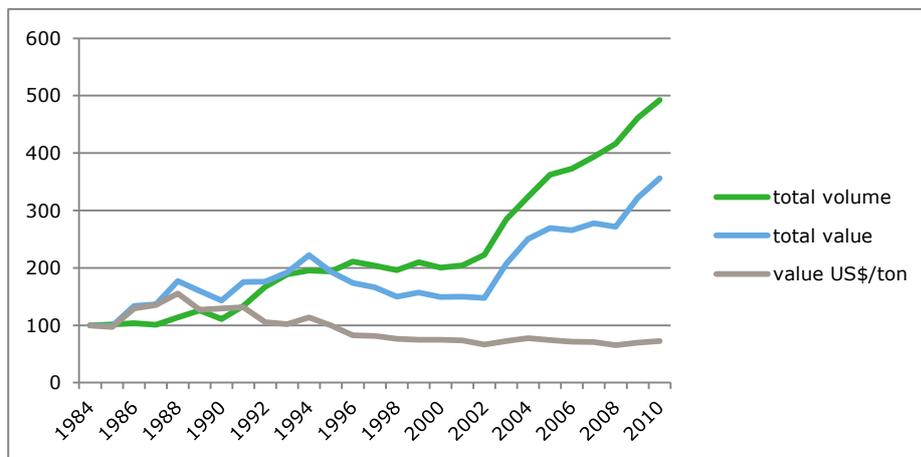


Figure 1.1 Indexed global seaweed volume and value, with reference 1984 (100).
Source: FAO/FishStat (www.fao.org), adapted by LEI.

The value of the world seaweed market was almost €6bn in 2004, over 90% of which was cultivated (Douglas-Westwood, 2005). Asia is responsible for the vast majority of this production, with China and Japan as main contributors. There is a very high market demand in Asia, for human consumption and alginate production. China's demand has outstripped the domestic supply, leading to importing from countries such as Korea. Commercial harvesting occurs in about 35 countries, spread between the Northern and Southern hemispheres. The farming of seaweed has expanded rapidly as demand has exceeded the supply available from natural resources.

Harvesting and use of seaweed is not a new practice in Europe. Historical data shows that the collection of seaweeds was common practice in, among others, Ireland where after burning they were used as fertiliser (Walsh and Watson, 2007). FAO data on European seaweed production shows a sharp decline in the early 2000s when a low of 181 tonnes was reached (2002). Since then, production levels have increased to circa 800 tonnes annually.³

1.5 Relation to European seaweed research

Recognising the potential of seaweed, various research projects are established throughout Europe, investigating different aspects of seaweed production and utilisation. In, among others, Ireland, Norway, Portugal and the Netherlands projects on cultivation techniques are taking place.

- The Irish research project *Development and Demonstration of Viable Hatchery and Ongrowing Methodologies for Seaweed Species with Identified Commercial Potential* aims to 'develop and trial industry-scale hatchery and ongrowing methodologies for a number of seaweed species which have been identified as having commercial value, and to transfer that technology to create new business opportunities in seaweed aquaculture.'⁴
- A Norwegian and Portugal based company investigates the possibilities for large-scale seaweed production in various locations, believing that 'bioenergy production utilising the Earth's vast oceans

² <http://www.fao.org/fishery/statistics/global-aquaculture-production/en> [18-3-2013]

³ <http://www.fao.org/fishery/statistics/global-aquaculture-production/en>. [13-3-2013]

⁴ <https://www.marine.ie/home/aboutus/newsroom/pressreleases/Seaweedfarmingproject2010.htm> [4-12-2013]

offers tremendous opportunity as a worldwide renewable energy resource. Current advanced and proven technologies in marine biology, offshore structures, aquaculture and biomass processing are bringing this promise ever closer to commercial reality'⁵

- The Dutch province Zeeland has co-funded a research project that investigates how seaweed can be produced effectively in the Eastern Scheldt. Wageningen UR is a partner in this project.⁶

A European-wide project on market development titled Netalgae 'aims to create a European network of relevant stakeholders within the marine macroalgae sector. Compilation of information from different regions will result in a wide ranging policy study of existing practice within the macroalgae industry.'⁷

Various projects investigate the potential of seaweed as source for biofuel. The Biomara project aims to demonstrate the feasibility and viability of producing third generation biofuels from marine biomass.⁸ The Crown Estate has also commissioned research that analyses this potential, with a focus on biogas production (Kelly and Dworjanyn 2008).

The Seaweed Biorefinery project, funded under EOS LT, aims to adapt the biorefinery concept to seaweed. There are many potential applications for the products of the biorefinery. Seaweed components or products derived thereof can be used as building blocks for polymers, starting materials for bleach activators, carbohydrate derived chemicals etc. Wageningen UR is involved in this research project.

Lastly, there are various research projects that investigate whether it is possible to combine offshore seaweed production with offshore wind parks in MUPS. This includes:

- Blauwdruk, an EFRO project in which an ecological and economic model to evaluate production of seaweeds and mussels in offshore wind parks is being developed. Wageningen UR participates in this project.
- The work of the Alfred Wegener Institute for Polar and Marine Research in Germany, experimenting with offshore seaweed cultivation in the German Bight (Buck and Buchholz, 2004).
- An Ecofys research project that aims to show whether a seaweed production module is 'position accurate' and can be used in offshore wind farms.⁹
- An FP7 project Mermaid which is geared at the design of MUPS in collaboration with the concerned stakeholders. Seaweed is among the envisioned production functions for the North Sea case-study. Wageningen UR is involved in this project.

1.6 Purpose of the feasibility study

This research focuses on the production, processing and profitability of seaweed as a source for feed and non-food applications. Current production is concentrated in Asia. The North Sea climate is favourable for production of seaweed but at this moment, there is no commercial production. Research on production techniques and application of produce for feed, food and energy still takes place. Private actors are uncertain about the future value-chains of offshore produce. Furthermore, it is not clear how to organise the offshore production and value chains, given the huge number of stakeholders involved and the absence of established procedures.

This project differs from other ongoing research in the following aspects:

- It combines knowledge from various research projects that Wageningen UR is involved in, integrating knowledge from various disciplines;

⁵ <http://www.seaweedenergysolutions.com/> [13-3-2013]

⁶ http://provincie.zeeland.nl/milieu_natuur/duurzame_energie/zeewierteelt/ [13-3-2013]

⁷ <http://www.netalgae.eu/netalgae-project.php> [13-3-2013]

⁸ <http://www.biomara.org/> [13-3-2013]

⁹ (<http://www.ecofys.com/en/press/ecofys-launches-trial-module-for-seaweed-cultivation-in-offshore-wind-farm/>); [13-3-2013]

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- The project includes the feasibility of seaweeds for feed, which is not given much attention in other research projects;
 - The feasibility of seaweed production is shown from a Triple P perspective.

This project is part of the Wageningen UR TripleP@sea research programme and consists of three components that will be addressed in four years of research. In component 1, the production of seaweed is addressed. The overarching question is what production system will look like, improving the performance while reducing risks. In component 2, we address the usage of the seaweed produced, describing how products be used with a focus on feed (animal and fish), and non-food usages. The third component focuses on the license to produce. Under what conditions seaweed production could take off, in an economically and socially sensible manner?

The objectives of the first year are the following:

- Integrate existing knowledge on the feasibility of offshore seaweed production
- Identify knowledge gaps
- Based on the above, conclude on the feasibility of offshore seaweed production and usage where possible
- Identify research challenges for the following years

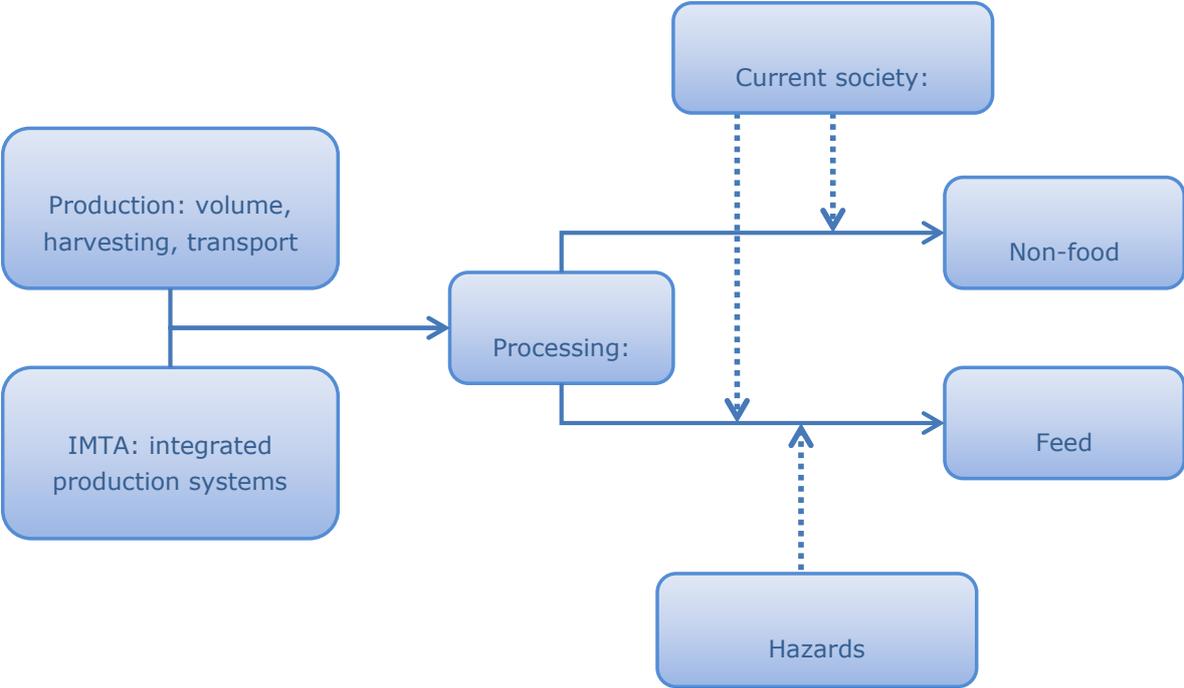
1.7 Reading guide to the feasibility study

This report consists of two main parts. In the first part, a state-of-the-art of knowledge about seaweed production is presented, either in separate production systems (chapter 2) or in combination with fish farming (Chapter 3), processing (Chapter 4) and use in diets for farm animals and fish (Chapter 5). Hazards are described for feed and food production in Chapter 6. Chapter 7 describes non-food applications of seaweeds.

In the second part, the feasibility of North Sea seaweed production is assessed from a Triple P perspective, addressing economic feasibility (Chapter 8), the ecological feasibility (Chapter 9) and social feasibility (Chapter 10).

Special acknowledgements for Dr. L.W.D. van Raamsdonk from RIKILT Wageningen UR for providing an extensive review of this report.

Part I: STATE OF THE ART



2 Growing conditions and production of selected seaweed species

2.1 Overview of North Sea species

Starting point in this report is a focus on seaweed species endemic to the North Sea area. Endemic North Sea seaweed species with the most potential are the following (Reith et al., 2005):

- *Laminaria digitata* (Finger kelp; brown seaweed)
- *Saccharina latissima* (Sugar kelp; brown seaweed)
- *Palmaria palmata* (Dulse; red seaweed)
- *Ulva lactuca* (Sea lettuce; green seaweed)

In the past, various alien seaweeds have found their way to the North Sea, sometimes with adverse effects on ecosystem (Williams and Smith, 2007) and other production species (Ducrotoy et al., 2000). For example, the brown seaweed *Sargassum muticum*, either introduced with Japanese oyster brood or through ballast water of ships, has now begun to colonise mussel beds in Germany resulting in the displacement of native species (Schories et al., 1997). Soon after its introduction it caused large populations in harbours and estuarine areas, such as the Eastern Scheldt (the Netherlands), due to its high reproduction rate and fast growing nature in warmer waters (up to 22°C). Collection of this species can be an interesting alternative source of seaweeds but is for now excluded from this research.

Growth patterns and growth potential of these seaweed species are described in this chapter, drawing upon first-hand experiences in ongoing seaweed production test in the Eastern Scheldt and in the North Sea. Findings of these tests are often not yet published. As a result, the overview in this chapter is either based on public literature or on continuing research of Wageningen UR.

2.1.1 *Laminaria digitata*

Among the four candidate species, this one is the most robust species. It has already been cultivated under North Sea conditions. The growing period is September - March >> May. Starting from seedling lines that are twisted around the production lines, it grows from 4mm seedlings up to 2m long kelps, as is observed in 2011 at de Wierderij. Primary growth starts from the base of the thallus whereas secondary growing zones (meristoderms) are responsible for its typical fingered shape. It can create a constant quality of biomass. It grows under low temperature conditions: above 18°C, the thallus starts to degrade fast. During wintertime the thallus grows well, the majority of nitrogen is just stored until early spring, when it starts to make its protein content and further secondary metabolites (Lüning and Pang 2003). Subject to further investigations is whether repeatedly harvesting will increase production volumes and will prevent unwanted growth of Bryozoa and other organisms on the thallus, whether we can grow the species for more years, and the determination of the optimal size of the seedlings when fixed to the production rope for the grow out phase.



Figure 2.1 *Laminaria digitata*.

2.1.2 *Saccharina latissima*

Also known as sugar Kelp, this is another candidate species that, although less robust, has proven its ability to grow under North Sea conditions. With regard to cultivation opportunities a marked difference with *Laminaria digitata* is that it is a short living species and has to be grown every year from fresh seedlings. Primary growth starts from the base of the thallus whereas secondary growing zones (meristoderms) are responsible for its latitudinal growth. Like *L. digitata*, the growing season runs from September until March - May: the kelps growing from 4mm, end of August to 2.5m tall, one-bladed thalli. It also grows under low temperature conditions. It is more susceptible to herbivores and as the thalli are less leathery than those of *L. digitata* a better substrate for Bryozoa and other colonisers. Apart from its adaptation to low temperature conditions, it is therefore not suitable for extended cultivation into summertime. Subject to further investigations is whether repeatedly harvesting will increase production volumes until May and the determination of the optimal size of the seedlings when fixed to the production rope for the grow-out phase.

2.1.3 *Palmaria palmata*

As far as we know, with *Palmaria Palmata*, there is no experience of cultivation under North Sea, but the species is interesting by its high protein content (up to 35% of DM). Under natural conditions it's a slow growing species, but preliminary results from growing at lab scale (Nergena, Wageningen), show that under cultivation conditions it can grow faster. Apart from producing inoculating seedling lines, it may also be propagated vegetatively like *Ulva*. Subject to investigation is whether it may grow during summer time.



Figure 2.2 *Palmaria palmate*.

2.1.4 *Ulva lactuca*

A fast growing seaweed (under optimal conditions 50% daily increase of DM) growing in shallow waters or at the sea surface. Under natural conditions starting from a small obstacle (stone, shell) it has a fragile stipe and a diffuse growing thallus, because of its fragile stipe it is rather soon floating seaweed. This seaweed can be vegetatively propagated and therefore directly fixed to the production rope. Since it is a green seaweed it needs a lot of light and grows during summer months. During the summer months it has to be repeatedly harvested each three weeks. Critical success factors are its fragile nature the need for repeatedly harvesting by its fast growing nature, its need for relatively high temperatures (15-20°C) and the fact that we cannot explain its sudden disappearance. It is questionable whether it can be grown under North Sea conditions. In 2011 under estuarine conditions (de Wierderij, Schelphoek, Eastern Scheldt) we have observed good growth and repeatedly harvesting was possible during the period May - August).

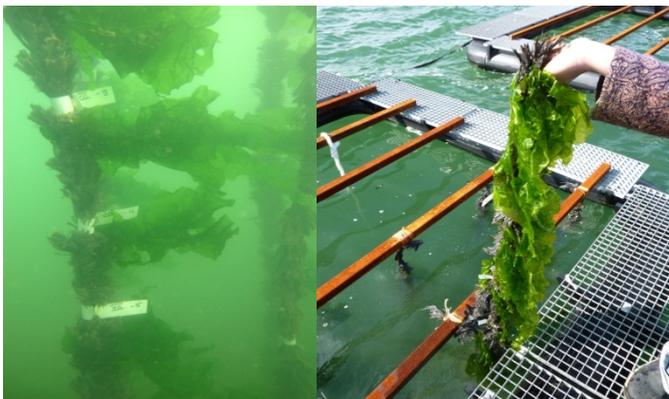


Figure 2.3 *Ulva lactuca*.

2.1.5 Overview of North Sea species

In Table 2.1, four species of seaweeds are presented on different categories of growth conditions, respectively: growth seasons, optimal water temperature, wave conditions, nutrients, grow speed, yield, vulnerability for diseases and production risks.

Table 2.1

Overview of growing conditions of North Sea seaweed species.

Group:	Brown algae	Red algae	Green algae
Species:	<i>Laminaria digitata</i> , <i>Saccharina latissima</i>	<i>Palmaria palmata</i>	<i>Ulva lactuca</i>
Growth season	September-May	Presumably summer	Summer
Optimal water temperature	<18	15-20	15-20
Wave conditions		Uncertain whether it can withstand harsh conditions	Uncertain whether it can withstand harsh conditions
Nutrient requirements	During wintertime, it just stores nitrogen in its tissue, to produce proteins during early spring	Uses all nitrogen sources during summer	Uses all nitrogen sources available in warmer water
Grow speed	Up to a daily increase of DM of 20% under optimal conditions	Up to daily increase of 35% of DM under optimal conditions	Up to a daily increase in DM of 50% under optimal conditions
Yield/ha (DM)	15	15-20	20
Vulnerability diseases	Colonised by several organisms, thus hindering its growth during spring and summer	Unknown	It tends to be free floating under harsh conditions
Production risks	Fast degradation in spring (<i>Saccharina latissima</i>)	As semi perennial seaweed it is unsure whether the plant will recover after wintertime	Sudden disappearance

2.2 Production systems

Currently, seaweed is not farmed in the North Sea. Tropical experiences with marine and brackish water seaweed cultivation are not comparable to seaweed farming in marine temperate waters like the North Sea. In China farming takes place near-shore and relies heavily on manual labour (Lüning and Pang, 2003). Offshore seaweed cultivation requires a degree of mechanisation that is not seen in tropical marine and brackish water regions. Various research projects investigate if and how seaweed farming is possible in marine temperate waters including the North Sea (Reith et al., 2005). These projects use various technologies and are only yet concept based.

Only in Germany, the US and Japan have pilot scale net and rope systems, either vertically, horizontally or circle shaped, been tested offshore. From these experiments a range of production indicators have already been published (Buck and Buchholz, 2004; Buck and Buchholz, 2005), such as from 3-12 kg per m of line. With 5,000m of lines per ha, production levels of 20 tonnes of DM per ha can be foreseen. However, regarding the seaworthiness of the offshore tested systems many operational problems were encountered such as drifting of the anchored systems and losing the attached seaweed on the lines/netting because of heavy swell and/or currents. Figure 2.4 and 2.5 shows conceptual designs for offshore seaweed cultivation.

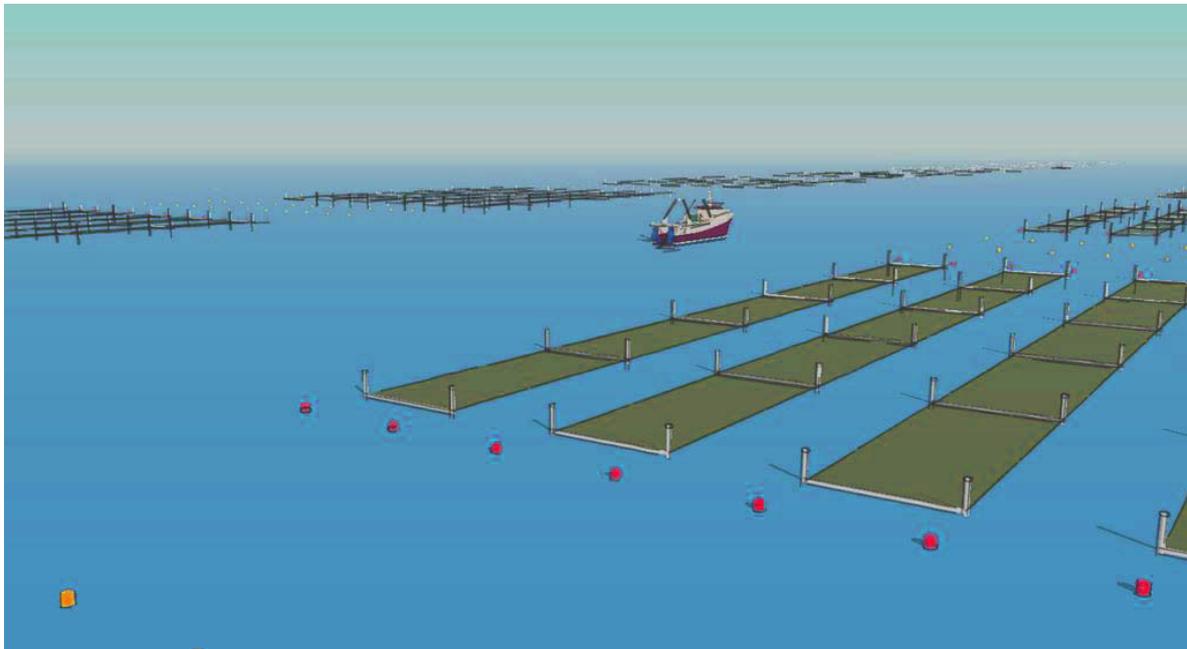


Figure 2.4 Concept offshore seaweed installations.

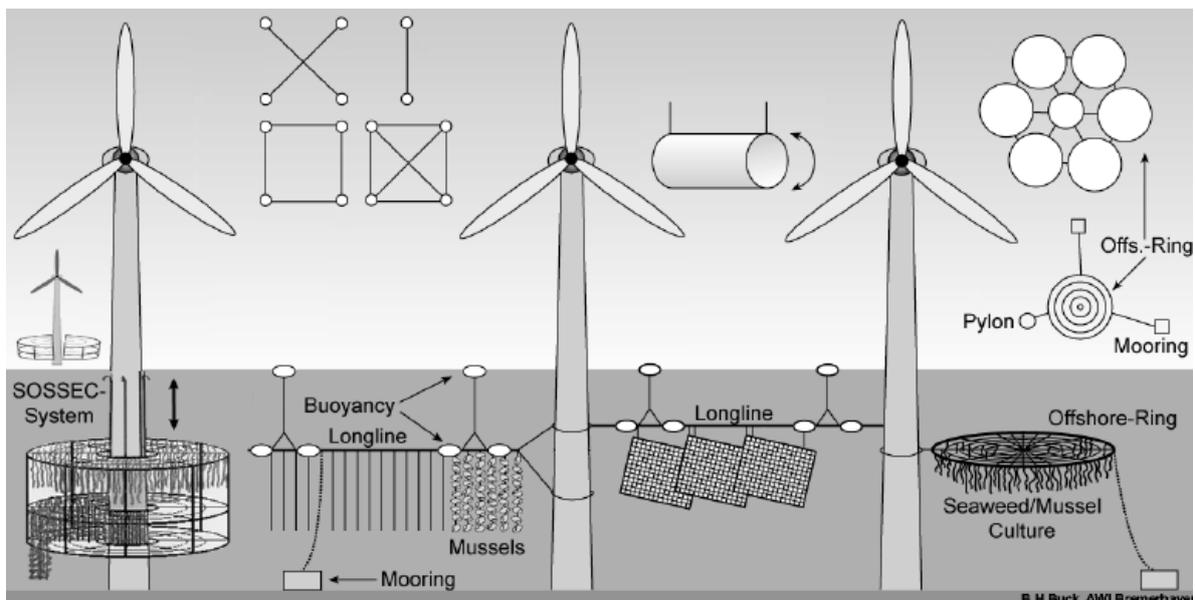


Figure 2.5 Concept multi-use installations for offshore wind and seaweed (Buck and Buchholz, 2004).

2.3 Synthesis

Experiments with offshore cultivation of these species are currently conducted and show that various seaweed species can grow under North Sea conditions. Each species has its own growth characteristics, and bottlenecks.

Ulva lactuca is a fast growing seaweed (under optimal conditions 50% daily increase of DM) growing in shallow waters or at the sea surface. It grows during summer months and has to be repeatedly harvested each three weeks. *Laminaria digitata* is one of the most robust species. It has already

grown under North Sea conditions. The growing period is September to March >> May. Starting from seedling lines that are twisted around the production lines, it grows from 4mm seedlings up to 2m long kelps. *Saccharina latissima* is another candidate species that, although less robust, has proven ability to grow under North Sea conditions. With regard to cultivation opportunities a marked difference with *Laminaria digitata* is that it is a short living species and has to be produced every year from fresh seedlings. Like *L. digitata*, the growing season runs from September until March - May: the kelps growing from 4mm end of August to 2.5m tall, one-bladed thalli. Regarding *Palmaria palmata*, so far there is no experience of cultivation under North Sea, but the species is interesting by its high protein content (up to 35% of DM). Under natural conditions it is a slow growing species.

3 Integrating seaweeds in production systems as tool for nutrient management

3.1 Introduction

Extractive species such as seaweeds and bivalves are able to remove (in)organic nutrients from the water column and can thereby be applied as bioremediation measure for eutrophication. Over the past decades the nutrient inputs to the aquatic system have increased as a result urban runoff, agriculture, and wastewater treatment leading to eutrophication of the receiving water bodies. Through culture of extractive species, biological organisms can be included in nutrient management strategies. Lindal et al. (2005) already proposed that bivalves can be incorporated into a nutrient trading system as an alternative to nutrient (nitrogen) reduction for improving coastal water quality. Similar concepts also apply to seaweeds.

In open water finfish aquaculture there is also increasing concern about the negative environmental effects related to nutrients discharged from fish cage aquaculture. One possible solution for this is to use the extractive properties of for example seaweeds and bivalves to remove these nutrients. This concept is known as Integrated Multi Trophic Aquaculture (IMTA). In open seas, IMTA fits with the concept of 'ecosystem-based management' as each activity is placed in a wider ecosystem context and managed so that it contributes to the sustainable development and equity of the whole (Ryther et al., 1975).

The current chapter describes a conceptual model for a marine IMTA system in which different species, including seaweeds, are combined to optimise total production and mitigate potential negative environmental impacts. The focus in this chapter is directed towards species selection for the North Sea and subsequently the objective is to exam the feasibility of developing IMTA systems in this area based on technological and biological factors.

3.2 The concept of integrated aquaculture

In IMTA systems different cultures are linked with the goal to maximise 'input' nutrient retention into harvestable products. Finfish retain only a fraction of the nutrients provided through feeding, and the other fraction is released in organic (feed/faeces) and inorganic (metabolic waste products) forms. The IMTA approach re-uses nutrient emission from fed finfish aquaculture and thereby creates value-adding products such as seaweeds, bivalves and/or other sources of marine proteins (Figure 3.1). IMTA is a wide-ranging concept and numerous examples are known both in freshwater and marine systems including a range of different species (Neori et al., 2004).

To encourage stakeholders (e.g. fish farmers) to get involved, it will be necessary to design profitable and environmentally sustainable IMTA systems which couple nutrient removal efficiency with high productivity. To achieve these goals it will be important to recognise economic drivers (species) of the IMTA system that have inherently valuable commodities.

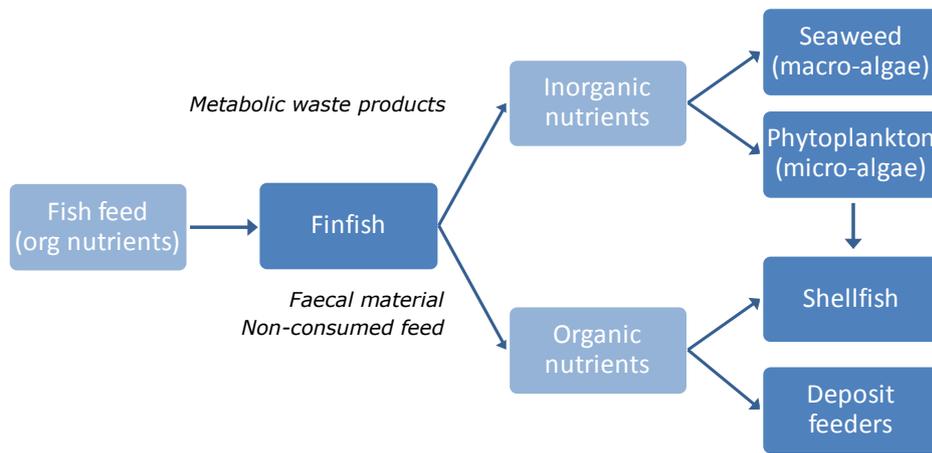


Figure 3.1 Example of an IMTA-flow diagram.

3.3 Species selection for IMTA in the North Sea

3.3.1 Finfish culture

As to date, no fish culture activities take place in the Dutch North Sea. The conditions in the North Sea differ from the conditions in locations where most of the European aquaculture production is realised nowadays (Norway, Mediterranean). Therefore it is not possible to directly apply common culture techniques to the North Sea situation. Besides the specific hydrographical conditions, the space for aquaculture along the coast and in the North Sea competes with a multitude of other functions in these areas. Combining aquaculture with other functions (e.g. wind energy) is therefore frequently proposed. The challenge of planning and organising combinations of functions is addressed in Chapter 10.

Fish, like any other organism, have specific requirements for its environment. In a culture setting, the optimal environmental conditions should be achieved in order to realise fast growth and a profitable production. Water temperature is an important parameter affecting growth rates. The specific environmental conditions in the North Sea are not suitable for all species of economic interest. Reijers et al. (2008) performed a step-wise selection procedure to test which finfish species have highest potential for culture in the Dutch North Sea. The procedure consisted of the following steps: (1) list species which naturally exist in the North Sea (non-native species were excluded), (2) examine biological, technical and economic feasibility for each species, (3) scan which locations in the North Sea are suitable for each species based on temperature and current speed. Species excluded in one of the steps were not further analysed in the succeeding steps. Results from this study indicated that in the Dutch North Sea the culture potential is highest for seasonal culture where fast growers are fattened (Appendix to Chapter 3 -Table 1). Based on these criteria only the Bluefin Tuna and Cod are promising species for aquaculture in the North Sea. Production of Cod is only feasible when systems are available that can be situated at lower depths during the warm summer months. Consequently, depth is a restriction to location choice for this type of culture. Production of Bluefin Tuna may be realised during the summer season.

3.3.2 Shellfish culture

Shellfish are extractive species removing organic particles from the water column, indicating that no feed source is added in this type of culture. Organic particles consist of micro-algae, detritus, and in case of IMTA food/faeces particles originating from the finfish component. That shellfish can benefit from fish cage effluents was shown in various studies. Most recently, using a Dynamic Energetic Budget (DEB) model Sarà et al. (2012) predicted close to double growth of a mussel species (*Mytilus*

galloprovincialis) and the pacific oyster (*Crassostrea gigas*) within 100 m of fish cages compared with areas not influenced by fish farming. This concurred with an empirically monitored 45% higher Chla concentration close to cages, indicating that food levels for bivalves increased due to enhanced primary production (stimulated by inorganic nutrient release). However, care should be taken for each specific situation as a study by Both et al. (2011), comparing blue mussels in normal seawater to mussels receiving an effluent from an Atlantic cod farm, recorded changes in the mussel's fatty acid composition. This indicated that cod farm effluent lacked essential fatty acids, which negatively affected mussel growth.

Four shellfish species have been identified as 'promising for culture in the Dutch North Sea': the blue mussel (*Mytilus edulis*), flat oyster (*Ostrea edulis*), pacific oyster (*Crassostrea gigas*), scallop (*Pecten maximus*) (Reijs et al., 2008). For the current study focus will be given to mussel culture because this is an important sector in Holland. The mussel sector has an average yearly production of 50.000-60.000 tons, and there is commercial interest to expand mussel culture from the Wadden Sea and Delta towards offshore areas. There are also pilot scale examples in other countries providing some data and reference material for mussels, while information on e.g. suspended offshore oyster and scallop culture are currently not available. It should be noted that the research on offshore mussel culture is dominated by reviews and desk studies, and few resources are invested in field scale trials to identify the best offshore production concepts, thereby improving the quality of the knowledge to the current topic. Commercial viable culture systems for offshore mussel production of mussels are used for green lipped mussels in New Zealand (Cheney et al., 2012). There are initiatives for pilot scale offshore mussel culture in Belgium, Germany, UK, Ireland, Denmark, France, Italy (for details see Kamermans et al., 2011), but technical feasibility at a commercial scale still has to be proven.

Buck et al. (2010) provided an economic feasibility study for offshore mussel culture within areas used by wind-farms in the Germany Bight (theoretical, based on results of a pilot-scale culture). From this study it can be concluded that suspended mussel culture with longlines in offshore cultivation areas can be profitable. The extent of profitability depended on the possibility of using existing equipment and the type of culture chosen (consumption mussels, seed mussels) (Table 2 in the Appendix to Chapter 3). The break-even-points for mussel consumption shown in Table 2 (Appendix to Chapter 3) are below the price at auction in Yerseke over the past years.¹⁰ Since mussel seed is not brought onto the market it is difficult to put a value to it. MZIs (mussel seed collectors) in the Waddensea and Oosterschelde have average yields between 2-3 kg m⁻¹ (MarinX 2011), which is below the break-even-yield shown by Buck et al. (2010; Table 2 in the Appendix to Chapter 3).

3.3.3 Seaweed culture

Seaweeds are, like shellfish, extractive species which remove inorganic nutrients from the water column. Within an IMTA context these species can be applied to remove e.g. ammonia excreted by the finfish component. Positive effects of cage aquaculture on seaweed production seem to be site and situation dependent. Suspended cultures of *Gracilaria chilensis* close to salmon cages reached a production of 800 g m⁻² month⁻¹ which was twice as high as at control (non-farm) sites. On the other hand, Halling et al. (2005) could not detect a fertilising effect of fish farm effluents on *G. chilensis* in open sea experiments close to salmon cages. *Ulva* sp. grown close to fish cages in the Mediterranean showed above background level growth when cultured within 150 of fish cages. This concurred with higher levels of N and P in the *Ulva* sp. grown closest to the cages (Dalsgaard and Krause-Jensen, 2006).

3.3.4 Deposit feeders

A large share of the particles originating from finfish farms settle quickly at the seafloor. Although deposit feeders are considered important species in land-based IMTA systems, there are only a few examples for marine open water IMTA systems where deposit feeders are added to the set of culture

¹⁰ <http://www.visserijnieuws.nl/component/content/article/70-archieff-2011/7474-meer-mosselen-over-zeeuwse-klokomzet-mosselfeiling-yerseke-stijgt-met-137-miljoen-naar-70-miljoen-euro.html> [04-12-2012]

species. In Canada the CIMTAN project recently introduced sea urchins and sea cucumbers to their systems (personal communication G. Reid). Integrated aquaculture in Scotland and Ireland combines intensive aquaculture (Salmon) with extractive species such as seaweed (inorganic extraction), blue mussels and sea urchins (organic extraction) (Kelly and Chamberlain 2010). No or little biological data (growth rates under IMTA conditions), and economic data are available.

3.4 Synthesis

Fish culture appears to be challenging in the Dutch North Sea as there are technical and biological constraints for production and just a few sites might be suitable for fish culture. Therefore it is advised for the first stages in the development of MUPS to focus on the development of mussels and seaweed production. For mussels there is a clear commercial interest and the market is already established. When shellfish and seaweed cultures are established it is easier to add a module of finfish. As the fish component is then directly integrated with mussel and seaweed modules.

Development of technical solutions for offshore culture of bivalves, seaweeds and even fish culture are a key issue for aquaculture development in offshore areas. It is also important to define the growth potential of each species for the specific environmental conditions in the North Sea.

IMTA systems have the aim to reduce the environmental impact and it is therefore important to select species groups that are able to capture the waste streams originating from the higher trophic levels. (Shell)fish produce faecal material which is in theory available for deposit feeders. In low turbulence areas it has indeed been shown that faecal production increases the organic loading to the seafloor (both for fish and shellfish production). In high turbulence areas, like the Dutch North Sea, it is questionable whether particles originating from the (shell)fish farms will settle in the proximity of the farm or whether resuspension and high current regimes will transport particle fluxes away at longer distances. Hydrodynamic modelling approaches and/or pilot studies around offshore (shell)fish farms should therefore first indicate that enough particles are available before the production of deposit feeders should be considered. Due to the high turbulence in the North Sea particles might actually be transported far away from the farm.

4 Processing of seaweed

4.1 Introduction

The rapid developments towards a biobased economy have led to increasing global demand for sustainable renewable transport fuels (biofuels) and platform chemicals. There is a need to reduce dependency on fossil fuels and to find sustainable alternative processes for fuels and chemicals with less negative environmental effects. Different types of plant biomass, including energy crops, cereals and agricultural by-products, are considered promising feedstock, or starting materials, for the production of fuels and chemicals. This requires a so-called biorefinery approach in which the whole biomass is being valorised into a range of different products (Luguel, 2011). The most developed biorefinery concepts are currently based on lignocellulosic feedstock, where sugars are fermented into ethanol or other energy carriers and other fractions (such as lignin) are converted into high value chemical additives (Cherubini, 2010). To meet the expected increasing demand for biofuels and biochemicals, and to diversify the feedstock and product portfolio of biorefineries, there is a need to find additional suitable biomass sources, in particular those that do not rely on using large amounts of agricultural land. This explains recent interest in the use of biomass supplies originated from aquatic environments, such as seaweeds (Lüning and Pang, 2003; Subhadra and Grinson, 2010; John, 2011; Holdt and Kraan, 2011).

Currently, the main seaweed processing industry is the hydrocolloids extraction sector, producing alginate, carrageenan and agar (see Chapter 8). With the development of cultivation techniques that can ensure reliable supply of seaweeds at high volumes and constant quality, the use of seaweed components as feedstock for chemicals and fuels becomes interesting. This can lead to new applications for current products, or development of new products from fractions that currently are not commercialised. The biochemical composition of seaweeds differs significantly from that of lignocellulosic biomass, and fractionation and chemical conversion processes suitable for plant biomass are not directly applicable to seaweeds (Adams, 2009; van der Wal, 2013). Using a biorefinery approach, the entire seaweed biomass could be used for different purposes. Potential applications include sugars and polysaccharides as chemical building blocks or as substrate for fermentative processes, mineral residues for fertiliser applications, proteins for food, feed or non-food applications and other residues for bioenergy (Reith, 2005).

4.2 Composition

The composition of seaweed varies greatly depending on the seaweed type (Kraan, 2011). The biochemical composition of different seaweed species for biorefinery purposes has been determined recently within the Wageningen UR project 'Seaweed biorefinery' (López-Contreras, 2012). The composition of four different North Sea native seaweed species belonging to the three different major seaweed phyla (red, green and brown) was determined. These species, which were selected based on their availability, good potential to be cultivated under controlled conditions and relatively high content in sugars and proteins, were *Laminaria digitata* and *Saccharina latissima* (brown), *Palmaria palmata* (red) and *Ulva lactuca* (green). The amounts of ash, protein, fat, polysaccharides and free sugars were determined in freeze dried samples of biomass harvested at the coast of Ireland (see Table 1.3). Further details on composition are presented in Chapter 1.

4.3 Biorefinery routes

Residues of the current hydrocolloids extraction industry are used as fertiliser or feed-component (McHugh, 2003). To date, seaweeds have not been well studied for biorefinery processes as such in which individual components are fractionated and further used for bioenergy and high value

applications. To our knowledge, there are no public reports or scientific literature available where seaweed-based biorefinery is described and characterised in detail, although the potential of seaweeds for production of fuels and chemicals has been described (Holdt and Kraan, 2011). Based on the results of the biochemical composition obtained during the EOS-LT Seaweed Biorefinery project, the suitability of the brown seaweeds above mentioned for biorefinery routes was assessed (Harmsen, 2011). *Laminaria digitata* and *Saccharina latissima* are rich in mannitol and alginates, which can be extracted and be used as such for applications in the food industry or serve as precursors for other compounds (McHugh, 2003). To our knowledge, the red species *Palmaria palmata* does not have industrial applications yet, but it is rich in xylose, which could be extracted and used as feedstock for the biological production of fuels and chemicals, such as ethanol or butanol. The green seaweed *Ulva lactuca* is considered as promising source of proteins, since approximately 25% of its DM is protein, and this species has been extensively characterised (Fleurence, 1995). Sugars in *Ulva lactuca* can be efficiently extracted using a mild pre-treatment followed by enzymatic hydrolysis and are fermented into acetone, butanol, ethanol and 1,2-propanediol (van der Wal, 2013). Based on this work, a biorefinery scheme for *Ulva lactuca* has been proposed and is shown in Figure 4.1.

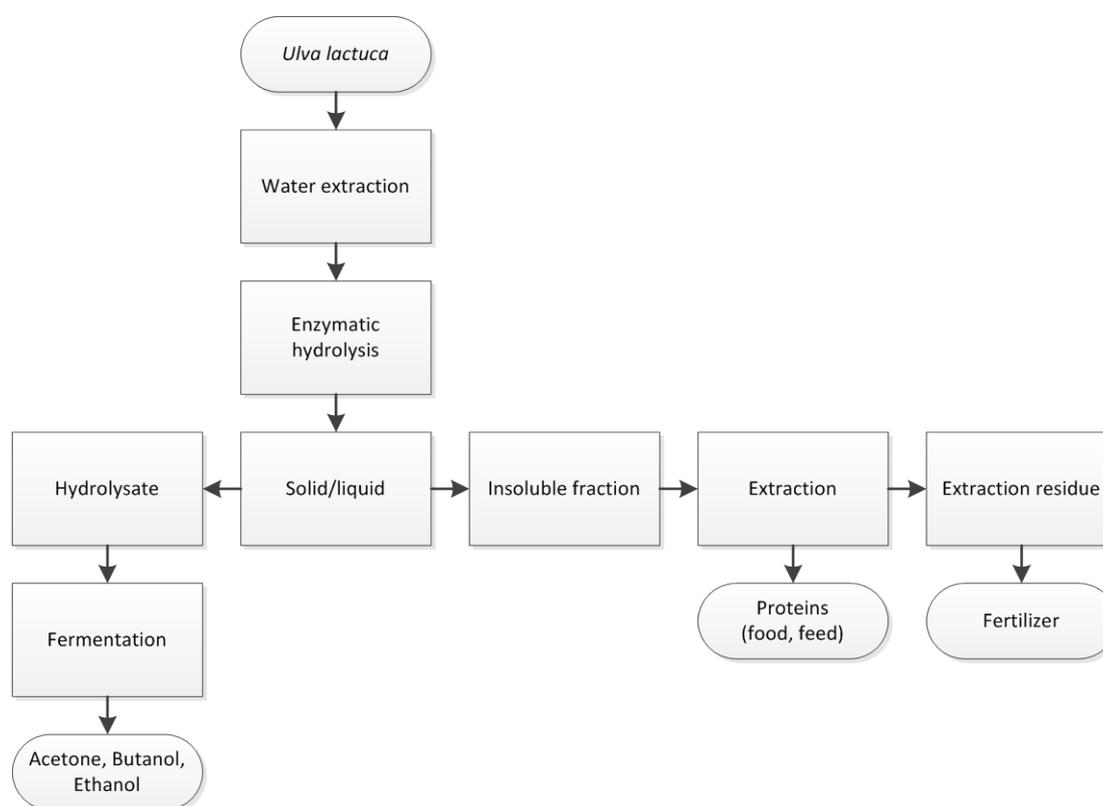


Figure 4.1 Proposed biorefinery scheme for the green seaweed *Ulva lactuca*, based on Van der Wal et al. (2013).

4.4 Processing of seaweed

4.4.1 Dewatering

Fresh seaweeds have high water content, 75 to 85% of its fresh weight is water. In the biorefinery concept the seaweed is dewatered (or dried) after harvesting in order to reduce weight of the biomass. After dewatering, the seaweed is fractionated into its main components (i.e. sugars, proteins and minerals), the so-called primary biorefinery. In the secondary biorefinery, these components are converted into bulk chemicals and energy carriers.

Experiments with fresh *Laminaria digitata* revealed that, although seaweed contains a lot of water, it is very difficult to remove. Removal and subsequent discarding of water from seaweed on sea will result in substantial loss of DM, including valuable components like mannitol (Harmsen, 2011).

4.4.2 Recovery of carbohydrate fraction from seaweeds

4.4.2.1 Pressing

Fractionation of the brown seaweeds *Laminaria digitata* and *Saccharina latissima* by pressing of the fresh biomass in a screw press resulted in a press cake (70-75 wt%) and a press liquid (25-30 wt%) (Harmsen, 2011). Increase of the DM content of the press cake was limited, but the total sugar content of the press cake was reduced with 20 wt%, mainly due to the removal of mannitol. Analysis of the press liquid revealed that the mannitol concentration was 10 g/l for *Laminaria digitata* and 16 g/l for *Saccharina latissima*.

4.4.2.2 Extraction

Horn et al. (2000) and Huesemann et al. (2012) adapted a method from Percival and McDowell (1967) to extract sugars from seaweeds (Horn, 2000; Huesemann, 2012). Horn extracted one kg of fresh, milled seaweed (*Laminaria hyperborean*) in 1 l of tap water at pH 2 and 65 °C for 1h and obtained extracts with approximately 20g/l of both manitol and laminaran. Huesmann extracted freeze-dried and milled *Saccharina* spp. under the same conditions. The extract was further concentrated by freeze-drying to achieve a mannitol concentration of approximately 52 g/L.

4.4.2.3 Enzymatic hydrolysis

Adams (2009) showed that acidic pre-treatments were not necessary prior enzymatic hydrolysis to obtain good hydrolysates for fermentation. In their study, higher ethanol yields were achieved in untreated fractions compared with those in which the biomass has been subjected to altered pH or temperature pretreatments (Adams, 2009). This result was seen both in fresh and defrosted samples from *Saccharina latissima* with laminarinase as enzyme. Results showed highest ethanol yields of 0.45% (wt/wt) and the largest reduction in laminarin when no pretreatment was employed in both fresh and defrosted substrates. This single-stage hydrolysis would reduce the number of steps necessary for solubilisation of sugars in seaweeds and result in lower processing costs. Similar yield patterns were obtained in fermentations with fresh and defrosted seaweed, implying that future fermentations on fresh and defrosted seaweeds would be comparable.

In the case of the green seaweed *Ulva lactuca*, the solubilisation of 75-90% of the total carbohydrates has been reported by applying water extraction followed by enzymatic hydrolysis using commercial cellulases (van der Wal, 2013).

4.4.2.4 Dilute acid hydrolysis

Acid hydrolysis at elevated temperature (120-150 °C) has been applied as an alternative for enzymatic hydrolysis, having advantages of low-cost, short hydrolysis time and simple operation (Jang, 2012). They solubilised carbohydrates in dried samples of *Ulva pertusa* (green), *Laminaria japonica* (brown) and *Gelidium amansii* (red) using sulfuric acid and hot-compress treatment. Rhamnose (37.89 wt. %) and glucose (16.14 wt. %) were extracted from *Ulva pertusa*, while galactose (49.32 wt. %) and glucose (12.62 wt. %) were extracted from *Gelidium amansii*, and mannitol (31.53 wt. %) was the main soluble sugar in *Laminaria japonica* hydrolysates. In another study, diluted acid hydrolysis using sulphuric acid has been applied to a green seaweed (*Ulva lactuca* harvested in a Bay in New York) for the production of hydrolysates for butanol production (Potts, 2012).

4.4.2.5 Dilute acid- combined with enzymatic hydrolysis

Wang et al. developed a saccharification method for the production of ethanol from *Gracilaria salicornia* (red). Dilute acid hydrolysis (120 °C and 2% sulfuric acid for 30 min) of the homogenised plants yielded a low concentration of glucose (4.3 g glucose/kg fresh algal biomass), whereas a two-stage hydrolysis (combination of dilute acid hydrolysis with enzymatic hydrolysis) produced 13.8 g glucose/kg fresh algal biomass (Wang, 2011). In the case of *Ulva lactuca*, pre-treatment using diluted

acid hydrolysis did not improve yields of sugar solubilisation compared with pretreatment by water extraction followed by enzymatic hydrolysis (van der Wal, 2013)

4.4.2.6 High Temperature Liquefaction Process (HTLP)

The hydrolysis yields of *Ulva pertusa* Kjellman by a high-temperature liquefaction process (HTLP) has been described recently (Choi, 2012). Optimal hydrolysis conditions for the high-temperature liquefaction process (HTLP) were determined to be 15 MPa and 150 °C for 15 min, with water as the solvent. Under these conditions, the conversion yields of glucose and xylose were 9 and 21%, respectively. After cellulase and amyloglucosidase treatment, 61% of the glucose in the biomass was solubilised.

4.4.2.7 Supercritical water

Daneshvar et al. (2012) studied supercritical water for treatment of *Codium fragile*, a green seaweed species also called 'Green sea fingers' which is wide spread in the Pacific and Atlantic oceans. Supercritical water reactions were carried out for 10 min at temperatures ranging from 100-240 °C, and after the reaction three main phases were isolated (i.e. aqueous, residual solid and hexane soluble). Analysis of the aqueous phase showed that production of the sugars began at 170 °C and reached a maximum amount at 210 °C. By calculation, more than 50% of the solid algae were converted into water-soluble sugars. At temperatures above 210 °C the amount of soluble sugars sharply decreased due to rehydration and decomposition reactions. For the solid phase, the amount declined with increasing temperature, and finally reached a constant amount at higher temperatures (approximately 36% based on DM), attributed to the inorganic composition of the algae. The hexane soluble content was found to be very low (Daneshvar, 2012).

4.5 Synthesis

The use of seaweeds as feedstock for fermentation processes or chemical conversions has been getting attention in recent years, because of the potential to cultivate seaweeds at a large scale with high yields and their interesting biochemical composition (Gao and McKinley, 1994).

Sugars and other nutrients present in seaweeds represent an interesting alternative to the first generation feedstock (grains, starchy substrates) currently used for the production of biofuels (ethanol) or other compounds (Holdt and Kraan, 2011). The fermentation of sugars from brown seaweeds (mostly mannitol and glucose) for production of ethanol has been reported by some authors (Horn, 2000; Adams, 2009). Recently, the fermentation of hydrolysates from green (Potts, 2012; van der Wal, 2013) and from brown seaweeds (Huesemann, 2012) to butanol has been reported. In these studies, it has been shown that the pre-treatment and hydrolysis methods needed for the solubilisation of seaweed sugars are less severe than those needed for pre-treatment of lignocellulosic materials, most probably due to the absence of lignin in their cell walls and the relatively lower crystalline of sugar polymers compared with cellulose or hemicellulose. Although the number of studies concerning fractionation of seaweeds is limited, several methodologies (including extractions, and chemical and enzymatical hydrolysis) have been described for the efficient solubilisation of sugars into hydrolysates to be used as feedstock in fermentation processes to biofuels (ethanol, butanol), demonstrating the great potential of seaweeds for biorefinery.

5 Use of seaweed and seaweed functional components in diets of farm animals and fish

5.1 Introduction

This chapter addresses the value of seaweed as an ingredient in diets for farm animals and fish. In the first part of this chapter the nutrient content and the functional properties are addressed. Thereafter, a brief overview is given of *in vivo* studies in farm animal and fish to determine the nutritive value of seaweed enriched diets and effects on production performance. Subsequently, we included studies into the potential of seaweed products with an additional value beyond the supply of macro- and micronutrients, also referred to as functional or bioactive components. These functional components may contribute to the health and well-being of the animal, increase the quality of the edible end product (meat, milk, eggs), reduce the environmental impact of animal husbandry or have other specific beneficial features. Finally, results are briefly discussed and some preliminary conclusions are drawn.

5.2 Nutritive value of seaweed as a dietary ingredient

In the previous century, seaweed was a commonly used feed of cattle, horses, and poultry in several coastal regions of Europe (Norway, Scotland, France) and America (Chapman, 1970). This author concluded that inclusion levels up to 10% for cattle, horses, and poultry were common. Further work on the use of seaweed in diets for different sheep breeds was regarded necessary, whereas the use for pigs did not seem to be justified. In some studies, seaweed showed negative effects on digestibility of other nutrients. Until the early 1970s, the nutritive value of 1 kg dried seaweed meal from *Ascophyllum nodosum* was estimated by Norwegian agriculture authorities similar to about 0.6 kg of grain. After introducing a new calculation method the energy value for pigs and poultry was reduced to 65% of the previous value, whereas protein digestibility was reduced to zero (Guiry and Blunden, 1991). Protein digestibility is low due to binding of proteins to phenols (tannins; see chapter 6), thereby forming insoluble compounds (Guiry and Blunden, 1991). The number of *in vivo* experiments with seaweed in diets of farm animals is small. Below some examples of studies in pigs, poultry and fish, focusing on growth performance, are presented.

5.2.1 Growing finishing pigs

Different seaweed species may vary in nutrient digestibility. Black (1955), cited by Chapman (1970) reported a DM digestibility of 0.26 for *Ascophyllum* and 0.71 for *Laminaria*. The digestibility of several seaweed species was also summarised by Duckworth (1955) (see Table A.7). Although the nutritional value of *Laminaria* species indeed was superior to *Ascophyllum* and *Fucus*, this author concluded that in general seaweeds are unpredictably variable as source of energy for pigs. A low digestibility of *Ascophyllum* residue in pigs was found in a digestibility experiment of Whittemore and Percival (1975). In this experiment, the digestibility of the residue of *Ascophyllum nodosum*, after extraction of alginate, which has applications in food processing, pharmaceuticals, feed and cosmetics (Holdt and Kraan, 2011), was investigated in 40 kg pigs. The dietary inclusion level of the seaweed residue was 50%, which is extremely high. The digestibility coefficients of the seaweed residue were 0.12 for energy and -0.25 for N, resulting in a digestible energy value of 2.2 MJ/kg DM and a digestible crude protein value of -30 g/kg DM. Moreover, half of the pigs developed acute diarrhoea and refused to consume any more of the diet. The soluble energy sources in seaweed were lost during the extraction process. The remaining carbohydrate sources in this seaweed extract were fucoidans and structural polysaccharides from the cell walls. The N fraction was largely insoluble, whereas the product might contain a low but significant level of protease inhibitor activity. Endogenous pig enzymes are not able to digest these nutrients. The small amounts of digestible energy and nitrogen are mainly the result of

microbial fermentation of the nutrients in the large intestine. The authors concluded that the seaweed residue in its present form was unsuitable as major dietary ingredient for the supply of energy or N to pigs. This may be the result of combined effects of the extraction process, the removal of digestible nutrients and a low digestibility of the intact seaweed in this study.

5.2.2 Poultry

In line with the results of Whittimore and Percival (1975), Ventura et al. (1994) concluded that crude *Ulva rigida* seaweed (a green source) is not a suitable ingredient for poultry diets, at least at an inclusion levels of 10% or higher. These authors found a low AME_n value (2.9 MJ/kg DM) in a growth trial with chickens fed diets containing 0, 10, 20 and 30% seaweed. Feed intake and growth rate decreased with increasing dietary seaweed content ($P < 0.05$). In line with these findings, addition of 10-15% *Ascophyllum nodosum* meal to a complete poultry feed, resulted in diarrhoea, whereas additions up to 7% had no negative effects (Guiry and Blunden, 1991). Hatching results of laying hens were improved if *A. nodosum* meal was supplemented to an animal protein deficient diet. The authors related these positive effects to the contribution of vitamin B₁₂ from the seaweed meal (Guiry and Blunden, 1991).

Experiments with dried red seaweed (*Polysiphonia* spp.) in ducks demonstrated an useful nutritional value of this seaweed source (El-Deek and Brikaa, 2009). After collection, the fresh seaweed was washed several times with water in order to remove associated salts and water, and subsequently it was dried at 60°C for 72 h in a cross flow dryer. Chemical analyses of this ingredient (94% DM) showed a high amount of crude fat (17.7%), and reasonable amounts of protein (32.4%), crude fibre (14.9%), ash (6.0%) and nitrogen free extract (23.4%). Leucine and lysine were the most abundant amino acids in the seaweed protein. The metabolisable energy value of this seaweed was high, 3518 kcal/kg (14.7 MJ/kg) due to the unusual high fat content. Seaweed addition up to 3% did not adversely influence growth performance of ducks. The inclusion of seaweed meal in the diet for ducks had no significant effects on any carcass trait. The authors concluded that seaweed is a valuable feed resource for poultry feeding.

5.2.3 Fish

Seaweeds are regarded as an important nutritional source in fish feed because of its content of proteins, lipids, vitamins and minerals. Even though total lipid content is generally low, seaweeds are still a good source of health promoting PUFA's compared with other foods derived from plant and animal sources (Rajapakse and Kim, 2011). Their potential use as substitutes of protein and other ingredients such as alginates, pigments, fatty acids or potential as feeding stimulants could be applied to marine animal production by aquaculture, especially fish and molluscs. Alginates are sometimes used as binders in fish feeds to influence faeces consistency.

From a societal point of view and to assure sustainable growth of fish culture in general, minimisation of the use of raw materials originating from fish is necessary. Growth performance of fish fed with diets containing new feed materials should be at least comparable to growth when fed with commercial pellets that contain high levels of fishmeal and oil. Effects of seaweed incorporation in fish diets have been previously described. The advantages of incorporating seaweeds are not limited to an increase in growth rate but can in some cases include an improvement of protein assimilation.

Davies et al. (1997) tested the nutritional value of *Porphyra purpurea* meal for juvenile thick-lipped grey mullet (*Chelon labrosus*). Three isonitrogenous and isocaloric diets (control diet without seaweed addition and two diets with 4.5 and 9.0% protein of the control meal replaced by seaweed meal) were tested. Specific growth rate (SGR, expressed as % of total body weight) of the control diet was 2.99% while SGR values for the 4.5 and 9% seaweed inclusion diets were 2.65 and 2.47%, respectively. The authors mentioned that despite the absence of higher growth rates in diets with seaweeds, weight gain was still satisfactory. This because growth rates achieved in this study were in accordance and even exceeded values reported by others in literature (Papaparaskeva-Papoutsoglou and Alexis, 1986; Kandasami et al., 1987; Yoshimatsu et al., 1992). Moreover, seaweed inclusion levels in this study were high with 16.5 and 33%, respectively. Therefore, the authors concluded that, even though the

macro algae *P. purpurea* is of lower nutritional value than conventional ingredients in semi-purified diets for thick-lipped mullets, the (partial) substitution of fish meal by seaweed proved to be cost effective.

Wassef et al. (2005) studied the effect of adding 5, 10 or 15% of *Pterocladia capillacea* or *Ulva lactuca* as feed additives for gilthead bream (*Sparus aurata*) diet. The control diet contained only fishmeal as protein source. Best growth performance, feed utilisation, nutrient retention and survival were achieved when the diets contained 10% *P. capillacea* or 5% *Ulva lactuca*. Interestingly, this study also showed that fish fed with a diet containing 10% *Ulva lactuca* had a greatly improved stress response when challenged by 5 minute air exposure when compared with the control diet to which no seaweed meal was added. The mechanism behind this was not known as well as why it worked at 10 and not at 5 or 15%, but apparently it worked. These results suggest that in fish, stress response and probably disease resistance as well may also be improved with the inclusion of seaweeds in the diet.

The growth performance, nutrient utilisation and body composition of European sea bass (*Dicentrarchus labrax*) juveniles were studied by replacing 5 or 10% fish protein by *Gracilaria bursa-pastoris*, *Ulva rigida* or *Gracilaria cornea* (Valente et al., 2006). Inclusion of *G. bursa-pastoris* and *U. rigida* in the diets did not show a decrease in growth even when replacing 10% of the fish protein from the control diet. Growth performance was only reduced at 5% inclusion of *G. cornea*. Crude protein content of diets differed between treatments (5-8%), which is not a proper set up for a feeding trial. This makes it difficult to draw proper conclusions from this experiment. Kalla et al. (2008) pointed out the potential of *Porphyra* spheroplasts as feed ingredient. Growth performance, survival and nutrient retention of red sea bream (*Pagrus major*), were improved when introducing 5% *Porphyra* spheroplasts by replacing 3% fishmeal and 2% starch in a formulated diet, where fishmeal was still the main protein source.

The effects on growth, feed efficiency and carcass composition of rainbow trout (*Oncorhynchus mykiss*) of adding *Porphyra dioica* to the diet at levels of 5, 10 or 15% were studied by Soler-Vila et al. (2009). The control diet was a commercial trout diet without seaweed meal (diets where isonitrogenous and isolipidic). Results of this study suggested an effective inclusion up to 10% *P. dioica* in the diet without negatively influencing growth performance.

5.3 Functional nutritive characteristics in livestock

Several experiments have been published into effects of dietary inclusion of small amounts of intact seaweed or seaweed components, beyond the common nutritional value. These effects include the use of seaweed as a prebiotic substance to influence microbiota in the digestive tract and for immunomodulating properties in pigs, to influence rumen fermentation, digestion and milk production in cattle and to improve quality of end products: meat, milk and eggs. Some examples are presented below.

5.3.1 Sows and piglets

In young pigs, a number of experiments were performed to test the effects of intact seaweed or polysaccharides, e.g. laminarins and fucoidans, extracted from seaweed, on performance, gut health and immune status of different species. Supplementing a diet with 2% dried iodine-rich intact marine seaweed (*Ascophyllum nodosum*) to weaned piglets had a reducing effect on the *E. coli* load in the stomach ($P = 0.07$) and small intestine ($P < 0.05$), while the lactobacilli/*E. coli* ratio was enhanced ($P < 0.05$) in the small intestine, indicating a beneficial shift in the microbial population (Dierick et al., 2009). Moreover, an increase in iodine content was noted for several tissues in piglets fed seaweed. The supplementation of seaweed extracts: *Laminaria hyperborea* (1.5 g/kg), *Laminaria digitata* (1.5 g/kg) or a mixture of both extracts (1.5 g/kg) to diets of weaned piglets did not affect performance of the piglets, reduced the enterobacteria, bifidobacteria and lactobacilli populations in the caecum and colon, while only marginal effects on the immune response were observed (Reilly et al., 2008). McDonnell et al. (2010) and O'Doherty et al. (2010) investigated the effects of laminarin (300 ppm) and fucoidan (236 ppm), independently or in combination, on post weaning piglet performance and

selected microbial populations. In contrast to findings of Reilly et al. (2008), pigs in their studies offered diets supplemented with laminarin had an increased daily gain ($P < 0.01$) and gain to feed ratio ($P < 0.05$) compared with un-supplemented laminarin diets during the experimental period (days 0-21). Similar effects were found in weanling pigs, especially in low lactose diets (Gahan et al., 2009). Pigs offered laminarin supplemented diets had an increased faecal DM content and less diarrhoea ($P < 0.05$) during the critical period, day 7-14 post weaning. Pigs offered diets containing laminarin had reduced faecal *Escherichia coli* populations. There was a significant interaction ($P < 0.01$) on faecal *Lactobacilli* populations between laminarin and fucoidan. Pigs offered the fucoidan diet had an increased faecal *Lactobacilli* population compared with pigs offered the basal diet. There was no effect of fucoidan on faecal *Lactobacilli* populations when included in combination with laminarin. Overall, the reduction in *E. coli* population and the increase in daily gain suggest that seaweed polysaccharides, especially laminarin may provide a dietary means to improve gut health in post weaning piglets.

Leonard et al. (2012) investigated the effect of maternal dietary supplementation with seaweed extract from d 107 of gestation until weaning (d 26) in sows on immune functions and micro flora of suckling piglets. The seaweed extract (10.0 g/sow/d) contained laminarin (1.0 g), fucoidan (0.8 g), and ash (8.2 g) and was extracted from a *Laminaria* spp. Piglet body weight at birth and weaning, and small intestinal morphology were unaffected. It was found that maternal supplementation of seaweed extract showed an important immuno modulatory role characterised by enhanced colostral IgA and IgG concentrations, greater piglet circulatory IgG concentrations on d 14 of lactation, and enhanced TNF-alpha mRNA expression in the ileum after an ex vivo LPS challenge.

5.3.2 Beef and dairy cattle

Seaweed meal, processed in molasses blocks was provided to ruminally, duodenally, and ileally cannulated steers (initial BW 376 ± 8.1 kg) to evaluate effects of brown seaweed meal (*Ascophyllum nodosum*, 10 g/d) on intake, site of digestion, and microbial efficiency (Leupp et al., 2005). Diets consisting of switchgrass hay (*Panicum virgatum*; 6.0% CP; DM basis) were offered ad libitum, with free access to water, and molasses block (0.341 kg of DM/d, whereas the positive control group (POS) received blocks without seaweed. Steers fed seaweed blocks (SB) had greater true ruminal OM digestibility compared with steers fed POS (61.0 vs. $57.9 \pm 1.6\%$, $P = 0.10$), due to improved digestibility of the fibre fractions (NDF and ADF). Treatments did not alter ruminal pH, total VFA, or individual VFA proportions. Seaweed block increased the slowly degradable CP fraction compared with POS (39.5 vs. $34.0 \pm 2.1\%$, $P = 0.01$). Similarly, SB increased the extent of CP degradability (74.2 vs. $68.9 \pm 1.81\%$, $P = 0.01$). The authors concluded that the use of brown seaweed meal seemed to have beneficial effects on forage digestibility in low-quality forage diets.

In an old study of Dunlop (1953) the hypothesis was tested whether copper-rich seaweed would have a similar enhancing effect on the milk fat production of dairy cows as copper sulphate. Therefore, in several dairy cow herds supplementation of 200 g/d of dried *Ascophyllum nodosum* supply for a period of three weeks was compared with a single dose of 10 g copper sulphate. In some herds, the inclusion of seaweed meal would appear to stimulate milk fat production even to a greater extent than copper sulphate.

Daily supplementation of 200 g of a mineral-enriched *A. nodosum* meal (78.74% *A. nodosum* meal, 20% calcium phosphate, 1.2% magnesium oxide, 0.06% copper oxide) to lactating cows resulted in 6.8% higher milk yield compared with the control treatment that received the same ratio, with 100 g/d of a standard mineral mixture substituted for the seaweed meal (Jensen et al., 1968). Milk iodine content of the seaweed group was 0.6 mg/l compared with 0.1 mg/l in the control group. These results suggests that feeding this mineral-enriched seaweed supplement is able to increase milk yield as well as the mineral concentration of the milk.

5.4 Effect of seaweed on quality of animal products

5.4.1 Oxidative stability of animal products

Brown seaweeds contain polyphenolic components, such as phlorotannins, catechins, tocopherols, ascorbic acids, and carotenoids with antioxidant properties. Therefore, their dietary inclusion may improve oxidative stability in animal tissues. A fresh and spray dried brown seaweed extract, obtained by an undisclosed acid extraction technique, containing laminarin (L) and fucoidan (F), was used to investigate the effect of supplementation of pig diets with L/F (L, 500 mg/kg feed; F, 420 mg/kg feed) for 21 days pre-slaughter, on quality indices of fresh *M. longissimus dorsi* (LD) steaks. Susceptibility of porcine liver, heart, kidney and lung tissue homogenates to iron-induced (1 mM FeSO₄) lipid oxidation was also investigated. Dietary supplementation with L/F did not affect plasma total antioxidant status and the microbiological parameters. Supplementation of the fresh seaweed extract reduced the levels of lipid oxidation in the LD steaks, whereas liver tissue homogenates were less susceptible for iron-induced lipid oxidation, thereby demonstrating the potential benefit of the incorporation of marine-derived bioactive antioxidant components into muscle foods via the animal's diet (Moroney et al., 2012). Similarly, Kindleysides et al. (2012), studied the potential of seaweeds extracts (two brown seaweeds, *Ecklonia radiata* and *Macrocystis pyrifera* and two red species, *Champia* sp. and *Porphyra* sp.) as antioxidants in hoki (*Macruronus novaezelandiae*) oil. Results showed that all the lipid-soluble seaweed extracts prevented liver oil oxidation, with *E. radiata* being the most effective.

5.4.2 Colour of animal products

Besides the nutritional value, some seaweed species contain functional components such as bioactive peptides produced by hydrolysis of algal proteins, antioxidants and components with mineral binding activity. These components might play a role in the replacement of artificial ingredients (e.g. colorants and preservatives). It was assumed that seaweed would have a positive effect on the pigmentation of yolk colour, but Blount (1965) concluded that 5% seaweed addition did not increase yolk colour intensity more than 2.5% dried grass meal. A study of Soler-Vila et al. (2009) showed the positive influence of *P. dioica* addition to the diet on flesh pigmentation. Coloration of the flesh increased in intensity with increased seaweed inclusion. This effect may be of interest to the organic salmon farming industry.

5.4.3 Physicochemical characteristics

Apart from functional nutritive characteristics, seaweed may have physicochemical properties relevant in animal feed. In aquaculture, physical characteristics of the fish feed pellets in water have a major effect on feed utilisation and water quality. Hashim and Mat Saat (1992) evaluated the potential of *Ulva* spp., *Sargassum* spp., *Polycavernosa* spp., *Gracilaria* spp. and carrageenan as binding agents in pellet diets for snakehead (*Channa striatus*). The small differences in water stability between the carrageenan and the seaweed, especially *Ulva* spp., suggested that an inclusion of 5% crude seaweed meal to a diet is sufficient to form strongly bound feeds. These results indicate that seaweed use may contribute to the required pellet characteristics.

5.5 Review

From this brief summary of a selected number of publications we conclude that seaweed species contain a variety of polysaccharides that may contribute to human and animal health. Several of these polysaccharides may create a better intestinal environment by stimulation of the microbiota population, production of fermentation products, protection of the gut wall, etc. Most of the recently published seaweed studies focus on the functional components that might stimulate immune functions and increase gut health of livestock. Some evidence of these effects is available in pig, poultry and fish diets (Wassef et al., 2005; McDonnell et al., 2010; O'Doherty et al., 2010; Leonard et al., 2012). Evidence was found for gut health promoting capacities in piglets as a consequence of supplementing some β -glucans (laminarins and fucoidans). These favourable effects were achieved after direct feeding of these functional components to the piglets, or after indirect supplementation of the sow

during gestation and lactation. Addition of laminarins and fucoidans increased colostral IgA and IgG concentrations. Several studies showed positive effects of laminarins on performance and gut health. Although these studies were based on the use of seaweed extracts, it is likely that intact dried and ground seaweed may beneficially influence the intestinal tract as well. The precise effects of complete seaweed, being a mixture of polysaccharides with different characteristics, on intestinal health in different animal species is to be established.

With regard to protein and peptides, there is little evidence for beneficial bioactive effects in farm animal nutrition above the contribution to the amino acid supply of the animals. Rather, the presence of a high indigestible fibre content, lectins and polyphenols in certain species may contribute to a relatively low bioavailability of amino acids. The number of studies into the ileal digestibility of amino acids in pigs and poultry is very limited and more data are required to better evaluate the protein feeding value of seaweed(products).

With regard to lipids, seaweeds mainly contain C16 and C18 ω -3 and ω -6 fatty acids as many other plants, although the relative content of ω -3, especially C20:5 ω -3 (EPA) can be much higher in certain seaweed species. The total lipid content in many species is low, presumably too low to substantially contribute to the fatty acid requirements of the animals. Only specific species seem suited as a source of marine fatty acids (van Ginneken et al., 2011). The bioavailability of fatty acids remains to be determined. Marine fatty acids may have an added value in diets of laying hens for the production of ω -3 enriched eggs and in the diet of young pigs and reproductive sows for beneficial effects on vitality and health.

Seaweed is unique in its high iodine content and as such has been studied as a feed ingredient for iodine enriched meat products (Cloughley et al., 2008 ; Dierick et al., 2009). The use of seaweed as a source of vitamins and minerals seems more likely in human rather than animal nutrition because of the variability in content of micronutrients and the standardisation in animal diets via the premix. Due to the presence of phenolic components, dietary seaweed supplementation might also have potential for the incorporation of marine-derived bioactive antioxidant components into muscle foods (Je et al., 2009 ; Le Tutour, 1990).

A major question within the scope of this study is how much the feed application of bioactive components adds to the feasibility of (large-scale) seaweed production. We have discussed that seaweeds contain a number of compounds, mainly polysaccharides with potential beneficial effects on human and animal health. With regard to animal nutrition the feasibility of this application will largely depend on: 1) production costs, 2) competition with other sources: for certain components seaweed maybe a unique source, others can also be derived from plant material, yeast or other sources and 3) legislative aspects: in order to commercialise a feed ingredient with a special claim (feed additive, particular nutritional purposes) presumably a scientific dossier is required. Costs to build such a dossier are very substantial.

A large number of publications reviewed by Holdt and Kraan (2011) suggest potential use of purified seaweed components for medical application. It should be emphasised that in many examples (e.g. Table 1.4) results are based on a limited number of studies with in vitro cell lines and in animal models. It would require a large investment in research to further develop this application and validate effects in clinical trials. A more thorough analysis of these perspectives is beyond the scope of this study. Moreover, we would also expect that for this application production of specific seaweed species in well controlled conditions would be preferred above large-scale production in open North Sea conditions.

The number of in vivo studies to determine the nutritive value (energy and amino acids) of intact seaweed in farm animals is too small and old to determine firm conclusions. In the previous century, harvested naturally grown seaweed was a well-known ingredient (up to 10%) in diets for cattle, horses, and poultry in several coastal regions of Europe and America. Nowadays, seaweed is not a standard dietary ingredient. The digestibility and nutritional value of seaweed species is not well known. Only a limited number of (mainly old) publications investigated the inclusion of whole seaweed in monogastric diets and considered intact seaweed as a poorly suited feed ingredient. However,

results vary between animals and seaweed species. Nutritive value of *Ascophyllum* in pigs was low, *Ascophyllum* improved forage digestibility in steers, and use of *Polysiphonia* spp. in ducks seems promising, but information on species relevant for cultivation in the North Sea is scarce. In addition, the high ash content is a point of concern in animal diets. In some studies a (too) high or low inclusion level may have blurred the conclusions, which may also be the result of the high mineral (ash) content. At present, higher digestibility coefficients of seaweed nutrients were found in rainbow trout and Nile tilapia as compared with pigs and poultry, Hence, seaweed or ingredients made of seaweed may be of prime interest for use in fish feed formulations. In general, more recent studies are required to better establish the value of seaweed in animal diets, both in terms of energy and amino acid content and digestibility. In addition, the large variation in nutrient content needs to be addressed. We have not found any recent studies into the composition and nutritive value of seaweed residues from a biorefinery process. More analytical and experimental data in this respect are required, especially since a combined use of seaweed for industrial purposes and as a source of feed or food products might be most promising. We conclude that the contribution of seaweed to the energy requirements of the animals is rather low because of the high fibre content and low digestibility of the polysaccharides and the relatively low fat content. In case the seaweed has been used in a biorefinery process, for example for acetone-butanol-ethanol (ABE) production (see chapter 7), polysaccharides may be largely extracted and the residue is unlikely to contain the above prebiotic effects on intestinal health. Nonetheless, the residue may be condensed in protein and/or fats thus potentially of higher value for the supply of amino acids or marine fatty acids to animal diets. Moreover, the biorefinery processes involved may have influenced the digestibility of the remaining nutrients. This application requires a joint effort from different research groups to explore the potential use of seaweed.

Seaweed can be used in animal diets in complete form, as a residue of bioprocessing, or as a source of bioactive components. Mainly in young piglets, positive effects of seaweed components on some immunological parameters, gut morphology and gut health are observed. An important aspect is the extremely high variation in chemical composition within and between seaweed species. This may hamper the application of seaweed in animal diets and needs to be addressed. In general, more research is required to determine the comparative feeding value of seaweed species suitable for cultivation in the North Sea, in diets for ruminants, pigs, poultry, and fish. Attention should be given to the (seasonal) variation in composition and the composition and consequences of the high ash content. Further research has to find out whether processing of intact seaweed, e.g. cell wall degrading techniques and enzymatic break down of structural carbohydrates and proteins improves energy and protein digestibility. This would enhance the economic value of seaweed in animal diets. Finally, no information is available on (residue) seaweed fractions from newly developed biorefinery processes. To implement the use of seaweed as a feed ingredient, the nutritional value, functional value and digestibility will have to be determined for the target species. Specifically designed trials where marine animal or soy derived ingredients are replaced by sustainable ingredients made from seaweed should be performed.

5.6 Synthesis

We conclude that the contribution of seaweed to the energy requirements of the animals is rather low because of the high fibre content and low digestibility of the polysaccharides and the relatively low fat content. At present, higher digestibility coefficients of seaweed nutrients were found in rainbow trout and Nile tilapia as compared with pigs and poultry, Hence, seaweed or ingredients made of seaweed may be of prime interest for use in fish feed formulations.

Various seaweed ingredients can be used as additive to feed:

- We conclude that seaweed species contain a variety of polysaccharides that may contribute to human and animal health. Several of these polysaccharides may create a better intestinal environment by stimulation of the microbiota population, production of fermentation products, protection of the gut wall, etc.
- With regard to protein and peptides, there is little evidence for beneficial bioactive effects in farm animal nutrition above the contribution to the amino acid supply of the animals. Rather, the

presence of a high indigestible fibre content, lectins and polyphenols in certain species may contribute to a relatively low bioavailability of amino acids.

- With regard to lipids, seaweeds mainly contain C16 and C18 ω -3 and ω -6 fatty acids as many other plants, although the relative content of ω -3, especially C20:5 ω -3 (EPA) can be much higher in certain seaweed species. The total lipid content in many species is low, presumably too low to substantially contribute to the fatty acid requirements of the animals. Only specific species seem suited as a source of marine fatty acids (van Ginneken et al., 2011).
- Seaweed is unique in its high iodine content and as such has been studied as a feed ingredient for iodine enriched meat products (Cloughley et al., 2008 ; Dierick et al., 2009). The use of seaweed as a source of vitamins and minerals seems more likely in human rather than animal nutrition because of the variability in content of micronutrients and the standardisation in animal diets via the premix.
- A large number of publications reviewed by Holdt and Kraan (2011) suggest potential use of purified seaweed components for medical application. It would require a large investment in research to further develop this application and validate effects in clinical trials.

6 Hazards of seaweed in feed and food production

6.1 Introduction

This chapter contains a presentation of the legal framework applying to the use of seaweed in food and feed, a summary of the results of monitoring for contaminants and metabolites which might give a hazard for use, a diversification of use and related hazards, and finally recommendations for application of seaweed as feed ingredient.

6.2 Legal framework

In order to use specific products of plant or animal origin in feed or food, a number of legal aspects need to be addressed.

As principle, the General Food Law (Regulation (EC) 178/2002; European Commission, 2002a) presents the basic set of requirements for feed and food. It covers general requirements, the primary responsibility of producers (Food and Feed Business Operators) for quality and safety, the founding of the European Food Safety Authority (EFSA) and of the Rapid Alert System Food and Feed (RASFF). The requirements for specific areas are laid down in additional regulations: hygiene of animal feed (Regulation (EC) 183/2005; European Commission, 2005), requirements for trade and labelling (Regulation (EC) 767/2009; European Commission, 2009), restrictions for the level of additives (Regulation (EC) 1831/2003; European Commission, 2003) and for undesirable substances (Directive 2002/32/EU; European Commission, 2002b). The organisation of official controls for monitoring any infringement of the regulations is laid down in Regulation (EC) 882/2004 (European Commission, 2004).

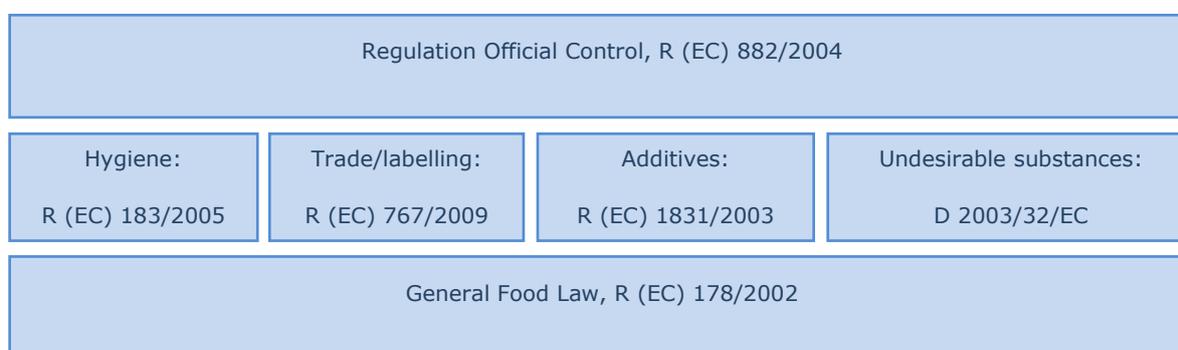


Figure 6.1 Overview of main regulations of the European Union applying to feed and the feed production chain.

Although other legislation in the European Union might apply for very specific cases, the set of regulations as illustrated in Figure 6.1 covers all major aspects if seaweed or products thereof are produced and applied as feed ingredients. Aspects such as hygiene, trade and labelling are part of the management system of the production chain and these will not be covered in this chapter. The main intrinsic hazards of seaweeds are those listed in Directive 2002/32/EU and these will be the current primary focus. Some attention will be given to already existing classification of seaweed products. Other (derived) products that are or will be placed on the market and which are not listed in the Feed Catalogue (Regulation (EU) 575/2011; European Commission, 2011a) should be notified as novel feed ingredient to the Competent Authority by the Feed Business Operator and its safety should be approved (European Commission, 2009).

The European Feed catalogue (European Commission, 2011a) contains one item referring to seaweed (7.2.6: seaweed meal). For comparison, five different products based on algae are listed (7.1.1-7.1.5: algae, dried algae, algae meal, algae oil, and algae extract). It is not obvious to classify all kind of specialised products based on seaweed as the only one existing category, considering the five different categories for a comparable set of products. With respect to E-numbers (European Union, 2008; implemented by European Commission, 2011b), the group of E-401 / E-405 consists of alginate derivatives, originating from 'seaweed'. In addition, E-706 is an indication of agar, E-407 is carrageen, and E-407a points to processed eucheuma weed. In this respect, 'seaweed' can have a broad definition. A category 'seaweed' is listed in the Combined Nomenclature (European Commission, 2010), which encompasses a system for Custom Regulations. Separate subcategories exist for seaweed and algae for human consumption (1212 21 00) and for other purposes (1212 29 00).

EC Directive 2002/32/EC (Consolidated version August 2012: European Commission, 2012b) lists a range of maximum limits for a range of undesirable substances in animal feeds and ingredients. Only for arsenic a separate limit is authorised for seaweeds, as is listed in Table 6.1. The European legislation does not currently provide diversified levels for organic and inorganic arsenic, although the levels of organic and of inorganic arsenic has to be produced upon request of the competent authority. In those cases the level of inorganic arsenic should be below 2 ppm (see also Hedegaard and Sloth, 2011). The directive emphasises special attention for the species *Hizikia fusiforme*.

For dioxins, dioxin-like PCBs and non-dioxin-like PCBs action limits are set. Directive 2002/32/EC also contains a range of limits for authorised feed additives following carry-over. These limits are unlikely to apply to seaweed as feed ingredient.

Table 6.1

Overview of limits for feed, feed ingredients of vegetable origin and for seaweed as included in Directive 2002/32/EC, as far as applicable to seaweed as feed ingredient.

Contaminant	Feed	Feed ingredient of vegetable origin	Seaweed
Arsenic	2 ppm (for fish and fur animals: 10 ppm)	2 ppm (exceptions: 4 ppm)	40 ppm *
Cadmium	0.5 ppm (for adult ruminants and fish: 1 ppm; pet animals: 2 ppm)	1 ppm	1 ppm
Lead	5 ppm	10 ppm (forage: 30 ppm)	10 ppm
Mercury	0.1 ppm (for fish: 0.2; for pet and fur animals: 0.3 ppm)	0.1 ppm	0.1 ppm
Fluorine	150 ppm (several exceptions)	150 ppm	150 ppm
Nitrite	15 ppm	15 ppm	15 ppm
Dioxins	0.75 ng WHO-PCDD/F-TEQ / kg (for pet animals and fish: 1.75 ng WHO-PCDD/F-TEQ / kg)	0.75 ng WHO-PCDD/F-TEQ / kg	0.75 ng WHO-PCDD/F-TEQ / kg
Dioxins and dioxin-like PCBs	1.5 ng WHO-PCDD/F-TEQ / kg (for pet animals and fish: 5.5 ng WHO-PCDD/F-TEQ / kg)	1.25 ng WHO-PCDD/ F-PCB-TEQ / kg	1.25 ng WHO-PCDD/ F-PCB-TEQ / kg
Non-dioxin like PCBs	10 ppb ((for pet animals and fish: 40 ppb)	10 ppb	10 ppb

* Footnote in Directive 2002/32/EC: 'Upon request of the competent authorities, the responsible operator must perform an analysis to demonstrate that the content of inorganic arsenic is lower than 2 mg/kg (ppm). This analysis is of particular importance for the seaweed species *Hizikia fusiforme*. Limits are set for feed additives such as copper and zinc (European Union, 2003). These trace elements can be added legally to feed in a large range of different compositions, such as minerals, organic components and chelates¹¹. Recently new copper containing components are legalised (European Commission, 2012a). The exposure to animals from feeds in general is limited.

A range of risk assessments have been published by the European Food Safety Authority. With respect to contaminants that might occur in seaweed, the relevant assessments apply to iodine, arsenic, cadmium, and pesticides (EFSA, 2009a; 2009b; 2012a; 2012b). A very elaborate risk assessment was published for arsenic (EFSA, 2009b). Sea products used for feed and food appeared to be the major

¹¹ http://ec.europa.eu/food/food/animalnutrition/feedadditives/comm_register_feed_additives_1831-03.pdf

source of human exposure to arsenic. Carry-over in the feed production chain of inorganic arsenic is considered low (EFSA, 2009b). For iodine only a Tolerable Upper Intake Level for human beings (adults and infants depending on age) has been advised (EFSA, 2009a). Besides a cadmium assessment (EFSA, 2012a), Directive 2002/32/EC provides specific limits for animal feed. No substantial risk was found when applying several marine algae extracts, all obtained from brown algae, in the feed production chain with respect to pesticides (EFSA, 2012b).

Quality systems such as GMP and HACCP might provide additional frameworks for the utilisation of seaweed products. These extra provisions are not evaluated in this chapter, since national differences are most likely to exist.

It can be concluded that besides the notification that seaweed in large sense is a known ingredient of feed and food, a lot of information is still missing. Therefore, precaution has to be taken in using the term 'risk', since use of certain products and/or exposure to certain contaminants is insufficiently known, but in more general 'hazards' could be evaluated in the framework of the current feasibility study.

6.3 Contaminants or metabolites

Seaweeds are known for their potential to accumulate minerals, as reviewed by Holdt and Kraan (2011). The mineral composition varies according to group (Holdt and Kraan, 2011), and additionally seasonal and environmental circumstances (e.g. Cavas et al., 2012). Several groups of contaminants or metabolites will be discussed, at first along the list of Directive 2002/32/EC, followed by some metabolites specific to seaweeds.

6.3.1 Heavy metals as listed in Directive 2002/32/EC

For a range of heavy metals the levels in seaweeds and seaweed products have been investigated. A general overview has been presented by Holdt and Kraan (2011) for listed heavy metals, as presented in Table 6.2.

Seaweed ('algae') is a specific subcategory in the EFSA food category classification (EFSA, 2009b). Levels used as basis for the risk assessment for total arsenic are: median = 24 ppm, average = 30.9 ppm, P₉₅¹² = 102.2 ppm, maximum = 236 ppm (n=448; EFSA, 2009b). These levels are comparable to those presented in Table 6.2. Algae based supplements (n=9: average = 19.5 ppm, P₉₅ = 116 ppm) and non-algae based supplements (n=772: average = 1.2 ppm, P₉₅ = 4.4 ppm) could have a further contribution to the exposure with arsenic (EFSA, 2009b).

Considering the 2 ppm level for inorganic arsenic (Directive 2002/32/EC), *Sargassum fusiforme* (Hijiki) exceeds this limit by a factor 39-47). Data of Rose et al. (2007) confirm these levels. Soaking of dried seaweed products before consumption will not substantially lower the level of inorganic arsenic in Hijiki (Rose et al., 2007). Further attention is given by a range of governments.¹³

More recently, Mok et al. (2012) found levels in *Euचेuma* for arsenic (4.1-4.8 ppm), cadmium (0.38-0.44 ppm), lead (0.22-0.36 ppm) and mercury (0.028-0.036 ppm). The arsenic level is much below the levels for red algae presented in Table 6.2; *Euचेuma* was not included in the list of genera for Table 6.2.

¹² P₉₅: the 95-percentile is the value for which 95% of the analysed samples show a lower level. Percentiles can be calculated for other percentages.

¹³ <http://www.food.gov.uk/multimedia/faq/hijikiqanda/> ; http://www.fsai.ie/faq/hijiki_seaweed.html ; <http://www.inspection.gc.ca/food/consumer-centre/food-safety-tips/specific-products-and-risks/arsenic/eng/1332268146718/1332268231124> ; http://www.foodauthority.nsw.gov.au/_Documents/science/inorganic_arsenic_seaweed_seafood.pdf ; http://www.foodsafety.govt.nz/elibrary/industry/Hijiki_Seaweed-Imported_Also.htm ; <http://www.efic.org/article/en/artid/Seaweed-exploring-its-dietary-value/>

Table 6.2

Data (ppm) for four different heavy metals in 23 samples of seaweed.

Data extracted from Holdt and Kraan (2011), based on Almela et al. (2002: marketed products) and Durcan et al. (2010: western Ireland). Ranges indicate lowest average minus 1*SD to highest average plus 1*SD. Levels exceeding legal limits are printed in bold.

Group:	Brown algae		Red algae	Green algae
Genera:	<i>Eisenia, Fucus, Laminaria, Saccharina, Undularia</i>	<i>Sargassum fusiforme</i>	<i>Porphyra, Palmaria</i>	<i>Enteromorpha, Ulva</i>
Number of samples:	11	3	6	3
Total Arsenic	23.3-54	103-147	7.54-31	2.2-6.98
Inorganic Arsenic	0.05-0.38	78-94	<0.15-0.50	0.30-0.44
Cadmium	0.13-2.0	0.9-1.48	0.16-0.73	0.02-0.18
Lead	0.09-0.55	0.47-1.04	0.285-0.37	0.91-1.36
Mercury	0.011-0.045	0.0257-0.038	0.003-0.016	0.016-0.021

In comparison, 35 samples of seaweed intended for feed ingredient have been investigated in the Dutch monitoring programme in the years 2009-2012. Seven samples of *Spirulina* (blue-green alga, see Table 1.1) and *Chlorella* (a green micro-alga), declared as 'seaweed' have been excluded from the evaluation as presented in Table 6.3. They are not comparable to the seaweeds analysed in this study. Twenty-three per cent of the investigated samples showed arsenic levels above the legal limit. For some of the samples a more detailed description than the general indication 'seaweed' was available. This condition allowed to make a stratification for two types of weed. In both samples of kelp levels exceeding the legal limit were found. A product called Acid buf, a mineral mixture produced by some species of red algae in the Northern Atlantic and used for rumen conditioning¹⁴, did not show relevant levels of arsenic. Levels of inorganic arsenic in the years 2009 and 2010 ranged from <0.5 ppm to 1.9 ppm. The highest level (1.9 ppm) was found in a sample with 5.8 ppm total arsenic. This indicates that there is no clear correlation between the levels of total and inorganic arsenic.

In the year 2012 of the Dutch monitoring programme, levels for cadmium (0.05 to 0.43 ppm, median: 0.2 ppm), lead (<0.1 to 5.6 ppm, median: 0.3 ppm) and mercury (< 0.01 to 0.022 ppm, median: <0.01 ppm) were found. In none of the nine samples these levels exceeded the limits.

Table 6.3

Results of the Dutch monitoring programme for feeds and feed ingredients for the levels of arsenic in seaweed (years 2009-2012).

Total arsenic	Range	Average	Median	P ₉₀	% above limit
All years, n=35	0-66 ppm	18.5 ppm	9.2 ppm	42.6 ppm	22.8%
2009, n=24	0-66 ppm	24.4 ppm	26.5 ppm	42.7 ppm	29.2%
2010, n=2	0.3-46 ppm	23.1 ppm	23.1 ppm	-	50%
2012, n=9	0-33 ppm	5.5 ppm	1.5 ppm	-	0%
Kelp, n=2	43-55 ppm	49 ppm	49 ppm	-	100%
Acid buf, n=6	1.1-4.4 ppm	2.0 ppm	1.6 ppm	-	0%

6.3.2 Other heavy metals and minerals

Several other studies on the content of heavy metals in seaweed species have been published: Apaydin et al. (2012) on Fe, Sr and Ba in *Ulva*; Mok et al. (2012) on Cr, Cu and Zn in *Eucheuma*). No interpretation of the published levels can be given, since neither risk levels nor legal limits for feed ingredients are available.

¹⁴ <http://www.celticseaminerals.com/acidbuf.html>

6.3.3 Iodine

An overview of different study results for iodine content is presented in Table 6.4. In contrast to heavy metals, the genera *Laminaria* and *Saccharina* show the highest content of iodine. The reported levels vary substantially among the studies and varieties of seaweed. For example, Wen et al. (2006) reported levels of 3040 ppm for *Laminaria* and *Saccharina*, which is in the lower part of the range for these genera, 36 ppm for *Porphyra*, and 4260 ppm for *Gracilaria*, which is the maximum for red algae.

Table 6.4

Data (ppm) for iodine contents in seaweed. Data extracted from Holdt and Kraan (2011) based on nine different studies.

Group:	Green algae	Red algae	Brown algae	
Genera:	<i>Ulva</i>	<i>Chondrus</i> , <i>Porphyra</i> , <i>Gracilaria</i> , <i>Palmaria</i>	<i>Fucus</i> , <i>Ascophyllum</i> , <i>Undularia</i> , <i>Sargassum</i>	<i>Laminaria</i> , <i>Saccharina</i>
Number of studies:	2	5	6	7
Iodine	20-250	5-4,260	30-3,000	230-12,000

In addition to this overview, also more recent publications report levels of iodine in seaweed species. Apaydin et al. (2012) found levels between 1550 and 2450 ppm in *Ulva*. This is comparable to the levels in red and brown algae, but much higher than presented in Table 6.4 for green algae.

6.3.4 Nitrite

The green alga *Caulerpa* is known for its capacity to bind nitrate and nitrite (Morrissey et al., 1988). It is used for that purpose in aquaria and escaped at several places in temperate waters. Since a maximum level is set for nitrite (Directive 2002/32/EC), a further investigation is required for this component. Although the genus *Caulerpa* does not belong to the five genera of primary attention, a putative accumulation of nitrite by green algae could be a matter of concern.

6.3.5 Halogenated components

Dioxins (PCDD/PCDF) and dioxin-like PCBs are found to occur in seaweed (Hashimoto and Morita, 1995). A large study among the population of Osaka, Japan (Nakatani et al., 2011) during 2000-2002 revealed that seaweed does not contribute as major factor to exposure to dioxins (PCDD/PCDF) and dioxin-like PCBs. The food category 'other vegetables, mushrooms' (including seaweeds) contributed for 3-5% of the total exposure with a share of 8-14% in the daily diet. For comparison, the category 'fish and shellfish' contributed 54-60% to the total exposure with a share of only 5.3-6.0% in the daily diet (Nakatani et al., 2011). Based on this single study it cannot be excluded that in other regions and under different circumstances significant levels may occur.

A range of different halogenated components can be produced by seaweeds, e.g. as part of defensive mechanisms against feeding (Holdt and Kraan, 2011). Apaydin et al. (2012) found the halogens chlorine and bromine at levels between 9180 and 21870 ppm (Cl) and between 480 and 1520 (Br), respectively, in *Ulva*. It is not mentioned whether these halogens originate from natural metabolites or from contaminants. Even in the case of natural metabolites adverse health effect could occur. For example, natural fatty acids can be halogenated, causing an effect on the functioning of cell membranes (Dembitsky and Srebniak, 2002, in Holdt and Kraan, 2011).

6.3.6 Toxic metabolites

Several metabolites are reported to show a toxic effect. Among these are the sesquiterpenoid caulerpenyne in *Caulerpa* considered to have a defensive purpose against herbivores (Cavas et al., 2012). Another sesquiterpenoid, elatol, showed an inhibiting effect on *Leishmania* (Oliveira dos Santos et al., 2010) and on trypanosoma (Veiga-Santos et al., 2010). Several metabolites have been extracted from *Gracilaria lemaneiformis* showing a species-specific allelopathic antialgal activity

against *Skeletonema* (Lu et al., 2011). Kainic acid shows a neurotoxic effect. In *Palmaria*, wild harvested material could contain up to 130 ppm, whereas cultivated material contained 2.5 ppm. Effective doses are between 10 and 30 mg/kg for mice (Holdt and Kraan, 2011).

Paralytic shellfish toxins (PST) are produced by dinoflagellates and blue-green algae. These toxins can cause severe health problems and are accumulated by filter-feeders such as shellfish and clams (Gerssen et al., 2010). This pathway of human exposure yielded the name to this group of toxin compounds. Unexpected exposures can occur as is illustrated by the following example. A dog died after swimming in a Dutch creek in 2012 due to excessive swallowing of marine toxins. The serum level in the dog could not be explained based on the water contamination level. It was assumed that the death was caused by digesting contaminated seaweed in the creek.

PSTs can enter the feed and food chain with macro algae as source or vector in several ways:

- A coralline red alga (Genus *Jania*) was assumed to be the source of PST accumulated in crab and gastropod species (Kotaki et al., 1983).
- The PST producing blue-green alga *Lynbya* was found to be able to grow in mixed cultures with some green algae (*Ulva* and *Cladophora*; Foss et al., 2012).
- The green alga *Cladophora* and duck weed (*Lemna*) appear to be able to accumulate PST from their environment (Mitrovic et al., 2005).
- Dinoflagellates can cause algal bloom and subsequent marine snow (Miller, 2004; Granéli et al., 2006). Additionally, the sessile form of dinoflagellates can grow directly on seaweed plants (macro algae) as growing substrate. In this way macro algae can act as vector for accumulated PSTs (cf. Mitrovic et al., 2005).

6.3.7 Seasonal influences

Levels of contaminants and of structural metabolites are reported to be highly influenced by seasonal differences and between years. This aspect is mentioned by Holdt and Kraan (2011), and more specifically addressed by other authors. The levels of eight minerals in *Ulva* differed among the years 2006 and 2007 between 3% (barium: 103 vs. 100 ppm) and 465% (potassium: 740 vs. 3444 ppm) at certain sampling sites (Apaydin et al., 2012).

6.4 Balance between risk and benefit

Utilisation of seaweeds can contribute to a high nutritional value of feed, whereas simultaneously negative effects can occur due to natural metabolites and contaminants. This balance has several aspects.

A range of putative health claims is recognised for the different polysaccharides and other metabolites. An overview is presented by Holdt and Kraan (2011) Possible adverse effects were not mentioned by these authors.

A second aspect is the highly varying content of the desired structural and additional polysaccharides, e.g. for agar or alginate production, illustrated in Table A.1. In any situation the production of the desired product will yield a by-product. There were no data found indicating the distribution of contaminants or toxic components over products and by-products. General principles are the distribution of hydrophilic components in the water (by-)products and hydrophobic components in the lipid (by-)products. Several scenarios can be assumed in the current situation of seaweed processing (Figure 6.2). If a contaminant does not show a specific preference all resulting fractions will show comparable levels of that contaminant (Figure 6.2a). In the situation that a contaminant does have a preference than either the by-product (Figure 6.2b) or the main product (Figure 6.2c) might show an over-contamination, illustrated by the red arrows in Figure 6.2. Considering the practical situation that agar, alginate and carrageenan products can be produced at least moderately safe, situation 'b' is likely to occur. Assume a level of 50 ppm of an undesired component in seaweed, an amount of main product equal to 70% of the total starting amount, and this product can be safely produced with a contamination level of 10 ppm. If no clean-up procedure is applied to both the product and the by-

product, the resulting contamination level in the by-product (30% of original mass) is 143 ppm. In this example it may be more appropriate to use the original, raw version of the seaweed as feed ingredient (situation 'a' instead of situation 'b').

A third aspect is the way a contaminant is present in the seaweed. The inorganic form of arsenic and the methyl-mercury form are the most toxic ones for arsenic and mercury, respectively. It is important to differentiate between these modi and analytical methods should be applied accordingly (Hedegaard and Sloth, 2011). Metallothionein is a sulphur-rich protein in seaweed with a high binding capacity for arsenic (Ngu et al., 2009). Other studies report on bioaccumulation by seaweeds of chromium, cadmium and lead (Tamilselvan et al., 2012; Hou et al., 2012). Heavy metal ions can either form organic components or can be sequestered in organic macromolecules, such as the polysaccharides (Murphy, 2007a). Binding of copper(II), chromium(III) and chromium(VI) by selected brown, red and green algae depend on the number and activity of binding sites, the acidity (pH) and the concentration of the metal ions. Equilibriums for binding were reached after 20-60 minutes for copper and after 120-180 minutes for the two oxidation states of chromium (Murphy et al., 2007b; 2008). The bioavailability and toxicity of the heavy metal ions when captured in macromolecules is not known. This issue is recommended to be investigated further for both main products (polysaccharides) as well as by-products (e.g. protein rich materials).

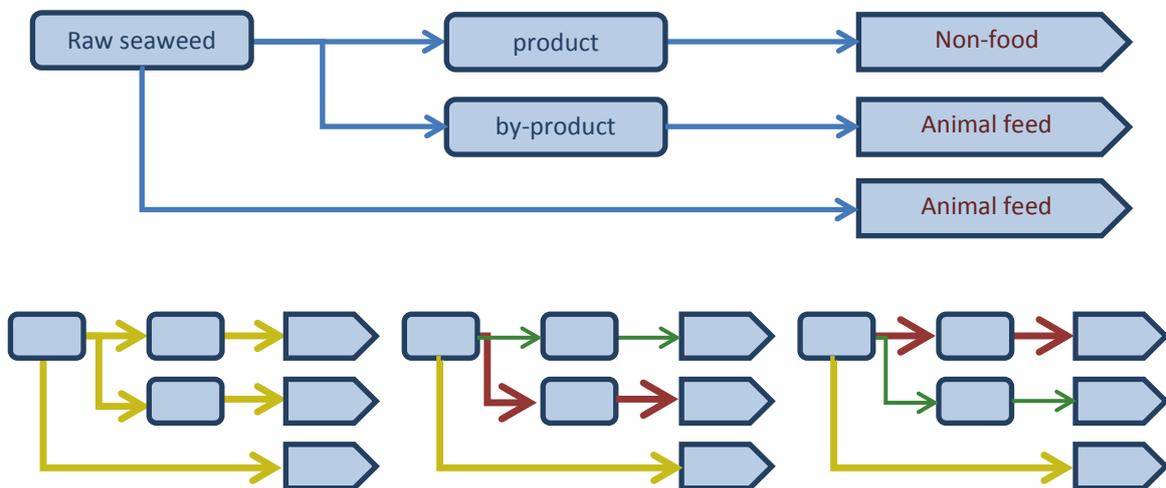


Figure 6.2 Possible routes for application of seaweed and derivatives, and examples of distribution of a contaminant in the sub processes.

6.5 Synthesis

Safety of primary or processed products intended for the production of feed and food can be assessed in several domains of knowledge:

1. Compliance with legal regulations, primarily EU:
 - a. knowledge is present: heavy metals, iodine.
 - b. Knowledge is scarce or not present: dioxins, fluorine, marine toxins, usually produced by certain species of micro algae.
2. Not legally regulated, but recognised concerns: substances with (undesired) bioactive function, e.g. lectins.

Basically it is necessary to carry out a survey to establish the background and normal levels of contaminants which can be expected to occur in seaweed as well as in derived products to find out possible effects of processing (for example along a scheme exemplified in figure 6.2). It is clear from

the arsenic survey that caution is required. A basic survey which can be used as zero measurement for future product developments need to cover realistic hazards: commonly reported or expected contaminants should be included, whereas hazards that are unlikely to occur can be omitted. It is important to find an optimal mix of putative hazards and benefits.

Based on the results of monitoring on a regular basis of both products and by-products, seaweed materials can be used as feed ingredient, provided that legal limits are not exceeded and levels of relevant risk assessments are considered. Provisions made in systems such as GMP and HACCP might be relevant for the utilisation of seaweed products.

It is recommended to pay attention to the following aspects:

- The botanic classification and its consequences need to be included in decisions on the choice of seaweed species targeted for cultivation.
- With respect to arsenic and mercury a further investment of speciation is required: balance between inorganic and organic presence of arsenic and mercury.
- The effect of sequestering on bioavailability of contaminants should be investigated in more detail. This recommendation applies to all raw and processed seaweed products, including those intended as feed additive.
- Halogenated metabolites or contaminants need further attention and monitoring.
- Investigation of the occurrence of micro algae because of simultaneous harvesting (e.g. on the surface of seaweed plants) or blue-green algae which can produce marine toxins, is required.
- Monitoring of all relevant contaminants as listed in Directive 2002/32/EC and other relevant legislation is necessary on a regular basis, provided that for every investigated sample the background and botanic classification is known.
- Novel feed ingredients needs a documented safety level and needs to be notified as novel feed ingredient.

Moreover, several other aspects should be considered for the harvesting or cultivation of seaweeds for human or animal production. These are:

- Recent information show relatively high levels of nanoparticles of plastic in seas and oceans. Harvesting wild or cultivated seaweeds could include certain levels of plastic particles (Anonymous, 2011).
- Although anti-nutritional factors were reported to be absent in seaweeds, except tannins at a very low level (1.50 and 1.67 g/kg) (Carrillo et al., 1992), more recently lectins were reported to be present in seaweeds (Holdt and Kraan, 2011). Certain lectins are known to belong to the most toxic components in nature (van Damme et al., 2008). Lectins from legume seeds (soy bean, *Glycine max*; common bean, *Phaseolus vulgaris*) have been shown to disrupt small intestinal metabolism and damage small intestinal villi via the ability of lectins to bind with the brush border surface in the small intestine and may lead to digestive disturbances, e.g. diarrhoea, bloating and vomiting. In addition, lectins can result in irritation and over-secretion of mucus in the intestines, causing impaired absorptive capacity of the intestinal wall. Heat processing can reduce the toxicity of lectins, but low temperature or insufficient cooking may not completely eliminate their toxicity, as some plant lectins are resistant to heat (Jackson et al., 2006). In a more general way, lectins can act as anti-nutritional factors.
- Pesticides are found in seaweeds (Lorenzo et al., 2012).

These aspects are not evaluated further in the framework of this feasibility study. It is recommended to pay further attention to these concerns.

7 Non-food applications of seaweed fractions

7.1 Introduction

Chapter 4 gave an overview of state-of-the-art knowledge on biorefinery of seaweeds. To meet the expected increasing demand for biofuels and biochemical, and to diversify the feedstock and product portfolio of biorefineries, there is a need to find additional suitable biomass sources, in particular those that do not rely on using large amounts of agricultural land. In this chapter, the potential uses of several fractions of seaweeds in non-food applications will be described.

7.2 Protein and its applications

In the past, proteins were commonly used in technical applications. In the early 1900s, research demonstrated potential industrial applications of soy protein in both plastics and adhesives. Henry Ford was an important early pioneer in soy protein utilisation, applying these technologies to improve his automobiles. Regenerating protein fibres, for example based on casein and soy, is done commercially since the 1930s. In the paper industry, proteins have been used as sizing agents, binders, and adhesives. Glue, derived from collagen, was the first material used for bonding paper and was used as an adhesive in paper coatings. In addition, plywood adhesives based on soy protein were developed. In the recent past, gelatine was used for more than 100 years as a binder in photographic products. In the last few decades, hydrolysates from keratin, gelatine, and wheat gluten have been used in cosmetics, e.g., as surfactants in shampoos (Vaz et al., 2003, Meyers et al., 1993).

In the 1960s, proteins were replaced by synthetic polymers in the non-food sector. An important reason for this substitution was the lower price of petrochemicals, but differences in performance have been important in this respect as well. More recently, there is an increasing demand from consumers and industries to replace synthetic polymers with polymers from renewable resources.

7.3 Seaweeds as feedstock for biological production of fuels and chemicals

Because of the potential to cultivate seaweeds at a large scale with high yields (see chapter 2 of this report) and their interesting biochemical composition (e.g. high sugar contents for some species), their use as feedstock for fermentation processes is given attention in recent years. Sugars and other nutrients present in seaweeds represent an interesting alternative to the first generation feedstock (grains, starchy substrates) currently used for the production of biofuels (see Tables A.1 and A.2) (Holdt and Kraan, 2011).

As in plant material, most sugars in seaweeds are normally a part of polymers, making pre-treatment and hydrolysis a necessary step to make them available for fermentation (see Chapter 4 of this report). Some studies have shown that the pre-treatment and hydrolysis conditions needed for the solubilisation of seaweed sugars are less severe than those needed for pre-treatment of lignocellulosic materials, most probably due to the absence of lignin in their cell walls and the relatively lower crystallinity of sugar polymers (Horn, 2000a; Adams, 2009; van der Wal, 2013).

A number of seaweed species and residues from the seaweed industry have been tested as feedstock for the production of ethanol (to be used as biofuel) or acetone, butanol and ethanol (ABE), where butanol can be used as a platform chemical and biofuel (Table 7.1).

Table 7.1

Examples of utilisation of seaweeds as feedstock for fermentation for production of bioalcohols.

Seaweed		Sugars in feedstock ¹	Product	Reference
Brown seaweeds	<i>Saccharina sp.</i>	Glucose, mannitol	ABE ²	(Huesemann, 2012)
	<i>Saccharina latissima</i>	Glucose	Ethanol	(Adams, 2009)
	<i>Saccharina japonica</i>	Glucose, mannitol, alginate	Ethanol	(Wargacki, 2012)
	<i>Laminaria hyperborea</i>	Glucose, mannitol	Ethanol	(Horn, 2000b)
Red seaweeds	<i>Gracilaria salicornia</i>	Glucose	Ethanol	(Wang, 2011)
	<i>Kappaphycus alvarezii</i>	Glucose, Galactose	Ethanol	(Khambhaty, 2012)
Green seaweeds	<i>Ulva lactuca</i>	Glucose	ABE	(Potts, 2012)
	<i>Ulva lactuca</i>	Glucose, Rhamnose	ABE, 1,2-propanediol	(van der Wal, 2013)

¹ Refers to the sugars utilised for fermentation

² Acetone, butanol and ethanol

7.3.1 Ethanol production from seaweeds

The most common ethanol-producing microorganisms, such as the yeast *Saccharomyces* utilise preferably hexose sugars (all sugars as listed in Table A.2 except for xylose) for growth. Unlike terrestrial plants, glucose is not always the most abundant sugar in seaweeds. Depending on the species, other sugars can be present as major component of the feedstock, such as mannitol (in brown species), rhamnose (in green species) or xylose (in red species) (Table 7.1).

Brown seaweeds are known to store mannitol and laminaran (a branched polymer of glucose) during the light seasons (spring to autumn) and consume them in the winter. The content in these components can be very high, depending on the species. As an example, in *Laminaria hyperborea*, 25% DM content of mannitol and 30% DM content of laminarin are reported (Horn, 2000a). In most cases, the laminaran from brown seaweeds needs to be hydrolysed to glucose before fermentation, by for example, addition of laminarinase enzymes. The production of ethanol by several species of microorganisms from brown seaweeds is reported (Table 7.1).

The fermentation of hydrolysates derived from Asian red seaweed species to ethanol has is recently (Khambhaty, 2012) (Table 7.1). The potential to use Asian *Sargassum sp* for the production of ethanol is described, since some of these species are very rich in carbohydrates (Borines, 2011). Experimental data on fermentation of this species were not reported.

7.3.2 Butanol from seaweeds

Some species of *Clostridium* are able to produce acetone, butanol and ethanol (ABE) by fermentation from a wide variety of sugars, both hexoses and pentoses, a process known as ABE fermentation. Solvent-producing Clostridial species are able to use sugars in different substrates, including (lignocellulosic) hydrolysates derived from plant biomass (López-Contreras, 2010). Since seaweeds are composed by different sugars, these organisms are expected to efficiently convert most sugars into an ABE mixture. The ABE process is nowadays commercially re-introduced for the production of biologically derived butanol (biobutanol) to be used as biofuel or to replace petrochemically produced butanol in the bulk chemicals market (López-Contreras, 2010; Green, 2011).

The fermentation of hydrolysates from brown seaweeds to ABE is reported (Huesemann, 2012). In this study, the utilisation of mannitol, glucose and laminarin in extracts from *Saccharina sp* by *C. acetobutylicum* is described. This strain shows a diauxic growth pattern when grown on glucose/mannitol mixtures, with a strong preference for glucose over mannitol. Interestingly, *C. acetobutylicum* appeared to use laminarin in the extract without external addition of enzymes.

A pilot scale test on the production of butanol from *Ulva lactuca* collected in a bay in New York is described in Potts (2012). Product levels were relatively low. A study using *Ulva lactuca* collected in

Zeeland (The Netherlands) as feedstock for ABE, demonstrated the production of ABE and 1,2-propanediol by *C. beijerinckii* from rhamnose (the major sugar in *Ulva lactuca*) (van der Wal, 2013).

7.4 Non-food application of proteins

In recent years, based on the world demand for proteins for human nutrition and feed, 'new' protein rich biomasses such as seaweed, micro algae, insects, dug wheat and grass have become subject of studies. Despite the fact that the main outlet for proteins is in the food and feed area, they also can be used in numerous technical applications, such as coating systems, as surface active substances and green chemicals, such as polyurethanes (Mulder, 2010). It is expected that the market for green chemicals will significantly increase in the coming years. A strong motivation for studying the possibilities of technical applications based on these 'new' protein sources is that the isolated proteins, due to the legislation restrictions, cannot be used in human food. Many of these sources are used as animal feed. The added value of these proteins may be increased by isolation and purification for technical applications. At present, in the case of seaweed research is mainly focused on the extraction of hydrocolloids and carbohydrates. To make this process viable, it will be necessary to use and valorise the protein fraction in the biomass. It is therefore important to look at the perspective from a biorefinery point of view and extracting and valorising the different seaweed components.

The protein content of seaweeds can roughly vary between 5% and 40%, depending on the species (see Table 7.1). The protein content differs not only between species, but it also depends largely on the seasonal harvesting period. For example, for *Palmaria palmata* protein contents between 9% DM, during the summer months, and 25% DM by the end of the winter and spring period, were reported (Fleurence, 1999). For biomass with protein contents between 5% (fresh grass, corn stover, sunflower seed hulls) and 15-20% (rapeseed hulls, soy bean pods, beet leaves), currently no applications with significant market value are available. Biomass with high protein content of approximately 50% (soy meal, rape meal, meat meal) and other protein sources with a protein content between 25% and 50% (press cakes of rapeseed, sunflower seed and slaughterhouse waste) are already used in animal feed. On average the protein content of the majority of seaweed is situated in this last group and are therefore interesting resources for finding suitable protein applications (Mulder, 2010).

To make this biorefinery processes economical viable it is important to extract and valorise all fractions of the biomass, including proteins. Proteins have complex structures based on their amino acid composition, three dimensional structures (helices, beta sheets) and the way subunits are linked together. Molecular weights vary from thousands to millions of Daltons. Apart from these structural properties, their applicability is dependent on a number of physical and chemical properties, such as solubility, surface active properties, barrier properties against moisture and gasses (oxygen, carbon dioxide), adhesive properties and the ability to form films. These same properties can also be used to exploit proteins in non-food uses.

For the recovery of proteinaceous material from seaweed, it is important to acknowledge the desired end application (Barbarino and Lourenço, 2005). In case the protein is used as binder in coating or adhesive systems, the proteins have to maintain most of their functional properties. The proteins should be isolated, using mild processes, in such a way that the molecular back bone (molecular weight) is kept intact and avoiding major denaturation of the protein. In the case protein fragments and/or amino acids are transformed into green chemicals, depending on the specific target molecules, more severe extraction conditions could be used. A potential scheme for protein and amino acid recovery from biomass is given in figure 7.1. Most of the native proteins are water soluble at a certain pH. Therefore, proteins can be isolated in acidic or alkaline solutions. In biomass mixtures, where apart from proteins also other materials like fat or cellulose is present, extraction efficiency can be increased by the use of enzymes (cellulases, amylases, proteases). The use of acids, bases, or enzymes can hydrolyse the protein material during the isolation process. This has to be taken into account for applications in which the molecular weight of the protein is important. In general, the isolation process has an effect on the chemical and physical properties of proteins.

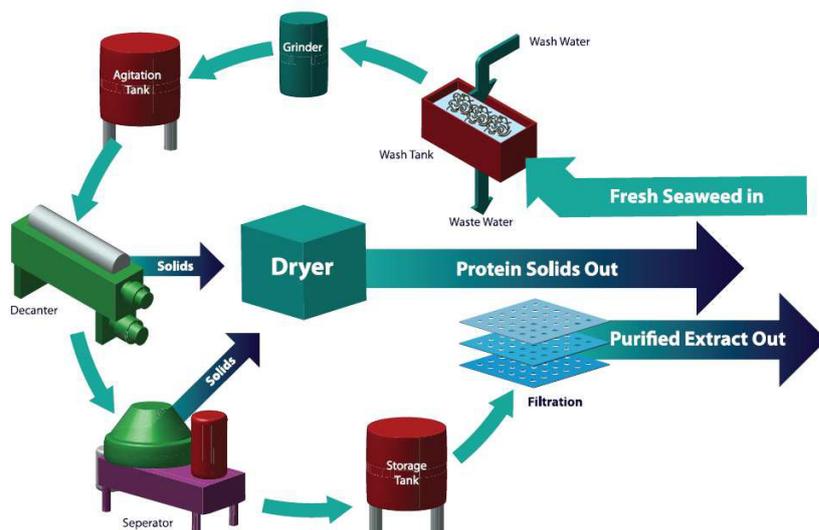


Figure 7.1 Proposed biorefinery scheme for the recovery of proteins (source: www.oceanharvest.ie).

Proteins need to be hydrolysed for the production of amino acids. In the food industry it is general practice to obtain hydrolysed vegetable proteins by exposure to 6 M hydrogen chloride at elevated temperatures over a prolonged period of time. A major drawback of this method is the considerable amount of base required to neutralise the hydrolysate, which will lead to undesirably high concentrations of inorganic salt in the hydrolysate. These inorganic salts need to be separated from the amino acid mixture as it may interfere with downstream processing. In addition, a number of amino acids are destroyed during the hydrolysis process. Protein extraction under more mild conditions is currently under development and this technology is already able to extract over 80% of the total available protein. An alternative method for protein hydrolysis is based on the use of proteases. Using mixtures of proteases, hydrolysis yields up to 90% can be achieved. The major drawback in the application of proteases for the hydrolysis of proteins lies in the high enzyme costs. In this respect, enabling reuse of proteases by means of immobilisation might be promising. A more recent development is the application of super critical water in the simultaneous extraction and hydrolysis of proteins from biomass residues (Brunner, 2009).

Finally, after the extraction and production of proteins, hydrolysed (peptides) and/or amino acids, methods are required that isolate and purify the materials. Selective isolation is needed for their application in the production of nitrogen functionalised chemicals. In the case of simple mixtures of amino acids which differ enough with respect to their isoelectric point and polarity, selective precipitation can be achieved based on pH adjustment or addition of an organic solvent, or both, in combination with cooling and concentration. Protein hydrolysates are often complex mixtures and therefore more advanced separation techniques such as ion-exchange (IE) will be required. IE is effective in the separation of complex mixtures of amino acids but for large-scale applications costs are anticipated to be high due to elution times and the need for regeneration. Other purification techniques like chromatography and crystallisation can also be used.

Due to seasonal changes and different protein profiles between seaweeds, their applications for bulk chemical products may be limited, since for this purpose homogenous feedstock are needed. Probably one of the highest potentials of non-food applications of seaweed proteins would be in the field of healthcare, functional foods or anti-infectives due to the numerous bioactive compounds that have been detected in seaweeds. Several recent reviews summarise the most important literature advances in these fields (Lee, 2004; Leiro, 2007; Arunkumar, 2010; Harnedy and FitzGerald, 2011; Holdt and Kraan, 2011).

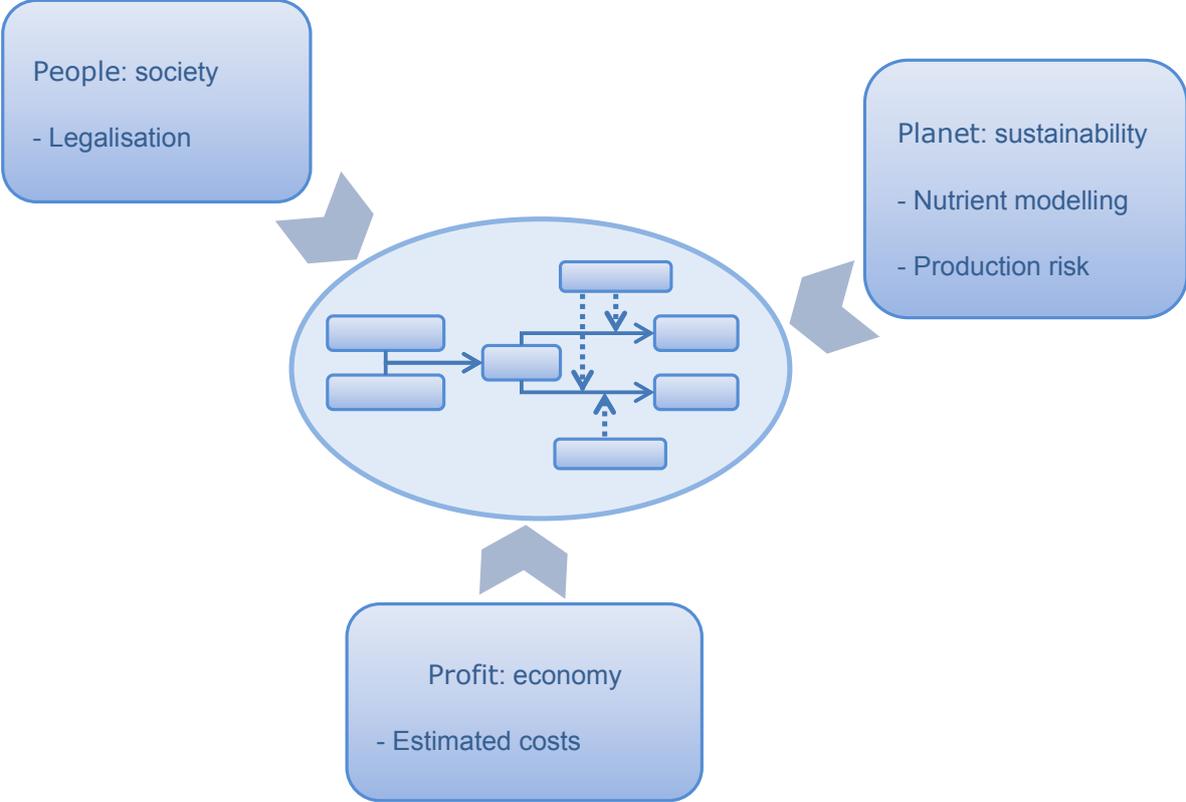
7.5 Synthesis

Seaweeds represent a diverse biomass feedstock. Because the high content in sugars of some species, such as *Palmaria* (Table 1.3), they are interesting substrates for fermentation processes. In general, seaweed biomass has a less crystalline structure compared with lignocelluloses, which makes that less stringent conditions are needed for the solubilisation of sugars in the biomass, making their use as feedstock potentially more economical. Fermentation of sugars derived from seaweed fractions to ethanol, butanol and other important chemicals has been reported for representative species (Table 7.2).

When using protein as a polymer it is important to maintain the molecular weight and the functionality of the protein. The specific properties of each protein should be considered depending on the target application considered. Examples are adhesion and bond strength for adhesives, resistance against water for coatings, and strength for plastic materials. In biorefinery processes often, due to the processes that are being used to extract these different components, the proteins will be (partially) denatured and hydrolysed resulting in the formation of peptides and amino acids. These fragments can be used to develop all kind of chemical structures (N-containing) and building blocks for production of polymers and resins.

Traditionally, the chemical industry uses fossil feedstock for the production of chemicals. Due to the decrease in availability of fossil feedstock and environmental issues, biomass becomes an important raw material for the production of chemical compounds. Apart from these aspects, the use of biomass can have also advantages in the synthetic pathways. The petrochemical industry uses simple molecules, like ethylene, to produce functionalised chemicals for which co-reagents, catalysts and many processing steps are used. Therefore, it is more efficient to make functional chemicals starting from proteinaceous materials, like amino acids, that already possess functional groups.

Part II: FEASIBILITY FROM A TRIPLE P PERSPECTIVE



8 PROFIT: Economic feasibility of a North Sea seaweed value chain

8.1 Introduction

In this chapter we assess the economic feasibility of a North Sea seaweed value chain. The envisioned approach was to assess the feasibility by conducting a Value Chain Analysis (VCA) by analysing the different steps in the chain with a focus on costs and added value.

Good data on the production and processing costs of North Sea seaweed is lacking. We use an adapted version of a VCA (Taylor 2005). A typical value chain consists of a number of steps where raw materials are transformed into products with a higher added value; a raw material is produced, harvested and processed before it is finally used in the production of consumption goods that can be sold in retail outlets. In reality, products can go through various processing steps.

Pragmatically, the following approach was used to analyse the economic feasibility based on available data:

- Brief overview of the total volume of seaweed production (worldwide and in Europe)
- Detailed estimation of the expected costs of North Sea seaweed production (cost-driven approach)
- Inventory of the potential use of North Sea seaweed, expected prices for each of these products and/or the price of competing products (value-driven approach)
- Analysis of the extent to which the cost-driven and value-driven approach match and formulation of future research challenges.

There have been and still are a number of experiments with seaweed production and some (very) local sales of seaweed products based on seaweed harvested from the wild. At present an operational value chain based on the large-scale offshore production of seaweed does not exist. This is the case in all European countries.

Various seaweed products are imported from other countries by large traders such as Cargill. For instance, within the seaweed/carrageenan value chain, there are six different products: raw dried seaweed; four types of 'pure' carrageenan products; and carrageenan-based blended products (Panlibuton et al., 2007). The latter are industry specific, customised blends. These products are used as ingredients in various production processes and - to a minor extent - sold for direct consumption.

Based on scientific literature, reports, interviews and personal communications we gathered insight into the current and potential status of the North Sea seaweed value chain. We collected data where possible and made assumption where needed. In this analysis, we alternate between seaweeds in general and North Sea species. Where possible, we focus on the selected species of chapter 2 and we include other species in the analysis if they have similar functionalities, are indigenous and (potentially) compete with North Sea produce.

In the analysis, we provide calculations to assess the economic feasibility of developing a North Sea seaweed value chain. It is important to emphasise that there is a high level of uncertainty when it comes to the production costs.

8.2 Global and European production volume and value

In 2004, the value of the world seaweed market was almost €6bn, over 90% of which was farmed (Douglas-Westwood 2005). This includes all commercial seaweed species. Commercial harvesting occurs in about 35 countries, spread between the Northern and Southern hemispheres and temperate and tropical waters. The farming of seaweed has expanded rapidly as demand outstripped the available wild supply. FAO data shows that the total traded volume of seaweed has increased five-fold

since 1984.¹⁵ The total value of seaweed increased by about 350% as the value per tonne decreased slightly. In 2010 total production was estimated at about 20m tonnes (FAOSTAT). Asia is responsible for the vast majority of this production, with China, Indonesia and the Philippines as main contributors. The majority of the global seaweed production consists of red (45% in 2010) and brown (36% in 2010) seaweeds. The market demand in Asia is high. In China, demand has outstripped the domestic supply, leading to imports from countries such as Indonesia.

The size of the European industry should be seen in the context to the global seaweed industry. Most of the European seaweeds is 'harvested' from wild resources. FAO data on cultivated European seaweed production shows a sharp decline during the late 1990s and early 2000s. In 2002 a low of 181 tonnes was reached following a high of 11,600 tonnes in 1995. Since then, production levels have increased to around 738 tonnes in 2010.¹⁶ In Europe, commercial seaweed aquaculture has developed to some extent in France, Denmark, Estonia and Russia. If we look at France, there the Asian kelp *Undaria pinnatifida* also called wakame is grown for human consumption. It is estimated that circa 50 tonnes are farmed in France (Mesnildrey et al., 2012). This is relatively small, compared with an overall French seaweed production of 60,000 tonnes. In Ireland, like in France, there is history of harvesting wild seaweed. This constitutes approximately 25,000 tonnes per year (Douglas-Westwood 2005). Norway is another seaweed producer, harvesting wild seaweed near shore. The total volume of *Laminaria hyperborea* and *scophyllum nodosom* harvested annually is estimated at 200,000 tonnes.¹⁷

8.3 Expected cost of North Sea seaweed aquaculture

Currently, seaweed is not farmed at a significant scale in the North Sea. Tropical experiences with marine and brackish water seaweed cultivation are not comparable to seaweed farming in marine temperate waters like the North Sea. In China farming takes place near-shore and relies heavily on manual labour. Offshore seaweed cultivation requires a degree of mechanisation that is not seen in tropical marine and brackish water regions. Various research projects investigate if and how seaweed farming is possible in marine temperate waters including the North Sea. These projects use various technologies.

In Spain and Portugal much research is being done regarding the use of *Gracilaria bursa pastoris*, *Chondrus crispus*, *Palmaria palmata*, *Porphyra dioica*, *Asparagopsis armata*, *Gracilariopsis longissima*, *Ulva rotundata*, *Ulva intestinalis* and *Gracilaria gracilis* as biofilters for use in Integrated Multi Trophic Aquaculture (IMTA) units. IMTA research along the Atlantic coast of the Iberian Peninsula is primarily focused on using algae (mainly Rhodophyta) with fish (mainly turbot, *Scophthalmus maximus*, and sea bass, *Dicentrarchus labrax*) (FAO 2009).

In France the majority of the work on IMTA systems is concerned with the use of marine ponds to treat fish effluents, and all are at the experimental stage. More specifically, researchers are investigating the use of high rate algal ponds (HRAP) to treat sea bass (*Dicentrarchus labrax*) effluents. Although these studies are pond or tank based, they are all relevant to the marine-based aquaculture systems in coastal waters of France, particularly the benefits of integrating macro algae and oysters. *Ulva* (as *Ulva* and *Enteromorpha*) and *Cladophora* were used in HRAP (FAO 2009).

In Ireland aquaculture, both mono-specific and integrated, is currently underway. Irish farmers have taken advantage of the abundance of commercially viable seaweed. Besides the commercial cultivation of *Asparagopsis armata* (Kraan and Barrington, 2005), there are three other seaweeds currently being farmed in Ireland: *Palmaria palmata*, *Alaria esculenta* and *Chondrus crispus*. Another IMTA research project integrated 4 different species on 3 different trophic levels. The system integrated 2 algal species (*Laminaria digitata* and *Porphyra sp*), abalone and salmon. In this integrated-looped system,

¹⁵ <http://www.fao.org/fishery/statistics/global-aquaculture-production/en>

¹⁶ <http://www.fao.org/fishery/statistics/global-aquaculture-production/en>

¹⁷ www.netalgae.eu.

the macroalgae are internalised food sources for shellfish and finfish, while simultaneously acting as effluent biomitigators, increasing the sustainability of the entire operation (FAO 2009).

A German research project made use of ring-system around the piles of wind-turbines. The costs for a ring are estimated at €1,000, with a life span of 10 years. They are limited in size and each produced 40 kg of DM (Buck and Buchholz 2004).

In a Dutch study it is claimed that large-scale offshore cultivation of *Gracillaria* and *Laminaria* is possible at costs between USD112-409 per tonne of DM (Chynoweth 2002; Reith, Deurwaarder et al., 2005). This study draws on rather old data and most likely these figures represent averages production costs for differing methods, countries and environments. Florentinus et al. (2008) report investment costs of €25,000 per ha for seaweed cultivation of the Dutch coast, with expected yields of 35 tonnes of DM per ha.

Lenstra et al. (2011) formulated three scenarios to calculate the production costs of systems varying in scale: 100 ha, 1,000 ha and 10,000 ha. In the 100 ha scenario, they assume a total investment of €25,000 per hectare. Operation and maintenance costs are set at €75,000 per year, harvesting costs at €104 per tonne of DM. With an estimated yield of 50 tonnes of DM/ha/year, they give a cost price indication of €669 per tonne of DM.

The most detailed information available is from a 1993 study near the Canadian coast (Petrell et al., 1993). This study concluded that initial investment costs for a 60x20 meter farm totalled CAD 60,910 (€45,615) (1992 data, including cost for boats, shed and dryers, exchange rates d.d. 28-5-2013). An overview of different predicted production costs is provided in Table 8.1.

Table 8.1
Estimated seaweed production costs in literature.

Technology	Investment	Lifespan	Operational	Yield	€ per tonne DM	Source
	€	Year	€/year	Tonnes of DM		
Ring	1,000 per unit	10	n.a.	0.040	2,500 costs ⁽¹⁾	Buck and Buchholz (2004)
Long-lines	n.a.	n.a.	n.a.		121-409 ⁽¹⁾	Reith, Deurwaarder et al. (2005)
	25,000 per ha	10	n.a.	35	71 ⁽¹⁾	Florentinus, Hamelick et al. (2008)
	25,000 per ha	n.a.	750 per ha + 104 per tonne of DM	50	669 ⁽²⁾	Lenstra et al. (2011)
	45,615	10	12,155	1.6	10,448 ⁽³⁾	Petrell, Tabrizi et al. (1993)

¹ excluding operational costs, capital costs, labour costs.

² method of calculation not available.

³ including cost for transport, labour and storage.

In the Netherlands there are two ongoing research projects experimenting with offshore seaweed cultivation, using either net cultivation or long-line systems. Good information about costs and yields is unavailable. We do know that the system is labour-intensive as the seedlings need to be attached to the rope manually and capital-intensive).

A third Dutch research project (Wierderij) makes use of a similar production method but applies this method near-shore. Based on the experiences within this project the required technology and expected costs can be estimated. The estimated total investments are in the order of €25.000 to €75.000 per ha. This includes 10 km of long-lines, (€ 1/m), buoys, mooring and employment. The expected lifespan is 10 years (pers. Comm. Brandenburg). For offshore application, we choose to double expected investment costs. Additionally, new ropes with seaweed seedlings have to be added each growth cycle (year) with an expected cost of €1/m (1 m rope + 1 seedling). Estimates for labour costs are unavailable.

Estimation of the labour costs is difficult in the absence of clear established procedures, but it can be argued that labour cost during operation and maintenance are relatively small. We assume that operation and maintenance of a 10,000 ha sea farm requires forty man years of work (40*261 days*8h = 83,520 hours). This would require production process mechanisation and usage of distance, online monitoring. At labour costs of €35 per hour, total labour costs are set at €2,923,200, equalling approximately €300 per hectare. Based on Lenstra et al. (2011), we assume harvesting costs of € 104 per tonne of DM. If we set the expected yield at 20 tonnes of DM per hectare, production costs are estimated as shown in Table 8.2.

The total production costs for seaweed - excluding harvesting and transport - if based on the calculation above would lie between approximately €1.000- and €1,500 per tonne of DM.

Table 8.2

*Estimated costs for offshore seaweed production using long-lines.
Capital costs are excluded.*

		Per ha	lifespan (year)	Per year	Per tonne of DM (20 tonne yield)
Investment in systems	Low scenario	50,000	10	2,500	250.00
Investment in systems	High scenario	150,000	10	7,500	750.00
Seedlings		13,000	1	13,000	650.00
Labour		300	1	300	15.00
Harvesting					104.00
Total	Low				1,019.00
	High				1,519.00

8.4 Potential seaweed uses and utilisation

In Europe, North Sea seaweed and North Sea seaweed derived products can potentially be used and used for the following purposes:

- Industrial gums
- Animal feed (ingredients and supplements)
- Chemicals
- Biofuels

Others uses on which little to none information is (yet) available are the following. These are excluded from further analysis.

- Human consumption
- Fertiliser (agricultural)
- Cosmetics
- Medicinal uses
- Biofilters in IMTA
- Use in climate change adaptation and coastal defence (Building with Nature)
- Seaweed to enhance capture fisheries

In the following sections, we review some of the possible applications of seaweeds of North Sea seaweed. An important remark to make from the start is that available literature focuses on single-use of seaweeds. The possibilities to combine different applications are not investigated but might be key to the development of a feasible business model.

8.4.1 Industrial gums

Seaweed industrial gums, also known as 'seaweed hydrocolloids', fall into three categories: alginates (derivatives of alginic acid), agars and carrageenans. These are commonly used in food products to increase viscosity and as emulsifier. It can be found in products such as ice cream, pet foods, bakery et cetera.

According to Perez (1997), in 1993 a total of 200,000 tonnes dry seaweed was used for the production of alginate. The value of the produce was estimated between USD5,000 and USD8,000 per tonne. This is in line with data provided by Sustainable Energy Ireland (2009) who concludes that the world market for alginates is roughly 30,000 tonnes at an average of USD6,000-10,000 per tonne. Only 0.5m tonnes of fresh brown seaweed would be required to meet this market as it takes 16 tonnes wet/fresh seaweed to produce 1 tonne of alginate. The FAO (2003) concluded that a total of 1m tonnes of seaweed is produced and harvested to produce the three hydrocolloids (agar, alginate, carrageenan). According to FAO data, total hydrocolloid production is 55,000 tonnes with value of USD585m. This is equal to an average market value of USD664 per tonne of fresh seaweed.

In the last decade, the hydrocolloids industry has gone through significant changes. In the sector, horizontal integration has occurred, increasing average company size, and much of the production capacity has moved to Asia. Seaweed costs have escalated, just as chemical and energy costs have but the emergence of low cost producers in China makes it difficult to pass the higher costs to customers (Bixler and Porse 2010). Bixler and Horse (2010) sketch market development for the three hydrocolloids.

- In 1999 the giant kelp, *Macrocystis pyrifera*, not native to the North Sea, was the principal source of the world's alginate supply. Nowadays, *Laminaria spp* is the largest source for alginate production. In the last decade, market volume for alginate has increased slightly (from 25,000 to 26,500 tonnes). Suitable seaweeds for alginate production has become more difficult and costly to obtain. Price estimations show a threefold increase, up to €745 (about USD950) per tonne.
- Carrageenans are derived from various red algal species (*Rhodophyceae*). This market is dominated by producers from the Philippines and Indonesia, using the species *K. alvarezzi* and *Eucheuma denticulatum*. Carrageenans can also be produced from *Chondrus crispus*, a red seaweed species which grows along the coasts of the northern part of the Atlantic, the main harvesting areas being the Nova Scotia area of Canada, the New England coast in the United States, Brittany in France and the Iberian Peninsula. Bixler and Horse (2010) report declining availability and use of *Chondrus crispus*.
- Agar is extracted from various *Gelidium* and *Gracilaria* species found in the coastal waters of Japan, Mexico, southern California, North Africa and Chile (Glicksman, 1987). These species are not native North Sea species.

The prospects for the alginate and thickeners market are not clear cut. Demand for thickeners in Europe is only growing slowly and alternative thickeners are available. Global demand is estimated to grow slowly, at a few per cent annually (CBI 2011) but others argue that there is danger of market saturation (Reith et al., 2005). It is observed that the demand for competing products (such as gelatine) is already decreasing (Sustainable Energy Ireland, 2009). However, demand for thickeners in other countries is likely to grow as this demand for processed food increases. This might put pressure on the availability of seaweed-based thickeners. Availability of seaweeds for alginate production has not been a problem during the last decade but can be expected to present supply and costs problems in the near future (Bixler and Porse, 2010).

8.4.2 Animal feed

One of the foreseen uses of seaweed is application as an animal feed ingredient or additive. The feed market is promising as it is a large industry which processes significant amounts of raw materials. To illustrate, the total soy imports for animal feed in 2010 equalled 2,765,000 tonnes (www.pdv.nl). Aside from the question whether or not replacement with seaweed is possible, it is clear that the volumes are huge compared with the 800,000 tonnes of seaweed produced in Europe.

By use of a feed optimisation programme (Bestmix) a preliminary simulation was made to calculate the economic value of several intact seaweed species present in the North sea region. Additionally, the red seaweed (*Polysiphonia SPP*) as described by El-Deek et al. (2009) and characterised by a high crude protein and fat content, was included in the calculation. Because of the lack of detailed information about energy and amino acid digestibility of seaweeds, the digestibility coefficients and other values of a well-known leaf ingredient (lucerne) were used. This assumption might largely affect the outcome of the calculation. In lucerne, digestibility coefficients of crude protein, crude fat and NSP for pigs were 57%, 32% and 48% respectively. The economic value was expressed as the price (€/100 kg dry product, 94% DM) which resulted in 5% inclusion of seaweed into a grower pig diet in the feed optimisation programme. Based on these assumptions, the economic value per 100 kg DM was €0.00 for *Laminaria digitata*, €4.40 for *Saccharina latissima*, €11.50 for *Palmaria palmate*, €4.60 for *Ulva lactuca* and €11.10 for *Polysiphonia SPP* (see Table 8.3). We emphasise that caution has to be taken into account by using these values and that possible differences in amino acid profile and digestibility between species have not been taken into account.

Seaweeds can also be used for the production of feed additives (see chapter 6 of this report). This applications appears to be more promising but exact data is lacking. Further research is thus required to assess the feasibility.

Table 8.3

Values of seaweed if used as animal feed (per tonne of DM).

	Value (euro/100 kg 94%DM)	Value (euro/tonne of DM)
<i>Laminaria digitata</i>	0.00	0.00
<i>Saccharina latissima</i>	4.40	46.64
<i>Palmaria palmate</i>	11.50	121.90
<i>Ulva lactuca</i>	4.60	48.76

8.4.3 Chemicals

Seaweed can also be used to produce a range of chemicals (see Chapter 7). Reith et al. (2005) conclude that the average value of the produce is €821 (USD1,050) per tonne, with lows of €235 (USD300) (lactic acid) and highs of €1,414 (USD1,808) (citric acid). Table 8.4 gives an overview of some possible chemicals that can be produced from seaweed and their market value. It is also stated how much can be produced from a tonne of dried seaweed.

Table 8.4

Selection of chemicals that can be produced from seaweed using fermentation.

Based on Reith et al., 2005, adapted by LEI.

Product	Market value €/tonne	Production Kg/tonne of dry seaweed	Value €/tonne of dry seaweed
Acetic acid	570	247	140
Butanol	707	123	87
Lactic acid	235	486	114
Propylene glycol	1,000	133	133
Citric acid	1,414	429	606

At this point, it is not known how seaweeds functionally and economically compare to alternative feedstock for the biorefinery process, such as soya and sugar beet.

8.4.4 Biofuels

Seaweed can be used for the production of biofuels. Two technological pathways can be identified (Ireland 2009). First, methane can be produced through anaerobic digestion. The methane can be used to generate heat and electricity or used as a transport fuel. Alternatively, seaweed can - through fermentation - be transformed to sugars which can be used to produce bioethanol or sugars. Some promoters of algal biofuel products describe the market for fuel as 'infinite'; there is unlimited demand for the product once it is available. Currently, there is only limited existing infrastructure for the distribution of biogas.

In their study, Reith et al. (2005) state that a maximum of 0.3 to 0.48 m³ of methane can be produced from a kilogram organic seaweed matter. This is comparable to what can be produced from sludge. There are numerous experimental projects examining production of bio-gas from seaweed, among them an interesting trial in Tokyo. Drift seaweed causes problems in Japan and for that reasons, it was examined if *Laminaria* and *Ulva* species could be used for the production of biogas. A test plant was constructed, consisting of four main components: pre-treatment, fermentation, biogas storage and generation. The results showed that 1 tonne of *Laminaria* yielded 22m³ of methane gas and 1 tonne of *Ulva* yielded 17 m³ of methane gas (Sustainable Energy Ireland 2009). Reith et al. (2005) have described a system for production of methane from *Laminaria* by means of anaerobic digestion and estimated involved costs. Taking into account investments and operational costs, Reith et al. conclude that the anaerobic digestion of seaweed to produce energy is economically viable if prices for seaweed are below €3.8 per tonne of DM for production of biogas or below €5 per tonne of DM for electricity production. In practice, subsidies for renewable energy allow for higher prices. Personal communication with a German biogas producer made clear that the maximum price for a tonne of DM seaweed should be around €30, assuming that the percentage of DM is increased to 24%.

Ethanol can be produced by fermentation of the main seaweed sugars mannitol and laminaran (see Chapter 7). This process requires extraction of the sugars from alginate, proteins and cellulose. These products can be fermented into methane. It should be noted for all biorefinery concepts that any extraction step is likely to lower the potential energy yield from seaweeds. For example extraction of alginate, laminaran and fucoidan would lower by almost 50% the amount of fermentable compounds in seaweed. When it comes to ethanol, there is a large world-wide market, in 2006 about 45m m³ expected to grow fivefold by 2020 based on mandatory blending obligations. Current prices for ethanol on the commodity market are around USD2.54 per gallon, equalling USD671 per tonne.¹⁸ Reith et al. (2008) calculated the break-even point for production of ethanol from seaweed and concluded that the production is viable if (1) the system is sufficiently large, processing 500,000 tonnes DM per year and (3) is the seaweed price is set at maximum €30 per tonne of DM. This excludes possible subsidies for renewable energy.

8.5 Synthesis

It is too early for draw a final conclusion on the economic viability of developing a North Sea seaweed value chain. There are still many uncertainties as there currently is no North Sea seaweed value chain. In Table 8.6, we provided an overview of the different usages of seaweed of North Sea seaweed species, required steps for harvesting and processing and value of the end product to assess the feasibility of some applications.

¹⁸ <http://ethanolmarketprice.com/>, [15-3-2013]

Table 8.6*Assessing the feasibility of North Sea seaweed applications.*

	Economic feasibility	Processing	Value (€)
Hydrocolloids	Possibly for alginates	Cleaning, production of hydrocolloids	333-1,250
Feed (direct addition to feed)	Low	Cleaning, drying,	0-121
Functional feed (after refinery)	Potential	Biorefinery	Not known
Chemicals	Selective possible, for some chemicals	Biorefinery	114-606
Biofuels	Low	Anearobic digestion or fermentation	3-30

The market for seaweed products is diverse. Direct consumption by animals offers low value. It seems more interesting to produce feed additives from seaweeds (see chapter 6) but more research is required. The use of seaweeds for the production of biofuels seems unlikely due to the low prices that are paid for biofuel material.

The most promising application is through biorefinery where seaweeds are refined into a range of products such as alginates, chemicals, feed additives. The question then is whether or not the remaining biomass it is possible to develop a cascade of seaweed applications from high-value to low-value (e.g. after biorefinery use as source for biofuel).

If we compare value to expected production costs, expected to be between about €1,000 and €1,500 per tonne of DM, an economically viable production of seaweed seems possible. However, further prove is needed that seaweeds can be produced at these costs at a large scale. Looking at the production costs, the annual purchase of seedlings constitutes the largest cost. Technical innovation and the design of production systems that enable multiple harvests per year can reduce production costs.

9 PLANET: Sustainability

9.1 Introduction & objectives

Marine protein production in open water systems per definition interacts with the surrounding aquatic ecosystem. Whether and to what degree this affects ecological sustainability depends on the type of culture and the extent of integration between different culture types and other activities. MUPS aim at optimal integration of activities, and each activity is thereby placed in a wider ecosystem context. The aim is to manage all activities in such way that it contributes to the sustainable development and equity of the whole.

There are different ways of evaluating the eco-sustainability of a production system, whether it concerns mono-culture, integrated aquaculture system, or integration of multiple activities.

Approaches for evaluation of eco-sustainability include for example:

- Nutrient (management) models (see 9.2) quantify nutrient dynamics within the cultures and the interactions between aquaculture and the ecosystem. They thereby provide quantitative insight in input, output and translocation of nutrients within a system.
- Risk assessment models (see 9.3) integrate nutrient models with other activities and their pressures (e.g. from operation and maintenance) and thereby provide a semi-quantitative evaluation of the risks and opportunities of combinations of aquaculture conditions.
- Life Cycle Analysis (see 9.4) is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.

The foreseen MUPS production system combines different production functions, probably with mutual interactions between the individual functions. Hence, for sustainability assessment the integral system should be considered. The current chapter describes ecological sustainability issues concerning offshore marine protein production. The mentioned approaches for assessing environmental effects are reviewed, with particular emphasis on how to assess eco-sustainability of marine protein production within an integral IMTA (Integrated Multi Trophic Aquaculture) and/or MUPs framework.

9.2 Nutrient management models for offshore aquaculture

Seaweeds can either be cultured as a single species (mono-culture), together with bivalves (co-culture), or be part of an integrated production system with finfish as the principal component (IMTA). Irrespective of culture type, development of nutrient management models (related to carrying capacity models) is important in order to predict and optimise growth, production, profitability and simultaneously assess culture-ecosystem interactions.

9.2.1 Mono-culture of seaweed

A rough estimate of nutrient dynamics in mono-culture production of seaweed can be provided by mass balance budget analysis. Budget analysis may address some consequences of seaweeds to ecosystem processes (removal of inorganic nutrients) but is based on a static approach. However, marine systems are complex, with inorganic nutrients being dynamic quantities subject to physical, biochemical and eco-physiological processes which fluctuate over both temporal and spatial scales. Simulation models are therefore an important approach in predicting dynamics of seaweed-ecosystem interactions. Dynamic growth analysis can be used to determine the nutrient assimilation and growth of seaweed cultured in mono-culture production systems. Spatial and temporal modelling of hydrodynamic conditions is an important feature of these assessments.

9.2.2 Co-culture of seaweed and bivalves

Co-culture generally refers to a production system where two or more species are cultured at the same culture locations without the occurrence of any apparent positive or negative biological influence between the two species. The reasons for co-culture can often be found in creating economical synergies (e.g. work-activities and expenses for the co-cultured cultivation) rather than creating biological synergies. There are limited interactions between seaweed and bivalve culture as the seaweed feed on inorganic nutrients and bivalves filter the organic nutrients from the water column. Cultivation of seaweeds and mussels can therefore be regarded as co-cultures, and separate nutrient models can be defined. These separate models are both linked to the same environmental model (including e.g. hydrodynamics, temperature, background nutrients, microalgae, and zooplankton sub-models). However, the nutrient models of seaweed and mussels are to some extent linked as (1) competition for inorganic nutrients exists between micro-algae (bivalve food) and seaweed, and (2) the pool of inorganic nutrients is enhanced by regeneration of nutrients by bivalves as a result of excretion of metabolic waste products.

Nutrient budget analysis can be applied to mussel culture. Jansen (2012) provided such nutrient budget analysis for a range of mussel cultivation areas all over the world (coastal zones). Jansen (2012) showed that 40-80% of the nitrogen ingested with the food can be rejected as biodeposits (feaces+pseudofaeces), 5-60% will be stored in tissue material, and 15-50% is excreted with metabolic waste products (inorganic nutrients such as e.g. ammonia). The latter study was based on annual average values and showed large variability between cultivation areas. It was also emphasised that allocation varies seasonally. The large differences in allocation (biodeposits, tissue, excretion) of ingested nutrients is related to the feeding behaviour of mussels, as this is known to correlate with temperature and food concentrations (Bayne et al., 1993; Grant 1996) and thus largely varies between cultivation areas. Offshore conditions in the foreseen MUPS will also influence feeding behaviour, and knowledge on growth and nutrient assimilation efficiencies specifically for the offshore areas are needed to provide reliable estimates. For mussel models, as for seaweeds described in the previous section, it is also advised to perform dynamic modelling to integrate spatial and seasonal variability. Multiple models are available for simulating bivalve responses, but each model needs to be calibrated for the specific area. In many areas one of the aspects restricting current modelling is the availability of empirical field data (FAO, 2008; Fulton, 2010), and it is therefore advised to empirically determine the essential parameters for modelling.

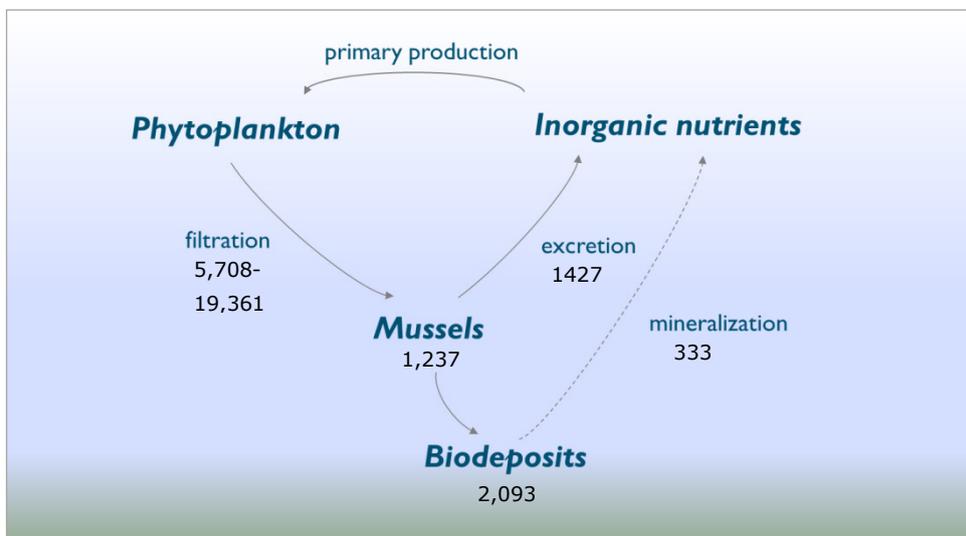


Figure 9.1 Example of a Nitrogen balance model for mussel culture including feedback mechanisms between mussels and phytoplankton. Numbers are based on a study in an oligotrophic fjord system (Jansen 2012), and values are therefore likely to vary for the nutrient rich and high turbulence offshore area in the North Sea. Numbers are expressed in kg N per year¹ for a mussel plot of 49 ha (see Buck et al., 2010).

9.2.3 Integrated Multi Trophic Aquaculture (IMTA)

The amount of nutrients released from finfish farms varies both within and between species depending on the type of feed applied as well as management at the farm (for an overview, see Reijs et al., 2008). The amount of the nutrients available for extractive species is the sum of natural available nutrients and nutrients released from finfish farms. Dynamic budget analysis and spatial models can be used to determine the nutrient flows between the different IMTA components, and to predict growth/production within each component (Reid et al., 2011). These models also provide insight in the potential mitigating effect of IMTA systems. These are complex models that require (besides environmental input), site specific knowledge on the nutrient (energy) uptake and conversion efficiencies of all species.

For land-based IMTAs, including an algae or seaweed component, retentions of N and P > 85% were reported, sometimes reaching 100% (Schneider et al., 2005). This is not the case at sea, where water/nutrient flows are difficult to control. Especially in high turbulence areas, like the North Sea, it is difficult to directly measure and quantify influences on nutrient dynamics within the close proximity of the farms. However, from an 'ecosystem based management' point of view, recuperating the same nutrients that were introduced into the system is not the principal objective. The main aim is to balance inputs and outputs between 'fed' and 'extractive' species. In an IMTA environment this means balancing the nutrient input (fish feed) and output (fish, shellfish, seaweed) (Chopin et al., 2001). This approach is also known under the term 'neutral-nutrient strategy' (in Dutch: 'Nutriëntenneutrale kweek'), and is related to the carrying capacity of the system (Reijs et al., 2008).

At present, too little is known about nutrient flows in open IMTA systems, specifically for the dynamic conditions in the North Sea. Therefore, general knowledge on growth and nutrient assimilation efficiencies is needed to provide reliable production and mitigating estimates. Study is also needed whether balancing the amount of nutrients added to and extracted from the ecosystem ('neutral-nutrient strategy') in itself guarantees sustainability. Therefore more insight into the fate of input nutrients (through fish feed) is required. It should furthermore be defined whether nutrients utilised for growth of extractive species originates from nutrient wastes of finfish cultures or from naturally available nutrients. To answer these questions and to obtain insights in the pathways driving the nutrients flows in IMTA systems, it would be beneficial to connect with existing IMTA systems (pilot or commercial), and meanwhile developing pilot scale facilities in the Dutch North Sea. The second step would be to translate results and conceptual models to the specific situation in the Dutch North Sea.

9.3 Risk assessment models

9.3.1 Cumulative Effects Assessment (CEA)

Traditional Cumulative Effect Assessment (CEA) models focus on the negative impacts of various pressures on ecosystem components. Ecosystem components can be species and habitats, but also include specific ecosystem services, processes or functions. The basic approach of CEA is the assumption that effects are a function of (1) the intensity of pressures and (2) the sensitivity of ecosystem components to those pressures. However, as described in earlier sections of this report, IMTA aims to recycle nutrients by extractive species. This implies that aquaculture activities may not only negatively impact its environment, but may also benefit to (other) ecological entities. Hence new approaches need to be applied that are able to include the beneficial effects as well. Positive effects can be directed towards the effect that an activity could have on both ecological components, as well as positive effects to other types of activities.

For an IMTA, the activities in CEA models refer to the different sub-activities of the types of aquaculture involved (fish, seaweed, bivalves). The pressures that may arise from these (sub)activities could be enrichment of the sediment with organic material, increase of nutrient concentrations in the water column by excretion (by feeding of cultured fish and/or bivalves), introduction of non-indigenous species, introduction of microbial pathogens, litter, and others. Different activities may contribute to the same type of pressures. The resulting pressure levels affect

the (natural) ecosystem components. As an example, organic enrichment of sediments, that may result from both bivalve and fish farming, may cause a shift in the species composition of the benthic community.

An analysis of the intensity of activities and pressures, and of the sensitivity of the ecosystem components, results in an identification of the most severe pressures, and defines most vulnerable ecosystem components. This enables the definition of effective mitigating or compensating measures, in order to reduce the ecological impacts. This approach currently lacks the ability to value the possible beneficial impacts that activities may have on the ecosystem, such as the grazing of abundant phytoplankton by mussels, diminishing the negative impacts related to eutrophication. Positive impacts could be included when in addition to 'pressures' also 'beneficial changes' of the (abiotic) environment are taken into account.

9.3.2 Eco-Optimisation models

A so called Eco-Optimisation model is designed here that would meet the requirements of IMTA in MUPs, enabling the assessment of both negative and beneficial impacts. The conceptual Eco-Optimisation model builds further on the Cumulative Effects Assessment (CEA). The Eco-Optimisation model is based on the philosophy and approach developed within the Building with Nature framework.¹⁹ The objective of Building with Nature is '*to deliver engineering services while delivering and/or ecosystem services*', thus focusing on the beneficial impacts that activities may have on the ecosystem. On this basis, a process is described called Eco-dynamic Development and Design (EDD)²⁰ that is in line with the ecosystem-based approach. This process involves the following steps:

- Understand the system (physical, socio-economical and governance),
- Identify realistic alternatives,
- Value the qualities of alternatives and pre-select an integral solution,
- Elaborate selected alternatives,
- Prepare the solution for implementation in the next phase on the road to realisation.

Below a conceptual Eco-Optimisation model is described that concentrates on the design aspects of IMTA within a MUPS framework. This entails the understanding of the ecosystem functioning, to identify the system's envisaged functions, and to determine how natural processes can be used and stimulated to achieve the project goals and others (using the power of nature). The conceptual model developed here for IMTA (Figure 9.2), combines the CEA and EDD approaches. As described above, the CEA model describes how activities result, via pressures, on impacts (or risks) to the environment. The activities lead to emissions, like the release of nutrients and the production of sound from fish culturing, which cause a pressures like eutrophication and noise. These pressures change the environment, or habitat, of the species present in the ecosystem. Since noise has an impact on the hearing and behaviour of e.g. sea mammals, negative effects may occur. Nutrients may be taken up by microalgae or seaweeds, resulting in a stimulation of their production. The growth of seaweeds depends on several environmental factors, including nutrients, light availability, temperature, CO₂ and other environmental pre-conditions (see also the nutrient management models described above). Thus, by providing these factors in optimal conditions for seaweed culturing, activities may contribute to IMTA (Figure 9.2). In other words, activities may be designed in a way that ecological components, in nature or kept in aquaculture systems, may benefit from it. In IMTA, the design of the activities aims to optimise culturing conditions of various species, by optimising several factors, including environmental conditions (like nutrient supply and oxygen concentrations), but also factors related to the operation and maintenance of the activities. It is obvious, that both figures shown below can be combined, in that the performance of the activity is designed to reduce or mitigate the impacts on the ecosystem, or optimised for (other) aquaculture activities.

¹⁹ <https://publicwiki.deltares.nl/display/BWN/EDD+-+Introduction> [4-12-2012]

²⁰ <https://publicwiki.deltares.nl/display/BWN/EDD+-+Introduction+-+Guideline> [4-12-2012]

The conceptual model of Eco-Optimisation can be applied for a semi-quantitative evaluation of the risks and opportunities of combinations of aquaculture conditions. This will be elaborated in the following phase of the project.

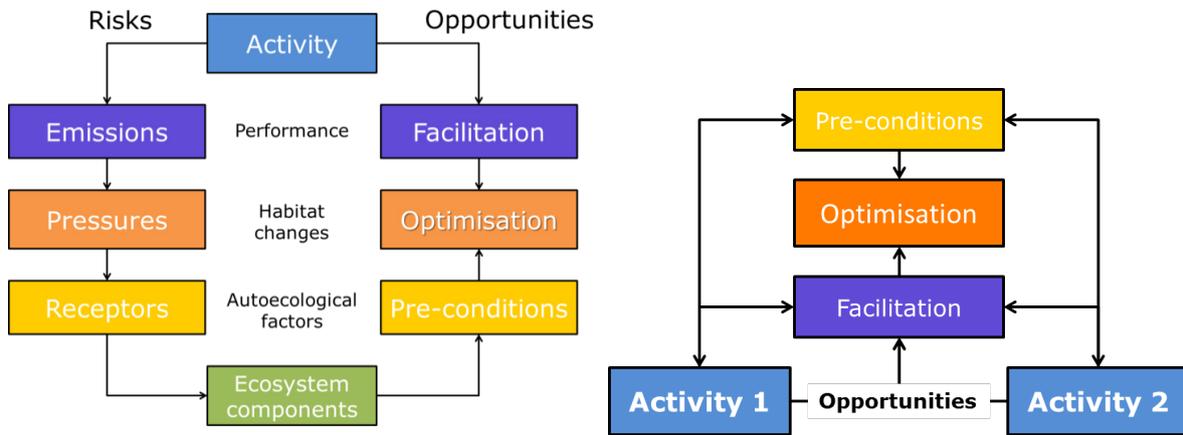


Figure 9.2 Left panel: Set-up of the Eco-Optimisation model, describing the potential risks and opportunities for ecosystem features arising from offshore activities. Right panel: The Eco-Optimisation model applied for two types of activities.

9.4 Eco-efficiency analysis by Life Cycle Analysis

Whereas the concept of eco-optimisation presented above focuses on the IMTA aquaculture system, the production sustainability efficiency can be analysed through an Life Cycle Analysis (LCA). This LCA eco-sustainability assessment method can be used to compare eco-effectiveness of MUPS variants. LCA is a widespread assessment method and can be applied for a range of products, production systems and processing methods, which allows us eventually to compare the eco-sustainability of marine protein production with alternatives such as plant based proteins.

Traditional eco-efficiency assessment methods like LCA have primarily been developed for assessing an individual product or chain. In these methods, ecological impacts (like greenhouse gas emissions, water usage, etc.) of inputs and processes are added together and attributed to the output of the system. When different products (often primary product + by-product) are produced by the chain, the loads are divided over the individual product streams (mostly with distribution code correlated to the economic value of the stream). However, MUPS systems are more complicated in two 'dimensions' as (1) different production chains interact, and (2) MUPS stands in open connection with the surrounding aquatic system. Hence, a more advanced variant of LCA will be needed.

Exergy analysis is an example of an advanced method that combines impacts of multiple production chains. The method of exergy analysis is a thermodynamic approach, developed for analyzing and improving the efficiency of chemical and thermal industrial products and processes (Szargut, 1988). In order to make it more suitable for complex production systems (with multiple processes, inputs and outputs), it has been generalised with various features. One relevant example is Cumulative Exergy Consumption (CEC) analysis that expands the analysis boundary by considering all industrial processes needed to convert natural resources into the desired industrial products or services, (see e.g. DeWulf et al., 2007; Figure 1 and 2 in the Appendix to chapter 9). This approach could also be applied for assessing eco-sustainability of MUPS production systems.

Adequate formulation of system boundaries is critical to obtain relevancy of the LCA results. As in exergy models, reference is made to the as-is non-productive system, which results in the following definition of system boundaries:

-
- The physical environment is considered as a reference system with infinite buffer capacity (that is for MUPS: the sea). That means for instance, that catching nutrients from the sea is for free. However, nutrients and other resources added to the system are not for free, and will be taken into account.
 - Product processing ('refinery') is part of the system.
 - Refined products (for food, feed, fuels, etc.) are considered end-products that leave the system
 - Dependent on the required level of detail, also exchanges between different production chains can be included.
 - Cumulative exergetic value of inputs are derived from the energy needed to produce them (that is: replacement value).
 - Exergetic value of outputs (and intermediates between chains as far as described) will be derived from exergetic costs (estimates) of alternatives in the market.

9.5 Synthesis

The current chapter reviewed the applicability of different approaches for assessing eco-sustainability of marine seaweed production within the MUPS framework. Each method has its specific goals, and selection of a particular method is therefore defined by the pre-defined request. Concluding, the following models seem suitable to assess eco-sustainability, yet still require further development to simulate the specific situation occurring for MUPS in the Dutch North Sea.

10 PEOPLE: Planning challenges and stakeholder perspectives for developing MUPS at the North Sea

10.1 Introduction

In Dutch policy documents, MUPS are mentioned as a promising way to make the most out of scarce available space (Ministries of V&W, VROM & LNV, 2009). They promise to combine aquaculture with offshore wind energy and perhaps other functions, which would need many technical and social innovations. Today, only Single Use Platforms on Sea (SUPS) exist. Offshore wind energy is the best example of a SUP. MUPS can be found today only as designs on paper, or as the first experiments with seaweed production on sea. The objective of this chapter is to assess the obstacles and opportunities for the development of the MUPS concept. It makes use of knowledge on governance arrangements and stakeholder perceptions to assess the future MUPS arrangements. First, the chapter will focus on a policy and legislation perspective. Are existing frameworks supportive of the development of MUPS? Second, we will analyse what the concept implies for governance arrangements that can facilitate the development of MUPS. Thirdly, we will give a preliminary insight in stakeholder perspectives. This leads to the assessment of the feasibility and the main challenges of MUPS development. We will close with a discussion on what knowledge is lacking.

The information is based on three research activities. Section 10.2 is based on a study of policy documents. Section 10.3 is based on a review of governance literature and literature on transition processes. The stakeholder perceptions in Section 10.5 are derived from interviews (which have been conducted in the FP7 Mermaid project) with key stakeholders from wind energy and aquaculture.

10.2 Legislation for MUPS in the North Sea

A multi-level governance system exists for offshore developments. This is expressed in the various policies that are in place. Offshore development needs to fit in these different regulatory frameworks.

Additionally, it is important to recognise that the authority over the sea depends on the distance to shore. A distinction is made between territorial waters (up to 12 nautical miles of the coast) and the Exclusive Economic Zone (EEZ) which ranges up to 200 nautical miles of the coast. Within their EEZ, nation-states have the right to use mineral resources, allow fisheries and perform scientific research. They also are responsible for nature protection in the EEZ.

The development of MUPS is at a very early stage and in the North Sea, at present there is no aquaculture. Offshore wind development is taking off, although new permits are not granted for the moment. We see the interest in the concept of MUPS but there are no real-life applications yet. As a consequence, there is no established framework of policies and regulations describing what conditions MUPS should meet. In this chapter, we describe the policy objectives for offshore aquaculture and offshore wind and describe - where available - how regulations and policies deal with combinations of functions offshore.

10.2.1 Policy objectives for aquaculture

Huge growth opportunities are attributed to the aquaculture-sector as (particularly European) policymakers assign an important role to aquaculture in the supply of aquatic seafood for human consumption. In 2009 the EU published a communication to give new input for the sustainable development of European Aquaculture (SEC 453/454). The three main objectives were (1) to increase competition, (2) securing its sustainability and improving governance and (3) ensuring a business-friendly environment in all governance levels (local, national and EU). Dutch policies for

offshore aquaculture are weakly articulated. The Integral Management plan for the North Sea states that it is unlikely that fish cultivation on open sea is to happen because open systems are environmentally unfavourable against closed systems. Aquaculture on open sea is more positively advocated when floating mussel docks become successful (Ministries of V&W, VROM en LNV, 2006). For seaweed, there is no policy objective formulated.

10.2.2 Policy objectives for offshore wind

Concerning offshore wind energy, a clear and unidirectional policy is lacking. A strange situation has arisen as energy policy moves away from offshore wind at a time when marine spatial planning accommodates offshore wind development.

In earlier energy policy, offshore wind was identified as an important sector, required to achieve energy policy objectives. These objectives were laid down in for example the 2007 'Werkprogramma Schoon en Zuinig' in which a growth of offshore wind capacity of about 500 MW/year was foreseen. At that time, reservation of sufficient space in marine spatial planning was considered the main bottleneck for development of offshore wind. In 2008, the Dutch government formulated the objective to reach 6,000 MW production capacity for offshore wind. In 2010, the Minister appointed the Taskforce Windenergie op Zee with the objective to identify bottlenecks for achieving the 6,000 MW target. The Taskforce identified a number of them, including for example problems in supply - and investment chains and lacking capacity at the government to deal with the topic (Taskforce Wind op Zee, 2010). Until 2010; offshore wind was subsidised under the SDE programme (Stimulerend Duurzame Energie). The Taskforce pleads for optimisation of the SDE programme - from an offshore wind perspective.

From 2012 onwards, offshore wind is no longer eligible for subsidy under the SDE+ programme. It is argued that, compared with other production methods, offshore wind is too expensive and the focus should first be on innovation, reducing the cost price. There are a number of limitations to the subsidy programme. First, there is a budget cap. Every year, the Minister decides what is available for the programme. In 2012, €1.7bn is available. Second, the programme prioritises cheap renewables over more expensive production methods. The available budget is allocated to different production methods based on the subsidy required per unit of energy production (€/kWh). The cheaper renewable energy production, the more budget is available. For this reasons, offshore wind energy was excluded for the subsidy programme.

10.2.3 Marine spatial planning

In 2007, the Dutch government presented their vision on the Dutch water strategy. Sustainable, climate-proof, and strengthening the economy were key words. The vision was important because it provided input and direction to the first Dutch National Waterplan (Nationaal Waterplan 2009-2015). For the North Sea area, the objective is to 'make the North Sea more sustainable', whilst keeping in mind the first priority: safety and protection from floods. Accepted on December 22, 2009, The National Waterplan integrated all areas water, from offshore and coastal to rivers and inland water. Based on the Waterwet and the law on spatial planning (*Wet ruimtelijke ordening/Wro*), the National Waterplan was also the Structure Plan (*Structuurvisie*), describing the rough outline of spatial planning of future water-related developments. The National Waterplan follows an area-oriented approach, for each water basin, specific objectives are formulated and a spatial plan is made to accommodate developments.

One of the ways to make the North Sea more sustainable is to reserve sufficient space for offshore wind parks. Informed by the 6000 MW ambition, it was envisioned that at least 1000 km² needed to be reserved for wind park development. Future developments (after 2020) might require more space. In the Policy Note North Sea 2009-2015 (Beleidsnota Noordzee 2009-2015), North Sea policies are further elaborated. After a first identification of areas where offshore wind could be developed, a second step was to balance the interests of the various users of the North Sea with offshore wind. This exercise resulted in the identification of two areas for offshore wind development and two so-called 'search areas' for future developments.

In the Beleidsnota Noordzee 2009-2015, it is explicitly mentioned that co-use of offshore wind energy parks, for example for recreation, fisheries and aquaculture, should be allowed as much as possible and needs to be discussed with the involved parties as the policy is implemented. In 2011 Rijkswaterstaat stated that smart uses of space could be a solution to the shortage of space on the North Sea (Verhaeghe et al., 2011). Aquaculture inside offshore wind parks was mentioned as a possible smart use of space, which leads to chances for clever entrepreneurship. However in the Integral Management plan for the North Sea (Integraal Beheerplan Noordzee, 2006) there is no space indicated for offshore aquaculture for the Dutch part of the North Sea. This means that aquaculture activities in wind energy platforms need to get exemption, to be applied for trough permits. This framework exists of five tests: 1. Defining spatial claim, 2. Precaution, 3. Usefulness and need, 4. Location choice and spatial use and 5. Reducing the effect and compensation. For new activities this means that developers have to reduce or prevent negative effects on the environment, which is tested using precautionary test. They have to address why it is important that this activity takes place in the North Sea using a social cost-benefit analyses. The space needed for the activity must be carefully chosen and sufficiently used and when the activity compromises important natural values these need to be compensated in another area.

There is a safety zone of 500 meter around static objects like windmills (IBN) all countries can designate such a safety zone (cf. UNCLOS). This means no shipping activities can take place less than 500 meter from constructions. Exemptions on this rule can be made, but one needs to apply for a permit.

10.2.4 Obstacles and opportunities

In Dutch policies, MUPS platforms are mentioned as a promising way to make the most out of scarce available space (Ministries of V&W, VROM en LNV, 2009). However, currently there is no 'demand' for MUPS; there are no companies who want to construct them yet. Energy companies have and will build various offshore wind parks but integration with other functions is not desired.

Consequently, policy-makers and regulators have not been challenged to handle request for permits and a regulatory framework for MUPS is missing. Also, in the spatial plans for the North Sea, there is no area designated for aquaculture.

There is no common framework to discuss and assess the risks associated with third-party access. This increases uncertainty. It also explains recurring discussions on the insurance of MUPS. Current practice of regulators is to forbid third-party access to the offshore wind parks. Differing insights between policy-makers and regulators can be an obstacle to further development.

A major obstacle to the development of MUPS is that the new renewable energy subsidy programme no longer includes offshore wind development.

10.3 Governance arrangements for the emerging innovations

In the development of SUPS and MUPS, various types of governance interventions can be applied by actors with a stake in their development. Those actors are organisations and individuals from businesses, governments, societal organisations and knowledge institutions. Relevant governance interventions include acquiring funding, and following the proper procedures, but this is only part of the toolkit present.

The proposition of MUPS is promising but for now, they only exist in imagination. SUPS exist in the form of offshore wind energy parks, but for the production of seaweed on sea so far only as experiment. Of course there are obstacles to overcome, as always when developing something innovative. When aquaculture has to be integrated with an offshore wind energy park, permits have to be obtained, for example but the law makers do not principally oppose aquaculture on sea and MUPS.

It can be expected that the most challenging part will be the realisation of different kinds of innovations simultaneously. For MUPS, technological innovations are needed and producers have to emerge and know how best to produce and harvest the aquaculture products. More challenging is to join the various worlds needed to develop a MUPS, like offshore industry, transport, fishery, nature organisations, food Industry, etc. These actors do not only need to interact with one another, but also to work collaboratively on specific MUPS business cases which are sustainable and are profitable. This involves creativity, bringing together all needed knowledge, developing new knowledge, and making agreements about the division of risks, benefits, etc. For MUPS this is relatively complex, because multifunctionality implies bringing together different worlds, with individuals who are not used to collaborate with one another. Offshore wind energy parks or oil platforms, already exist, now these organisations need to collaborate with fishermen, with pioneers in seaweed production, and probably with nature organisations.

10.3.1 Planning and governance of the North Sea and MUPS development

Two studies have been conducted on governance and planning issues which are of interest to the MUPS concept. The Dutch 'Raad voor de Leefomgeving en Infrastructuur' (RLI), an advisory body to the government of the Netherlands presented a vision on the usage of the North Sea and specifically on the role over government. The RLI advised to focus the governance interventions on 1) collaborating with stakeholders and using them as advisors en collaboratively set up a partnership for the North Sea, 2) to focus on integrated area development, instead of single use types, to engage in continuous knowledge development, in which research projects build on one another, and for government to commit itself to the partnership and to be willing to intervene with legislation if the partnership does not deliver enough results (RLI 2011).

Stuiver et al. (2012) formulated governance and planning lessons specifically for MUPS development. They focused on the process in which permits are provided and concessions granted to (consortia) of actors who are willing to invest in offshore development, and especially in MUPS development. According to Stuiver et al. (2012) governments should actively contribute to organising societal support for MUPS and to bind allies. This could involve research of the impact of an MUPS on the marine environment, and communication with stakeholders in which comments by stakeholders are taken seriously and used in the design process. It is also wise for governments to have clear objectives for projects on sea, before engaging in a process to provide a development with needed permits. The division of responsibilities is also a major issue, according to Stuiver et al. (2012). Divided responsibilities can lead to no one taking charge, so it is important to make agreements on who is responsible for what. Also the private parties should have responsibilities, and invest with capital. It would be preferable when they would take the project management for a commercial MUPS (Stuiver et al., 2012); to make sure that a MUPS development is executed within budget and on time. The last issue is the process to come to permits for MUPS development. The communication between private and public parties should be a major point of attention. When the process is transparent, agreements can be made and conflicts mostly can be avoided (Stuiver et al., 2012). By focusing on synergic possibilities and to work with covenants is preferable above 'walking the juridical road'. When governments start a call for concessions for the usage of the marine environment there is also the chance that too much interest will manifest itself or that opposition arises from stakeholders. Governments should have a clear strategy for this dilemma. A strategy can be to focus on initiatives that have proper funding and have a good chance to become reality. These consortia could be invited to apply to a call for a concession.

10.3.2 Governance styles

Much scientific literature exists on the governance needed to come to designs for governance and planning. The same is true for transition processes, which is very relevant for MUPS development when we assume that a MUPS is a system innovation. A literature study was conducted on governance styles and on transition processes and system innovations. These two studies are presented in the sections below. Afterwards we will use these insights for the formulation of a preliminary design of an optimal governance arrangement for MUPS development. First we start with existing ideas on the governance of developments in the North Sea, based on two studies.

An important first observation is that all stakeholders conduct governance. This is not restricted to governments or a consortium that wants to develop SUPS or MUPS. In general we can distinguish four types of governance: *hierarchy*, *network*, *market* (Meuleman 2008) and *knowledge* (Van Buuren and Eshuis, 2010; Gerritsen et al., forthcoming). Table 10.1 summarises these types of governance. In the text below they will be explained in more depth.

Table 10.1

Four types of governance.

Adaptation of Boonstra et al.; forthcoming.

	Hierarchy	Market	Network	Knowledge
Role of leading actor	Ruler and decision maker	Pricing, market player	Partner, network manager, facilitator	User and co-producer of knowledge, facilitator of the learning process
Reaction on resistance	Enforcement	Negotiations based on financial incentives	Persuasion	Participation in knowledge development, storytelling
Coordination mechanism	Norms	Price	Collaboration based on mutual interest	Learning, creative competition
Control mechanism	Power	Competition	Reciprocity	Mutual repertoire (language, signs, etc.) and identity
Type of instruments	Laws, rules, procedures	Pricing, funding	Covenants, strategic alliances	Knowledge agenda, vision

Hierarchic governance is governing by power and by rulemaking. This governance style is consistent with the idea of the democratically legitimated government, who for the general interest makes laws for society and controls that society remains within the limits set by law. Every actor will have to work with existing legislation and rules, as described in the previous section. Three instruments for how this can take place can be distinguished: *content instruments*, *procedural instruments* and *communicative instruments* (Stuiver et al., 2012). Content instruments deal with the specific spatial, technical, safety, or environmental characteristics of platforms on sea. Procedural instruments are directed to the usage of the possibilities in procedures, such as environmental assessments. Communicative instruments aim for the manner in which actors engage with one another, within the context of content and procedures of the development of platforms on sea. To make it more tangible: organisations will negotiate with one another, or will try to gain positions in which negotiations which will benefit their position, for instance by communicating formally with governments that one opposes or supports a platform on sea development.

In the 1990s, social scientists described the shift from government to governance (e.g. Rhodes 1997), and with it a decreasing influence of hierarchic governance and of centralised power. Later interpretations argued that in fact there is no shift towards governance, but of the emergence of other governance types next to *hierarchic governance* (Breeman, Goverde & Termeer 2009). The first of these 'new' types of governance is *market governance*, which is based on competing and pricing, on the rules of the market. This is associated with the private sector, but governments experiment with market governance too, for instance by stimulating competitions between departments or between task oriented organisations and private organisations, or giving them a preferred status altogether.

Our assumption is that MUPS normally will have to be developed by alliances of companies and governments in which societal organisations and knowledge organisations can play a role too. In the 1990s political scientists discovered the emergence of *network governance* (Kickert et al., 1997; Koppenjan en Klijn 2004; Sørensen and Torfing 2007). Networks exist of relation webs constituted by governments, businesses and societal actors (Klijn et al., 2010, based on Pierre and Peters, 2000 and Koppenjan en Klijn, 2004). Actors are positioned inside these networks, which empowers them, but also limits the movement space. Network governance uses actor networks for bring about societal change, also because they will often depend on one another to achieve their own aims. In these

networks it is important to maintain good relations and to realise benefits for all participants, so that the network remains intact and will remain producing benefits for its participants.

Knowledge governance often also uses networks but these networks function differently. It is focused on knowledge production, knowledge dissemination and learning which open up new pathways for societal change (Buuren and Eshuis 2010; Gerritsen et al., forthcoming). With knowledge governance the existing governance can be changed. Knowledge governance can take the form of a research project or programme, a pilot project, a learning network, etc. Knowledge governance needs a transdisciplinary form of science, needs social learning, a reflexive attitude, a reliance on self-organisation and a boundary arrangement with stakeholders not directly involved (Gerritsen et al., 2012; Gerritsen et al., forthcoming). Knowledge governance does not directly lead to the development of platforms on sea, it needs other types of governance for that. Knowledge governance provides policy input on what the challenges are and what measures could best be implemented. A business case of a MUPS could be the result of knowledge governance. Actors can use this input by applying one or all of the other three types of governance, to actually realise it in real life.

In practice actors at the same time use instruments from various types of governance. For example, when government should appoint sites for an aquaculture platform or a MUPS and provides funding for business, than a mix of hierarchy and market can be distinguished. When a knowledge development and dissemination programme is started and a platform is formed of governments and businesses to promote the business case, all governance styles can be distinguished. With the typology it can become obvious why a platform development programme stagnates, because a conflicting mix of governance instruments is used.

10.3.3 System innovations

Aquaculture on platforms at sea can be considered as innovation. We now do not know whether it will be feasible to develop aquaculture platforms on sea without other uses, as wind energy. MUPS development can be characterised as system innovations. System innovations fundamentally change both the structure of the system and the relation among the participants (Loorbach and Rotmans, 2006). System innovations need multiple innovations, simultaneously, and involving technical issues, but also organisational and governance issues. But also new or adapted rules are needed, new forms of funding, of collaboration between stakeholders and of governance. This is the case for MUPS, because this involves collaboration between wind energy and aquaculture, which complicates the development process profoundly.

Transition processes towards the implementation of system innovations (such as MUPS) start with small innovative ideas and practices (as novelties) and when they survive the first phases, grow conceptually and by conquering obstacles from vested structures and existing rules, and therefore cannot be governed hierarchically (Rotmans et al., 2000; Rotmans et al., 2001). As said before, hierarchic governance is relevant to the development of platforms on sea and hierarchic rules will have to be adapted to support the transition process. This is typically a contribution of governments to these processes. Rules can hinder transition processes, because normally system innovations do not fit in with existing regulation, but with rule setting it can also strongly be supportive, for example to make it more easy to get a permit for aquaculture for offshore wind energy parks. Knowledge governance will also be needed to explore what platforms on sea are, how they can be designed, what combinations with other activities are feasible, how SUPS and MUPS should be linked with other activities and companies in the value chains. The question if and how a value chain around North Sea seaweed can be developed depends on economic feasibility as well as business' interest to participate, risk management and effective stimulation by government. Consortia from the different stakeholder domains can use this knowledge for incorporating in network governance interventions, which again can lead to governments or businesses applying hierarchic and market instruments.

10.3.4 Optimal governance arrangements and metagovernance

What the optimal mix of instruments will be to realise SUPS and MUPS will become clear in practice. From transition theory, we do know that starting with pilots in a niche environment and from their

gradually upgrading of the proposition; expanding the network and alterations of policies and perhaps legislation is the route which is most promising (Rotmans et al., 2000; Rotmans et al., 2001; Loorbach and Rotmans, 2006). This can be supported by also developing a knowledge sharing and learning network with stakeholders, who do not actively engage in the pilots, but who have influence on networks and policies and therefore have the ability to support and disrupt MUPS development (Gerritsen et al., 2012). It is imperative to have all four of the governance styles included in the governance arrangements used, because they contain the whole spectrum of the types of governance interventions needed for a complex process, such as is the case with MUPS and SUPS. It is likely that each platform will need its own tailor made approach, although it would be wise to cooperate in knowledge development and dissemination and in approaching governments to adapt their rules.

Because system innovations are concerned, risk management is a major issue. These risks involve production details and consequences of seaweed production for cattle and consumer health, but also risks for participating actors, as financial and legal risks, marketing risks, etc. The occurrence of risks is not necessary problematic. We live in a risk society (Beck 1992) in which actors have to cope with risks, which are hard to control and potentially can have a big impact on organisations, on the environment and on society.

Metagovernance is likely a necessary activity in platforms on sea development. Metagovernance is about cleverly combining the different forms of governance, applied to the specific context and actual developments. Metagovernance is about having a helicopter view and using that to do interventions, if required (Boonstra et al., forthcoming). Metagovernance will mostly intervene in an indirect manner (Jessop, 2004, Bell and Park, 2006; Sørensen and Torfing, 2009. Metagovernors normally do not have 'their hands on the wheel', but influence other powerful stakeholders who intervene more direct (Boonstra et al., forthcoming). An example is that national government works with a competition to generate innovative ideas, or certain stakeholders are empowered to participate in MUPS development. An example is also that national government officials start communicating about the need for the multifunctional usage of the sea. In special situations the metagovernor can also intervene more directly, for example by making rules, providing or withholding of permits, etc. In principle all actors can take the role of metagovernance. If multiple individuals and organisation do this, coordination will be needed.

To summarise: actors in the development of a SUPS or a MUPS can select instruments and develop governance arrangements four types of governance (hierarchy, market, network and knowledge), and will likely need all of them. Therefore metagovernance will be part of the development process. The governance arrangement will focus on the execution of a transition process from a novelty and pilot projects to a full-fledged system innovation. Communication and the engagement in a learning process with stakeholders who are not directly involved is a strategy to be able to enable their cooperation for later on and to prevent resistance which will hinder MUPS development.

10.4 Perceived obstacles in planning for investing in MUPS

As mentioned in 10.1, in the spatial plans for the North Sea, there is no area designated for aquaculture. Energy companies are building offshore wind parks but an offshore aquaculture sector is absent. Aquaculture on sea is only practiced in experimental settings, involving research institutes. Consequently, policy-makers and regulators have not been challenged to handle request for permits and a regulatory framework for MUPS is missing. In the Gemini project²¹, which includes three building sites for offshore wind farming at the North Sea, for example, only permits have been granted for wind energy. The current practice of regulators is to forbid third-party access to the offshore wind parks.

²¹ www.typhoonoffshore.eu/projects/gemini [31-5-2013]

As we will see below, stakeholders are nonetheless curious about the benefits and possibilities for the MUPS concept and they see the future potential. This could potentially manifest itself in the form of willingness to invest in MUPS in the future. The FP7 MERMAID project (www.mermaidproject.eu) has conducted a study to identify stakeholders, and to map their perceptions on goals, prerequisites and obstacles for participation in MUPS development and on the conditions of their design (Rasenberg et al., 2013). The Mermaid project also involves other regions in Europe; in this study we use the information on the North Sea. The information below is derived from the interviews in the MERMAID project. Interviews were held with a wide range of stakeholders. Different views were collected on ecological, economic and societal objectives of MUPS, challenges and (technical, social-economic and natural) constraints faced.

10.4.1 Identification of stakeholders

Potential stakeholders can be found in the wind energy sector. For the development and operation of offshore wind farms these are companies as such as Eneco, Nuon Vattenfal, RWE, Bard, SSE Renewables & Dong Energy, Vestas, Siemens Windpower, and Energy Valley (all involved in the Gemini project). Investors in wind farms are Typhoon, Meewind and HVC. Companies in wind turbine design & manufacturing include XEMC Darwin BV, Siemens, 2-B-Energy. Offshore engineer, construction and maintenance firms include Ballast Nedam and Van Oord. IHC Offshore Wind / Merwede and Van Oord have vessels and equipment for offshore installation and foundations.

Next to the wind energy sector, companies from the aquaculture sector can be distinguished. Some of these companies are already importing large volumes of seaweed from Asia and France (for a very competitive price). For offshore bluemussel cultures these are companies as Prins & Dingemanse, Roem van Yerseke, Padmos and Schot, who are involved in a pilot on mussel seed collectors in the Voordelta (6 x 25 ha). Hortimare and research institutes as NIOZ, ECN, and Wageningen UR are involved in small-scale research pilots for offshore seaweed production of the coast of Texel and in the Eastern Scheldt estuary. The aquaculture sector also has companies involved in providing technology and processing activities.

Fishery companies are involved as stakeholders and discussions are conducted with wind energy companies on compensation fees for lost fishing grounds. Some stakeholders from the fisheries sector are also involved in idea development for more sustainable fisheries practices, including new fishing boat designs focused on service and maintenance work in wind farms (Masterplan Sustainable Fisheries). Umbrella Organisations as VisNEd, and Vissersbond have been involved, as was the Fish Auction Lauwersoog. Some small-scale firms are also involved in touristic activities, providing one day sightseeing trips to offshore wind farms that have a stake in MUPS design.

Next to the organisations above, also various governmental bodies are relevant, such as the Ministry of Economic Affairs, Rijkswaterstaat and the province of Groningen. Also societal groups, or non-governmental organisations, as the North Sea Foundation and Groningen Seaports are relevant organisations.

10.4.2 Stakeholder perceptions on conditions for participation in MUPS development

Although there is interest in seaweed production in the North Sea, there is no direct interest to invest in MUPS development among the stakeholders interviewed. Stakeholders find the proposition interesting. Some wind energy companies see the proposition as a strategy to create more social acceptance for offshore wind energy farms. They see it as a form of corporate social responsibility. The contribution of wind energy farms to regional employability, for instance for fishermen, is an important theme for this discussion. A second reason to participate in MUPS development would be if it is a contribution to cost reduction. Because of the decreasing of the subsidies for offshore wind energy the sector is aiming for a cost reduction of up to 40% of the current operational costs. Perhaps sharing the usage of the infrastructure with companies from other sectors is a strategy to realise this for them. From the interviews it became clear this is the most important reason why MUPS are on the agenda for the offshore energy sector. For the fisheries and aquaculture sectors it is interesting if

MUPS development can open up new markets for them, because ecosystem management regulations in the estuaries and near the shore will increasingly hamper their near shore fishery and aquaculture activities. For most stakeholders biodiversity and more efficient use of space and energy are also important goals. NGO's are exploring the feasibility of MUPS development. Up to now, they are interested in the potential of realising ecological valuable zones within the wind parks. Some scientists feed this discussion, arguing that high ecological values can be realised within the wind parks.

The results of the interviews) revealed some (potential) tensions between the offshore wind sector and the fishery community. Fishermen fear reduction in the areal available for fishing and object to offshore wind park development. The energy sector fears that it is difficult to come to agreements with the fishing communities, believing they often do not adhere to rules and regulations. At present, they perceive no incentive to collaborate with aquaculture at all. For wind energy companies the risk is a lack of reliable partners in the aquaculture sector for the offshore wind energy sector. According to them, at this moment in time offshore aquaculture has no proven technology and no serious business case. Respondents from the aquaculture sector also perceive risks attached to participating in a MUPS. First, some aquaculture entrepreneurs see MUPS and other examples of innovative production as threatening to their survival. It is a possibility that a breakthrough in MUPS development would lead to a loss of income and employability in the 'old' aqua culture sector.

Wind energy producers would consider to invest in a MUPS to improve the image of the offshore wind energy sector and the license to produce and if this would be a demand to obtain a concession. Another motivation would be to obtain support from fishermen and other local stakeholders. On forehand a clear business case with a sound financial plan is needed, in which risks and unexpected costs are minimised. The effects of an MUPS business case on ecosystems should also be clear. The wind energy sector is not interested in negative press, so ecological risks also should be minimised. These issues have to be solved for wind energy entrepreneurs to participate in collaboration with aqua culture entrepreneurs. It is also understood that this collaboration would be needed, as well as collaboration within the aquaculture sector. For aquaculture entrepreneurs MUPS could be interesting for the improvement of the image of the aquaculture sector and for its license to produce. When an MUPS leads to maintaining employability in the aquaculture sector, this could also be a reason to participate.

Multiple innovations are needed regarding technical and organisational and governance issues, according to respondents. For instance, new financial arrangements have to be developed, and new or adapted government rules are important. The licensing process should be reconsidered and become more business friendly, according to respondents. Other regulatory issues for the respondents are the availability a designated area for offshore aquaculture. The MUPS process also should contain sustainable management plans. MUPS developers will have to answer questions to the ecological effects of a particular MUPS business case. NGO's are exploring the potential of realising ecological zones within wind energy parks. The will also be their interest with a MUPS. Solutions also have to be found for technical problems, as the transport of aquaculture production from sea to the consumer (because aquaculture produce goes to waste so quickly) and the lack of proven technology in aquaculture production on sea. The integration of the MUPS approach to educational programmes is also a prerequisite for respondents, so that a workforce is available if the first MUPS developments are implemented. For instance, fishermen will need to learn how to navigate in large-scale offshore wind parks.

10.4.3 Stakeholder perceptions on the process design of MUPS and business cases

Although stakeholders stress there is no manifested interest in MUPS yet, some recommendations for the design of the platform on sea development process can be distinguished from the interviews. The first process design issue is that respondents review the current aquaculture entrepreneurs as conservative and as not able and interested in participating in MUPS development. These entrepreneurs will probably not be the ones to participate in the first SUPS or MUPS development on sea. They will be stakeholders, but not shareholders. It is recommended by one of the respondents to involve the mussels processing companies, who might be interested in innovative production. For participating in MUPS development it is important to increase the level of trust between the different

stakeholder groups. Stakeholder participation is a means to this condition. Therefore it is needed that roles of stakeholders become clear, and that the participants have an open mind to sharing knowledge and experience, and be able to bring their expertise to the development process.

For the development process of a MUPS it is imperative to address the need of the offshore wind energy sector. According to respondents, the process should be focused on producing realistic business cases, involving trustworthy partnerships, limited risks, and proven technology. When it is too early for that, the process could focus on the development of partnership arrangements, addressing the issue of differing insights between participants, and technological and logistical developments, leading to applicable and reliable solutions. The design of the process, according to respondents, should also address operations and management risks, and funding and insurance problems. The possibilities to reduce costs for wind energy will also be a major issue for stakeholders from this sector.

10.5 Synthesis

At present there is no manifest interest in investing in MUPS, because there is not yet a clear business case and many risks are identified. At the same time stakeholders found the proposition promising, engage in discussions about the design of MUPS. Stakeholders think it could be a solution for major problems for the various sectors and stakeholders that have a stake in the North Sea.

For MUPS to become feasible a transition process is needed, starting with the development of seaweed production on sea as a business case. The initial proposition needs to mature so that it becomes possible to develop a realistic and a reliable business case. After this, negotiations with energy companies can be held. So, at first, an offshore aquaculture sector has to emerge and mature.

This transition needs an optimal governance and planning mix, consisting of a mix of governance arrangements to support the development of such business cases. In this transition process, legislation needs to change too; by assigning an area for offshore aquaculture for example and to make it possible to obtain permits. However, this is not the most important obstacle. Bridging the worlds of aquaculture, fisheries and wind energy is a far more challenging issue. It would a major step if after the pilots in seaweed farming on sea, an experimental MUPS could be developed. Actors from the different domains in that case can learn about the proposition to combine activities on a platform and can get to learn from one another.

We conclude that it is needed to focus more on offshore seaweed farming and see MUPS as a promise for the future for which a complex transition process will be needed before it becomes a challenging proposition. It is important to keep the MUPS proposition in mind, when working on offshore seaweed farming.

11 Conclusions and R&D challenges

11.1 State of the art

In the first part of this study, we described state-of-the-art in North Sea seaweed production and application. Four species are addressed: *Laminaria Digitata*, *Saccharina Latissima*, *Palmaria palmata* and *Ulva Lactuca*. These are species native to the North Sea. Reasons for this restriction are the importance of (1) keeping the natural biodiversity balance and (2) using species acclimatised to the North Sea environmental conditions, with good growth and production properties.

Experiments with offshore cultivation of these species are currently conducted. They show that under North Sea conditions, various species reach yields of 15-20 tonne of DM per ha. Seaweeds are fast growing, with DM increasing up to 50% per day under optimal conditions. There are various bottlenecks, including sudden disappearance (*U. lactuca*) and colonisation by other organisms (*L. digitata* and *S. latissima*). Possibilities for production of seaweeds in Integrated Multi-Trophic Aquaculture (IMTA), where nutrients emitted from fin-fish aquaculture can be used for seaweed cultivation, were also addressed. This review showed that the conditions in the North Sea are not favourable for fish culture. It is therefore concluded that initial focus should be given to combinations of shellfish (mussels) and seaweed production. For mussels there is a clear commercial interest and the market is already established.

An important issue to address in commercial cultivation and harvesting is the diversity in composition and properties within and between species of seaweeds. The cultivation conditions and the harvesting time (season) are of essential importance for the biochemical composition of the seaweeds. Hence, production methods need to be defined that minimise biochemical changes in order to secure a consistent quality. Research into techniques for harvesting and first processing of larger offshore seaweed farms is scarce.

The use of seaweeds as feedstock for fermentation processes or chemical conversions is researched in recent years because seaweeds have an interesting biochemical composition (Gao and McKinley, 1994). Sugars and other nutrients present in seaweeds represent an alternative to the first generation feedstock (grains, starchy substrates) currently used for the production of biofuels (ethanol) or other compounds (Kraan, 2011). The fermentation of sugars from brown seaweeds (mostly mannitol and glucose) for production of ethanol has been reported (Horn, 2000; Adams, 2009). Recently, the fermentation of hydrolysates from green (Potts, 2012; van der Wal, 2013) and from brown seaweeds (Huesemann, 2012) to butanol has been reported. Several methodologies (including extractions, and chemical and enzymatical hydrolysis) are described for the efficient solubilisation of sugars into hydrolysates to be used as feedstock in fermentation processes to biofuels (ethanol, butanol), demonstrating the great potential of seaweeds for biorefinery.

Seaweed can be applied in animal diets in complete form. The digestibility and nutritional value of seaweed species is not well known. A limited number of publications investigated the inclusion of whole seaweed in monogastric diets and considered intact seaweed as an unsuited feed ingredient. However, results vary between animal species and seaweed species. Higher digestibility coefficients of seaweed nutrients were found in rainbow trout and Nile tilapia as compared with pigs and poultry. Seaweed or ingredients made of seaweed may be of prime interest for use in fish feed formulations.

Residues of processed seaweeds or extracted functional components with specific biological traits can be used in feed applications:

- Seaweed species contain a variety of polysaccharides that may contribute to human and animal health, e.g. by creating a better intestinal environment.
- With regard to protein and peptides, there is little evidence for beneficial bioactive effects in farm animal nutrition above the required amino acid supply of the animals. The presence of a high

indigestible fibre content, lectins and polyphenols may contribute to a relatively low bioavailability of amino acids.

- The lipid content in many species is low, presumably too low to substantially contribute to the fatty acid requirements of the animals.
- Seaweed is unique in its high iodine content and as such has been studied as a feed ingredient for iodine enrichment of meat products.
- The use of seaweed as a source of vitamins and minerals seems more likely in human rather than animal nutrition because of the variability in content of micronutrients and the standardisation in animal diets via the premix.
- A large number of publications also suggest potential use of purified seaweed components for medical application but often results are based on a limited number of studies with in vitro cell lines and in animal models.

Feed and food safety issues have been addressed. Based on the results of feed safety monitoring on a regular basis of both products and by-products, seaweed materials can be used as feed ingredient, provided that legal limits are not exceeded and levels of relevant risk assessments are considered. Provisions made in systems such as GMP and HACCP might be relevant for the utilisation of seaweed products. For their use in food and feed, the composition of seaweeds needs to be taken into account. An important aspect is the content of minerals and heavy metals in seaweeds, that may be significantly higher in some species than in land plants. It is necessary to carry out a survey to establish the safety of primary and processed products intended for the production of feed and food. A basic survey which can be used as zero measurement for future product developments need to cover realistic hazards: commonly reported or expected contaminants should be included, whereas hazards that are unlikely to occur can be omitted. New derivatives or processed forms of seaweed as feed ingredient need to be notified as novel feed ingredient with a documented safety level.

11.2 Feasibility from a Triple P perspective

In the second part of the study, we investigated the feasibility of seaweed production in the North Sea from a Triple P perspective.

Currently, there is no full value-chain for North Sea produced seaweeds. Based on expected production costs and revenues, an economically viable seaweed production appears possible if high value products can be obtained. Looking at the production costs, the yearly purchase of seedlings constitutes the largest cost. Technical innovation and the design of systems that enable multiple harvests per year can reduce production costs. The market for seaweed products is diverse. Direct consumption by animals offers low value. Higher value products include feed additives, chemicals and alginates. The use of seaweeds for the production of biofuels seems unlikely due to the low prices that are paid for biofuel material. To match production costs and the value of the produce, it is necessary to make multiple products from the basic material, using biorefinery.

To assess eco-sustainability of marine seaweed production within the MUPS framework, this report reviewed the applicability of different approaches and models. *Nutrient models* provide quantitative biological information about growth and nutrient assimilation efficiencies as a function of environmental variables (nutrient availability, oxygen, temperature, light intensity). *Cumulative Effect assessment (CEA)* and *Eco-dynamic Development and Design (EDD)* models identify the most severe risks and pressures, and thereby define most vulnerable ecosystem components. In addition, these models may help to design effective production systems that make optimal use of ecological conditions, and minimise adverse ecosystem effects. MUPS systems are complicated as they include multiple production lines and have open connections with the surrounding aquatic system. A more advanced variant of *Life Cycle Analysis* will be needed to evaluate the eco-sustainability of MUPS, and in that context the possibilities of integration of the Cumulative Exergy Consumption (CEC) analysis need to be explored.

We addressed seaweed production as part of MUPS from a governance perspective. At present there is no manifest interest by stakeholder to actually invest in the development of MUPS. This proposition

needs to mature so that it would become possible to develop a realistic and reliable business case, attractive for the potential partners in MUPS, e.g. energy and feed companies. This requires an optimal governance and planning mix, consisting of metagovernance, knowledge governance and other types of governance to support the development of such business cases. Legislation needs to change but this is not the most important obstacle. Bridging the worlds of different offshore business sectors (e.g. fisheries, aquaculture and wind energy) is a far more challenging issue. It would be a major step if after the pilots that focus on seaweed farming, an experimental MUPS would be developed to facilitate learning.

11.3 R&D challenges

We observed that seaweed production in the North Sea has potential, particularly in production of feed additives and chemical building blocks. There are still numerous technical, social and environmental issues to resolve. Research findings lead us to identify various R&D challenges that need to be tackled.

11.3.1 Profit

The organisation of a seaweed value chain, with accompanying business models requires further research into demands and preferences of the concerned businesses, particularly because economic viable value chain require that multiple products are produced from the basic material.

Research is required to determine the comparative feeding value of seaweed species suitable for cultivation in the North Sea, in diets for ruminants, pigs, poultry, and fish. The number of studies into the ideal digestibility of amino acids in pigs and poultry is very limited and more data are required to better evaluate the protein feeding value. The bioavailability of fatty acids remains to be determined. Further research has to find out whether processing of intact seaweed, e.g. cell wall degrading techniques and enzymatic break down of structural carbohydrates and proteins improves energy and protein digestibility. This would enhance the economic value of seaweed in animal diets.

The potential of biorefinery to add value to seaweed is recognised. The use of seaweed carbohydrates as feedstock for fermentation to fuels and chemicals is an innovative approach with a big potential. Studies into biorefinery of seaweed should be combined with assessment of the potential use and nutritive value of the (by)products in animal diets. More data on the possibilities to establish a cascade of processing applications is required. For example, one can imagine the extraction of valuable hydrocolloids, followed by extraction of functional food additives and use of remaining material as source of biofuels. The cost efficiency due to scaling up of production and biorefinery are unknown and need to be researched.

North Sea produced seaweed face heavy competition from Chinese production. However, Chinese production is often criticised for its environmental impact. If North Sea seaweed production claims to be more sustainable, the challenge is to prove such claims (for example through certification) and ensure additional value.

11.3.2 Planet

Regarding production of seaweeds, follow-up research will have to focus on improving techniques, increasing scale of production and yields and investigating the possibility to harvest throughout the year (combination of winter and summer seaweeds). Attention should be given to the (seasonal) variation in composition and to the composition and consequences of the high ash content, to establish both feeding value and suitability for biorefinery processes of North Sea seaweeds. The botanic classification and its consequences for feed and food safety regulation needs to be included in decisions on the choice of seaweed species targeted for cultivation.

Research on IMTA systems focusing on development of technical solutions for offshore culture of (fish), bivalves and seaweeds. Growth potential of each species should be investigated for the specific environmental conditions in the North Sea, and attention should be paid to the incompatible

production rates of extractive species and finfish. For development of reliable quantitative nutrient management models for mono-, co-culture or IMTA production systems, more insight is needed on growth and nutrient assimilation efficiencies and nutrient flows in offshore production systems, specifically for the dynamic conditions in the North Sea.

Management systems (bio-economic models) should be developed that integrate all activities (different mariculture production systems as well as other activities such as e.g. wind energy) in order to solve logistical problems associated with sharing space and equipment and to optimise the maximum output/efficiency of the complete IMTA and/or MUPS system.

11.3.3 People

Use of seaweed for feed and food might come along with certain hazards. The effect of sequestering on bioavailability of contaminants should be investigated in more detail. This recommendation applies to all raw and processed seaweed products, including those intended as food additive. With respect to arsenic and mercury a further investigation of speciation is required. Investigation of the occurrence of micro algae because of simultaneous harvesting (e.g. on the surface of seaweed plants) or blue-green algae which can produce marine toxins, is to be addressed. Recent information show relatively high levels of nanoparticles of plastic in seas and oceans. Harvesting wild or cultivated seaweeds could include certain levels of plastic particles (Anonymous, 2011).

Futhermore, monitoring of all relevant contaminants as listed in Directive 2002/32/EC and other relevant legislation is necessary on a regular basis, provided that for every investigated sample the background and botanic classification is known. This also points to a societal question, what risk related issues can be distinguished with regard to the acceptance of retail and bio refinery companies and of consumers a societal organisations?

To conclude this chapter, we stress that regarding the development of a full seaweed value chain, albeit in MUPS, the challenge is to bring together the different actors from diverse sectors (energy, transport, nature, bio refinery, etc.) to participate and discuss how they can contribute to the development of and profit from offshore seaweed farming. At present however, the knowledge on the conditions under which aquaculture entrepreneurs willing to engage in offshore seaweed farming is lacking. Government authorities should focus on research after and the development of smart governance and planning conditions under which entrepreneurs are willing to engage in MUPS and offshore seaweed farming.

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Annex 1 General information on biochemistry of seaweeds

Table A.1

Content of major chemical components (percentage of dry mass) in groups of seaweeds. Data extracted from Holdt and Kraan (2011).

Group	Polysaccharides		Additional	Share DM
	Structural	Share DM		
Brown algae	Cellulose	2-10%	Fucans ^s (e.g. fucoidan)	1.5-20%
	Algin	10-47%	Laminarin	0-33%
			Mannitol	1-25%
Red algae	Cellulose	(21-42%) ^a	Carrageenan ^s	22-88%
	Pectin		Porphyran	47.8%
			Floridean starch	25-41.8%
			Funoran	
Green algae	Cellulose	9%	Ulvan ^s	Up to 35%
			Xylan	

a amount of agar expressed as a percentage of the original dry weight; s: water soluble sulphated polysaccharides.

Table A.2

Biochemical composition (% of DM) of seaweeds with potential interest for biorefinery (López-Contreras et al., 2012).

Group:	Brown algae	Red algae	Green algae
Genera:	<i>Laminaria digitata</i>	<i>Palmaria palmata</i>	<i>Ulva lactuca</i>
Glucose	5.9	3.8	5.4
Xylose	0.4	31.1	1.3
Fucose	1.9	0.0	0.0
Mannose	1.9	0.0	0.0
Galactose	0.7	5.5	0.5
Rhamnose	0.1	0.0	4.1
Mannitol	3.6	0.0	0.0
Total sugars	14.5	40.5	11.3
Protein	10.8	17.8	23.5
Ash	27	19	19.4

Table A.3

Proximate amino acids (% of total N) in some seaweed species as summarised by Holdt and Kraan (2011), and compared with the amino acid composition of soybean meal (CVB, 2007).

Group:	Brown algae	Red algae	Green algae		
Genera:	<i>Laminaria</i> , <i>Saccharina</i>	<i>Palmaria</i>	<i>Ulva</i>		Soy bean meal
Amino acids (AA)	Mai et al. (1994)			Arasaki and Arasaki (1983)	
Alanine	8.0-9.0	7.5	8.5	6.1	4.4
Arginine	5.0-5.9	6.2	5.1	15	7.4
Aspartic acid	9.6-9.8	9.3	9.2	6.5	11.6
Cystine	0.6-1.3	1.3	2.2	1.2	1.5
Glutamic acid	11-13	13	10	6.9	18.1
Glycine	6.5-7.0	7.2	7.0	5.2	4.3
Histidine	2.3-2.4	2.1	1.8	4.0	2.7
Isoleucine	5.5-5.8	5.3	6.1	3.5	4.6
Leucine	8.7-9.2	7.1-7.8	9.2	6.9	7.7
Lysine	6.5-7.3	8.2	6.3	4.5	6.2
Methionine	1.9-2.2	1.9	1.8	1.6	1.4
Phenylalanine	5.7-6.2	5.2	6.3	3.9	5.1
Proline	4.8-4.9	4.4	5.2	4.0	5.1
Serine	3.8-3.9	4.6	4.0	3.0	5.2
Threonine	4.6-5.0	4.5	4.6	3.1	3.9
Tryptophan				0.3	1.3
Tyrosine	4.0-4.3	4.5	5.0	1.4	3.7
Valine	6.9	7.3	7.7	4.9	4.8

Cells in red: soy bean content consequently lower than listed for macro algae; Cells in green: soy bean content consequently higher than listed for macro algae.

Table A.4

Chemical composition and digestibility of brown seaweed extract determined in pigs (Whittemore and Percival, 1975).

Nutrient		Composition (g/kg DM)	Digestibility coefficient
Gross energy	MJ	18.4	0.12
Nitrogen	g	19.2	-0.25
Phosphorus	g	0.7	---
Potassium	g	5.9	---
Calcium	g	17.0	---
Sodium	g	12.0	---
Magnesium	g	6.9	---
Copper	mg	24	---
Manganese	mg	31	---
Iron	mg	55	---
Iodine	mg	77	---

Table A.5

Nutrient composition (% of DM, values provided by Ana Lopez Contreras and adapted from El-Deek et al., 2009) and calculated economic value of several seaweed species.

Group:	Brown algae		Red algae		Green algae
Genera:	<i>Laminaria digitata</i>	<i>Saccharina latissima</i>	<i>Polysiphonia ssp.</i>	<i>Palmaria palmata</i>	<i>Ulva lactuca</i>
Dry matter	94	94	94	94	94
Crude protein	10.8	12.4	34.0	17.8	23.5
Crude fat	4.7	9.6	18.8	8.3	2.8
Ash	27.0	36.3	6.38	19.0	19.4
Sugars	14.5	17.6	?	40.5	11.3
Economic value (€/100 kg)	€0.00	€4.40	€11.10	€11.50	€4.60

Table A.6

Chemical composition of seaweed genera of interest (Holdt and Kraan, 2011).

Group:	Brown					Red				Green
Genera:	<i>Laminaria</i> , <i>Saccharina</i>	<i>Fucus</i>	<i>Ascophyllum</i>	<i>Undularia</i>	<i>Sargassum</i>	<i>Chondrus</i>	<i>Porphyra</i>	<i>Gracilaria</i>	<i>Palmaria</i>	<i>Ulva</i>
Fresh weight (%)										
Moisture	73-94	68-84	67-87	88	61	72-78	77-91	85	84	78-80
Dry matter (g/kg of DM)										
Ash	150-450	190-300	180-270	270-400	140-440	210	70-210	80-170	120-270	110-550
Total protein ¹	30-210	14-170	12-120	110-240	90-200	60-290	70-500	50-230	80-350	40-440
Total fat	3-21	5-31	12-48	10-45	5-39	7-30	1-28	4-26	2-38	3-16
Polysaccharides	380-610	620-660	420-700	350-450	40-680	550-660	400-760	360-630	380-660	150-650
Dietary fibres Total	360			350-460	490-620		350-490			380
Soluble fibres			380	300	330		180			210
Lignin										30
Cellulose	100	20-45	20							90
Hemicellulose										90

¹) The commonly accepted factor of 6.25 in the conversion of total nitrogen to protein should be treated with caution as, among other factors, content of free nitrate will influence the total nitrogen level. Free nitrate is found in varying amounts both in brown and red algae (Guiry and Blunden, 1991).

Table A.7

The chemical composition and digestibility coefficients of dried *Laminaria* seaweed meals for pigs (Duckworth, 1955).

Material	Composition (%)						Digestibility coefficient			
	Dry Matter	Organic matter	Ether Extract	Nitrogen free extract	Crude fibre	Ash	Crude protein	Ether extract	Nitrogen free extract	Crude fibre
<i>Laminaria</i> spp.	83.7	66.9	1.1	45.8	8.6	16.8	6	74	52	22
<i>L. digitata</i>	89.5	74.8	0.4	61.2	6.2	14.7	27	231 ¹	75	50
<i>L. saccharina</i>										
October	96.0	69.3	1.7	56.4	3.9	26.7	7	180 ¹	88	---
January	94.1	53.7	0.8	36.4	5.9	40.0	32	250 ¹	45	33

¹) Observed, but fictitious because of the low ether extract content in the seaweed meal.

Annex 2 Chapter 3

Table 1

IMTA - species selection for the North Sea: Fish.

Results for identification of fish culture potential by Reijs et al. (2008), based on a step-wise approach.

Species	Production technique*	Temperature range	Estimated grow-out potential	Potential in North Sea
Cod	Y	0-20	+++	+
Turbot	Y	12-18	++	-
Sea Trout	<i>Not possible</i>	18-24	++	-
Sole	Z	8-24	+	-
Seabass	Z	8-24	+	-
Bluefin Tuna	X	5-30	+++	+ (summer)
Swordfish	X	5-27	++	+ (summer)
Shipjack tuna	X	15-30	+	+ (summer)
John Dory (zonnevis)	X	>16.5	+	+ (summer)
Golden grey mullet	Z	>7	+	+

* X - Strategy of seasonal culture of fast growers during 'warmer' conditions

Y - Strategy of vertical moving culture systems: sinking to deeper layers when temperature is too high in surface layers (summer)

Z - Strategy of vertical moving culture systems: sinking to deeper layers when temperature becomes too low at the surface (winter)

Table 2

IMTA- species selection for the North Sea: Shellfish. Profitability of offshore long line mussel culture indicated by Break-even-points (Source: Buck et al., 2010).

	Consumption mussels		Seed mussels	
	New Vessel + Land facility	Using existing equipment	New Vessel + Land facility	Using existing equipment
Break-even-price (assuming harvest of 10 kg m ⁻¹ longline)	€0.52	€0.37		
Break-even-yield (assuming €1 kg ⁻¹ consumption mussel)	5.2kg	3.7kg		
Break-even-price (assuming harvest of 5 kg m ⁻¹ longline)			€0.49	€0.34
Break-even-yield (assuming €0.5 kg ⁻¹ seed mussel)			4.9kg	3.4kg

Annex 3 Chapter 9

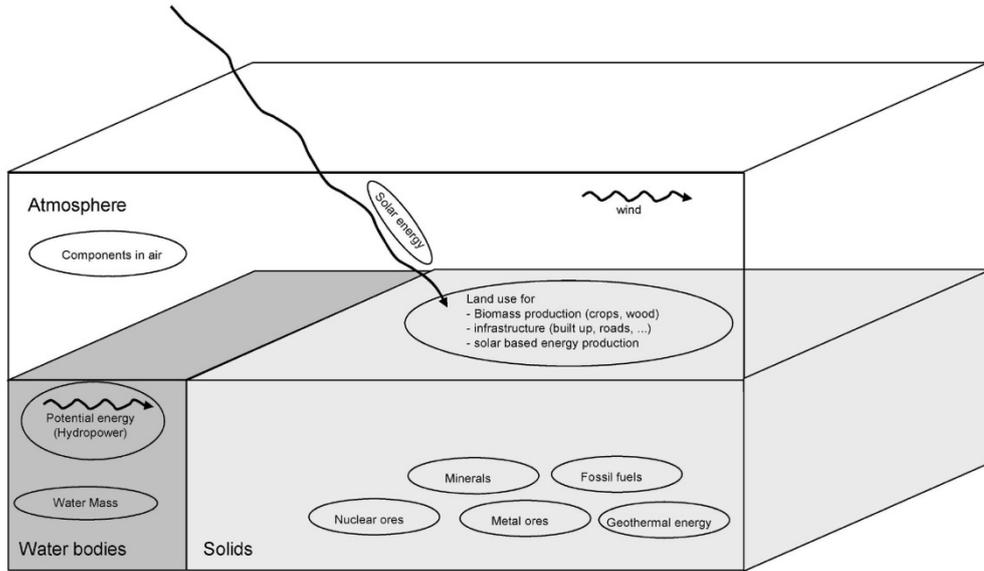


Figure 1 Natural resources taken away from the natural environment to establish industrial production and consumption: renewable resources (wind, solar energy, biomass, geothermal, hydropower), land use for infrastructure (built up, roads, ...), fossil fuels, nuclear energy, metal ores, minerals, water resources, land resources, and atmospheric resources. (DeWulf et al., 2007).

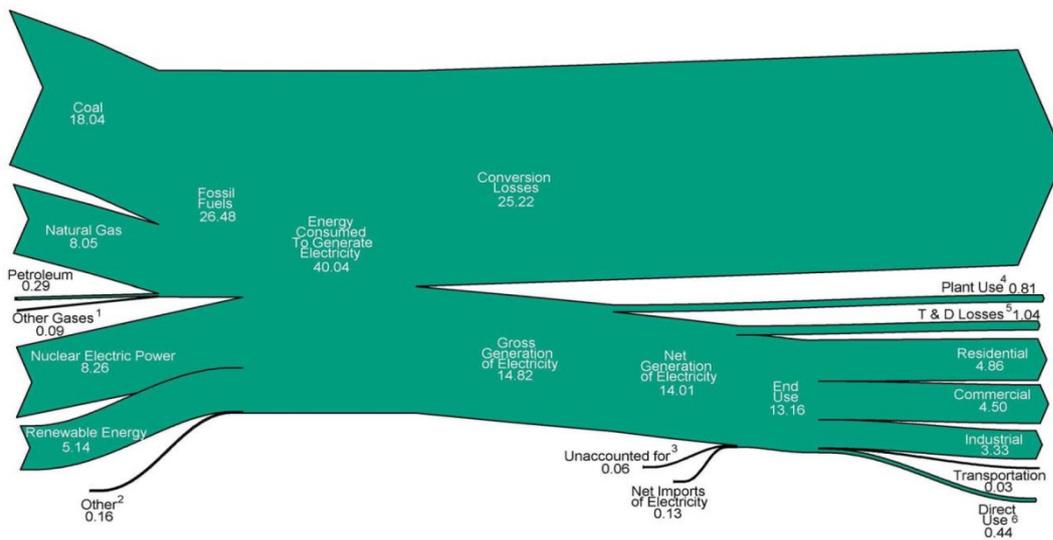


Figure 2 Example of an Exergy scheme (Grassmann diagram) of the US Electricity system, indicating 'exergetic values' of used materials, values of the valuable products generated and interactions between different production systems.



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