Large-scale carbon recycling via cultivation and biorefinery of seaweeds for production of biobased chemicals and fuels

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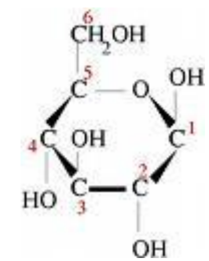
Solar Energy Conversion: Photosynthetic CO_2 reduction

- **$H_2O + CO_2 + (8+n)\ h\nu \rightarrow (CH_2O) + O_2$ + heat**
- **477 kJ chemical energy stored per mol fixed CO_2**
- **Maximum theoretical energy conversion efficiency is 8.2–12.2%**
  - Losses in photosynthetic system (fluorescence, heat)
  - Respiration for translocation/ biosynthesis demands 33% of stored energy
  - Effective surface usage is 10–80 %, depending a.o. on type of plants
  - Suboptimal growth conditions



- **Energy conversion efficiency most terrestrial plants 0.5 – 0.8%**
- **Micro-algae, seaweeds able to attain 4.3 – 6.5%**

Features of seaweeds

- CO_2 uptake from water/atmosphere
- High biomass productivity (also in cold seawater)
- Large cultivation area available
- Limited competition with food or other land use issues/resources
- Potential positive ecological effects cultivation
- Composition: carbohydrates up to 65 wt%, protein 15 wt%, minerals 20 wt%. Carbohydrate platform.
- Multiple options for biobased chemicals and fuels production >> net CO_2 reduction

- Cultivation in off-shore wind turbine parks
- Large-scale floating cultivation in the oceans

Marine biomass energy potential

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Most feasible technical concepts	Area	Potential
Set 1: Land based open ponds for microalgae	Arid land in (sub) tropical zones (deserts) and close to coast (max 100 km)	90 EJ
Set 3: Horizontal lines for macroalgae	At existing infrastructure – f.e. offshore wind farms (up to 100 km offshore)	110 EJ
Set 5: Vertical lines for macroalgae	Near coast (max 25 km) in nutrient rich water	35 EJ
Set 6: Macroalgae colony	At open sea (biological deserts), up to 2000 km offshore	~6000 EJ
TOTAL		**~ 6235 EJ**

Source: Ecofys, 2008. Worldwide Potential of Aquatic Biomass. 100 Million km2 @ 30 ton d.w. (20 GJ/ton) seaweed ha.yr

World energy consumption: 480 EJ/yr.

Current seaweed exploitation

Macrocystis pyrifera (giant kelp);California*

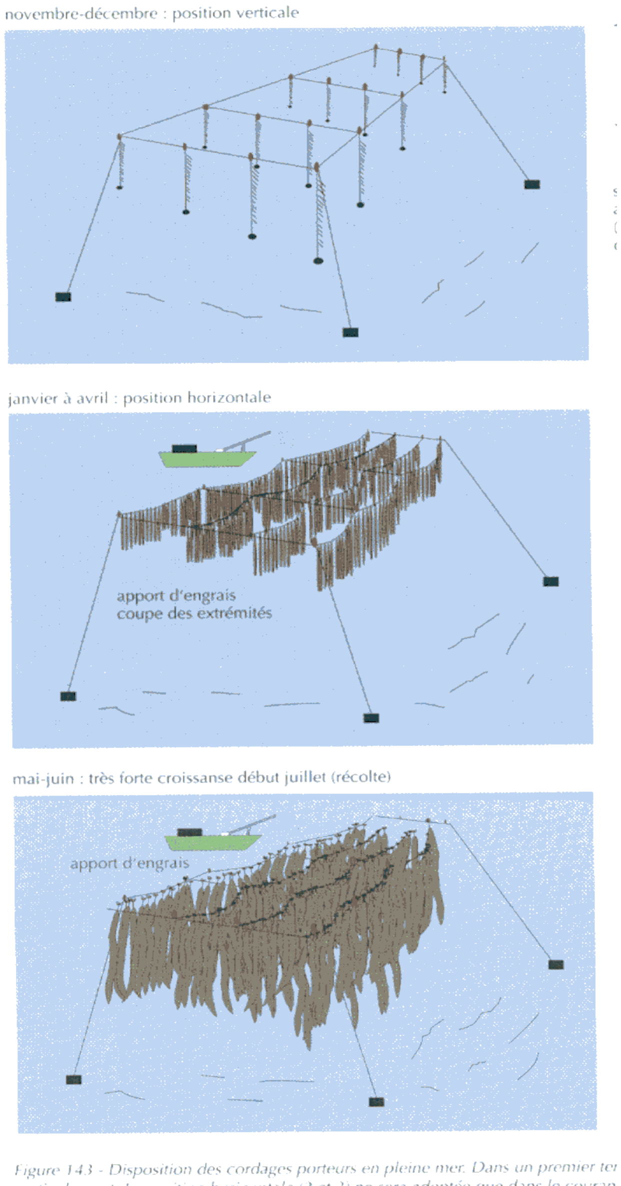
Gracillaria line cultivation

* © C.J. Dawes

- Current world production: >10 Mton yr (China, Philippines, Indonesia, USA, France, Ireland, Norway, …)
- Harvest natural populations / Cultivation: line systems
- Major applications: food, phycocolloids as thickeners/gelling agents, extracts for cosmetics, animal feed/aquaculture, fertilizer….
- Market size ca. 6 Billion US$ / year; 2 a 3% growth per year

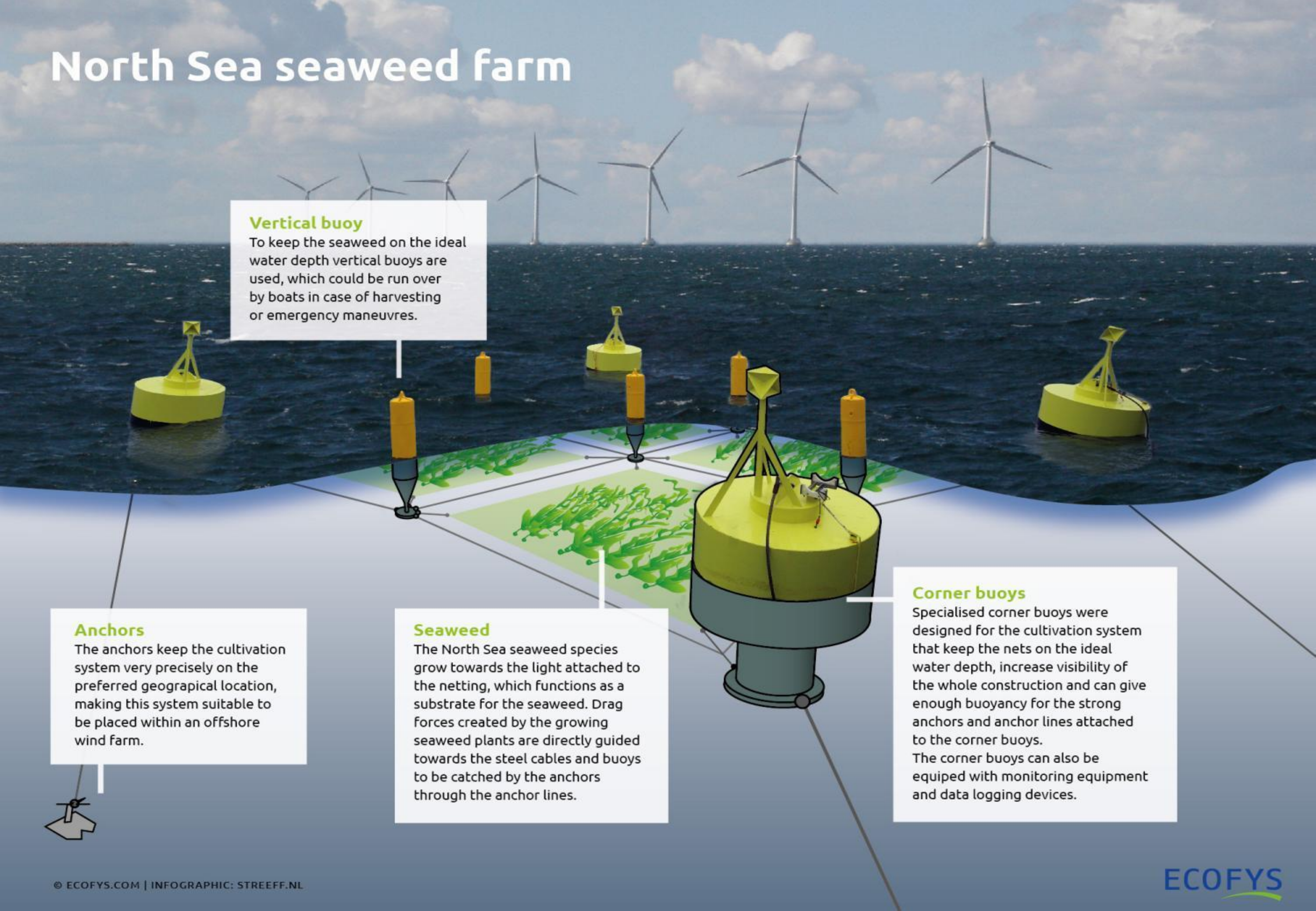
Seaweed harvest in Asia (Photo Ifremer)

Harvest of Macrocystis in the Pacific (Kelco company)



Experimental ring system for cultivation of Laminaria (AWI-Bremerhaven, B.H. Buck *et al*): Good stability in the German North Sea shown

Photo R. Perez,1997. Ces algues qui nous entourent. Ifremer.


North Sea seaweed farm
Vertical buoy
To keep the seaweed on the ideal water depth vertical buoys are used, which could be run over by boats in case of harvesting or emergency maneuvres.
Anchors
The anchors keep the cultivation system very precisely on the preferred geograpical location, making this system suitable to be placed within an offshore wind farm.
Seaweed
The North Sea seaweed species grow towards the light attached to the netting, which functions as a substrate for the seaweed. Drag forces created by the growing seaweed plants are directly guided towards the steel cables and buoys to be catched by the anchors through the anchor lines.
Corner buoys
Specialised corner buoys were designed for the cultivation system that keep the nets on the ideal water depth, increase visibility of the whole construction and can give enough buoyancy for the strong anchors and anchor lines attached to the corner buoys.
The corner buoys can also be equiped with monitoring equipment and data logging devices.
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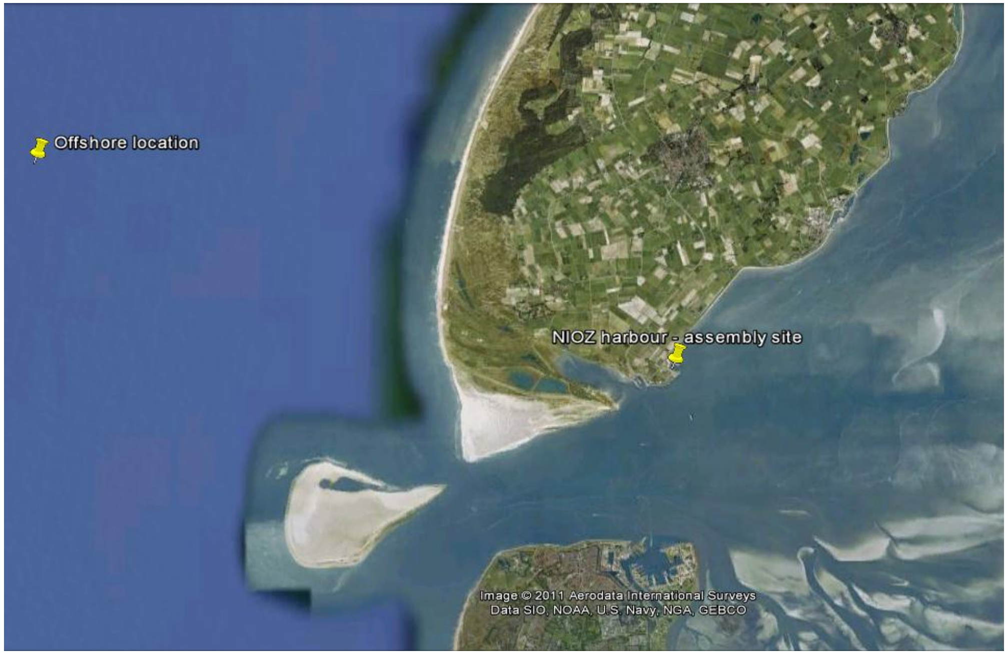
North Sea Test Farm

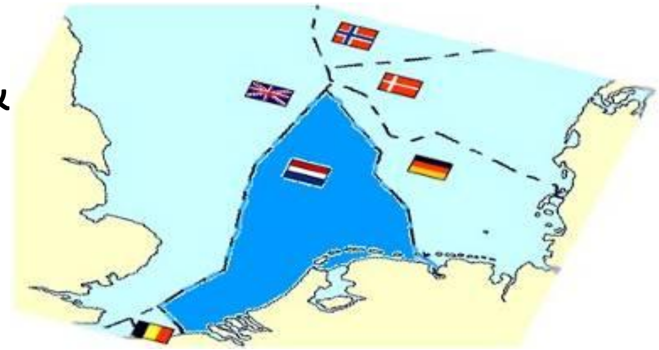


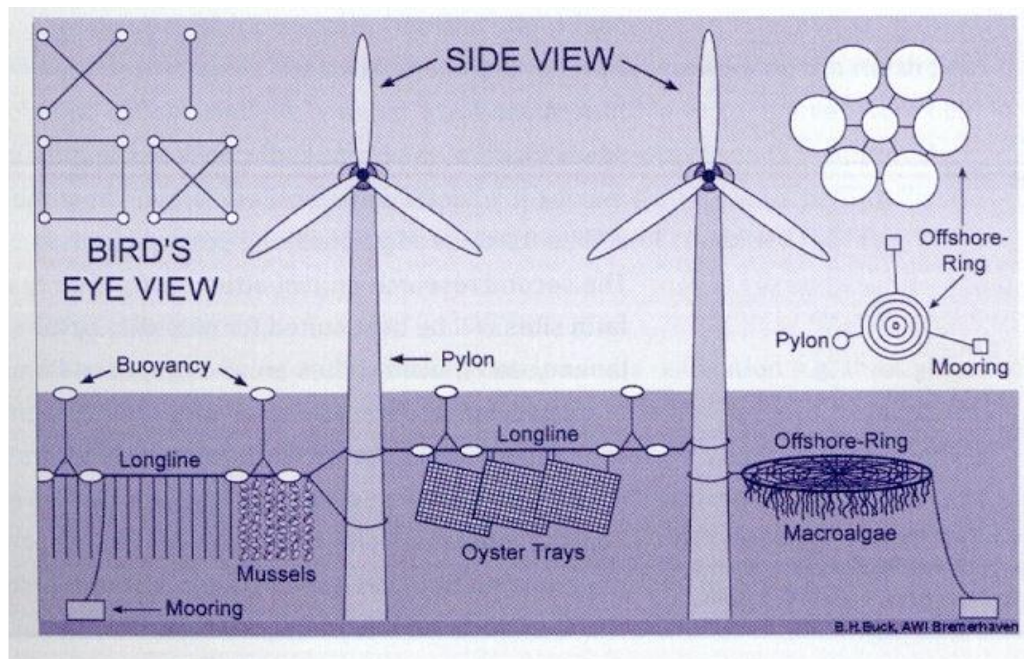
- Realistic, off-shore conditions
- Complete monitoring phase including harvest
- Analyse strength and weakness of design

- Plans to expand North Sea Test Farm: Ecofys, NIOZ, Hortimare, ECN
- Facilitate 3rd party research initiatives
- Investigate sustainability of seaweed farming

Cultivation in offshore wind parks

- Wind turbine parks planned & developed in the North Sea
- Area closed for shipping
- Multifunctional use of area and offshore constructions
- Potential combination with other aquaculture, mussel cultivation
- Joint O&M: personnel, vessels, equipment: Synergy and cost benefits





Source: Bela H. Buck, Alfred Wegener Institute, DE.

Seaweed species native to the North Sea

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Saccharina latissima

Laminaria digitata

Laminaria hyperborea

Ulva sp.

Alaria esculenta

Palmaria palmata

Product options *Laminaria* sp.

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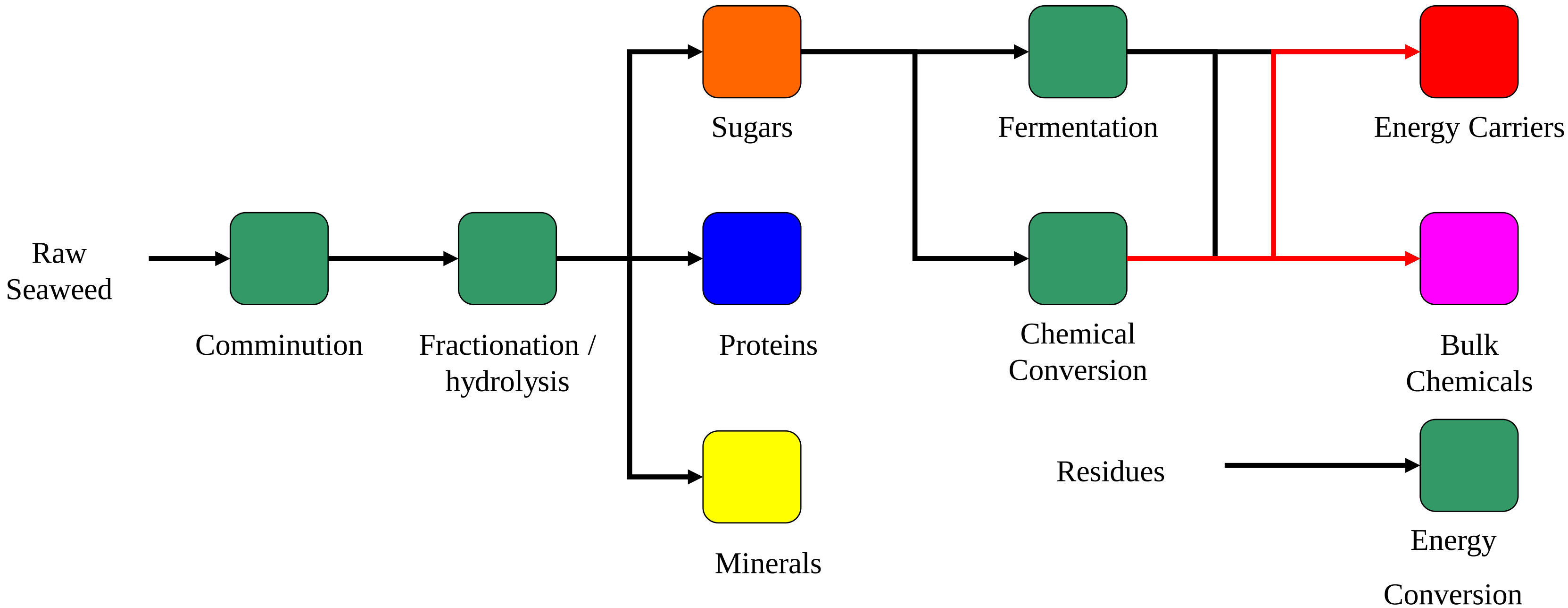
Component	Contents in w% d.w.
Cellulose	6
Hemicellulose	0
Lignin	0
Lipids	2
Proteïns	12
Starch	0
Alginates	23
Laminaran	14
Fucoidan	5
Mannitol	12
Total fermentable sugars	60
Ash contents	26

- Range of polysaccharides, proteins, minerals, no lignin
- Suitable feedstock for biorefinery for co-production of chemicals and fuels to attain optimum valorization

- Higher value compounds: alginates, fucoidan, proteins, mannitol.......... (extraction)
- Animal feed (protein fraction)
- Furanics (carbohydrate conversion)
- Butanol (fermentation)
- Bleach activators (derivatization)
- Phosphate recycling/fertilizers (Ash utilization)
- ....

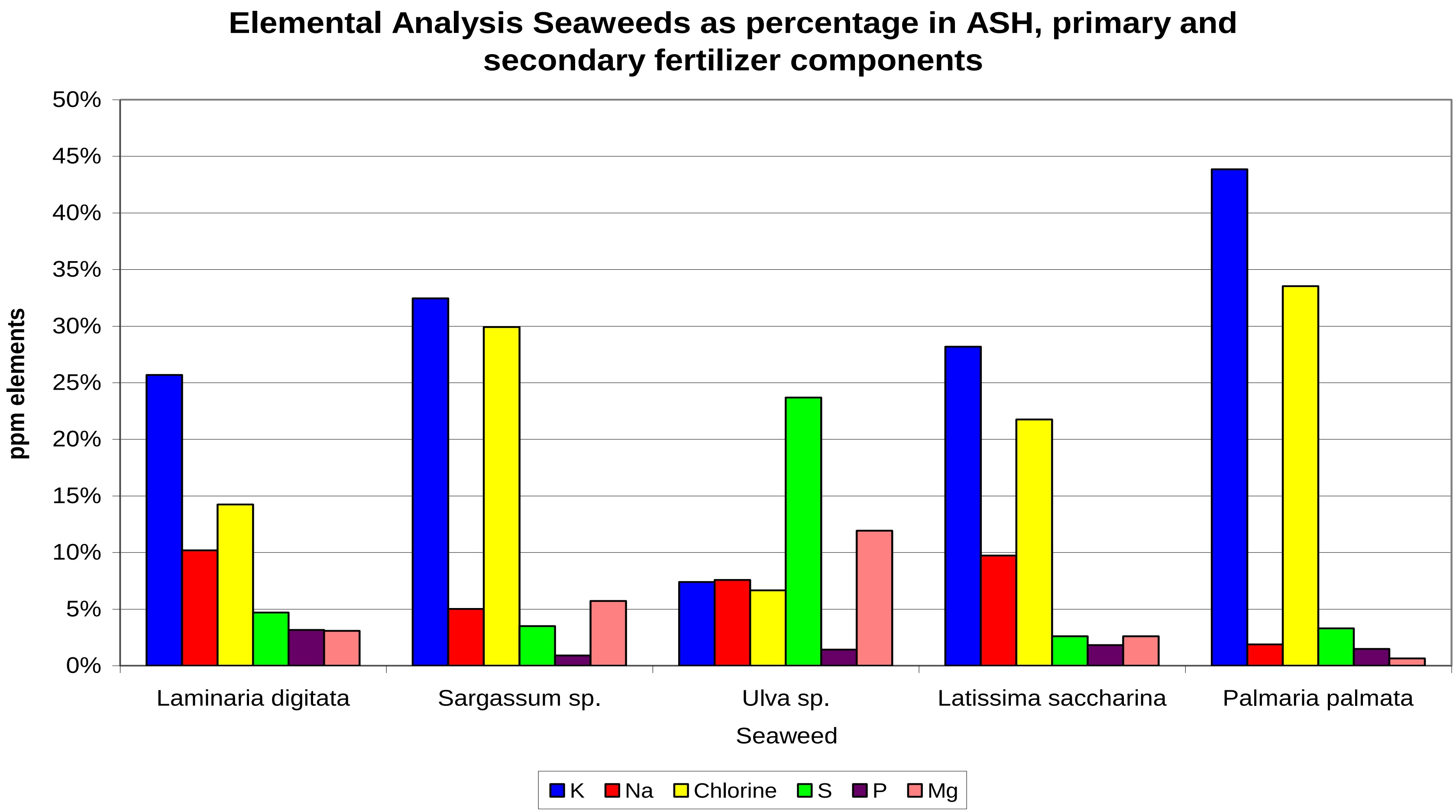
Development of biorefinery technologies for chemicals and fuels production



NL project Seaweed Biorefinery, results to date:

- Mild fractionation to preserve structure and functionality of components
- Enzymatic hydrolysis feasible using commercial enzyme cocktails
- Successful fermentation sugars to Acetone-Butanol-Ethanol (ABE) shown
- Catalytic conversion sugars to furanics

Minerals



- Plus appreciable amounts of trace elements, incl. B, Mn, Fe, Zn, Cu, Mo, Se,..
- Fertilizer ‘ore’ or recycling to sea

Economics: Product spectrum

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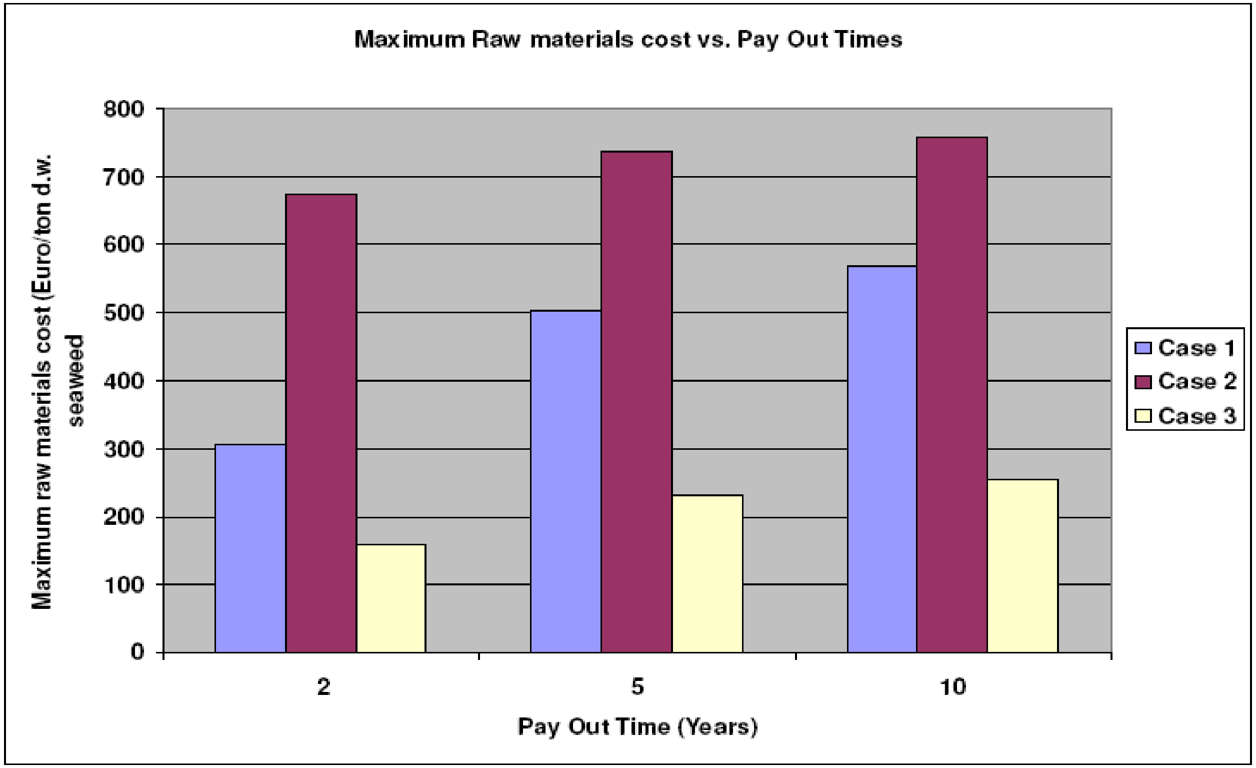
Product	Estimated Value (Euro/ton)
Mannitol (valued as sorbitol)	1,500
Fumaric acid (as adipic acid)	1,600
Fucoidan (as detergent)	2,900
1-Butanol (chemical grade)	1,200
Ethanol (fuel grade)	600
Protein	1,000
Fertilizer (as ore)	350
Furanics	800
Alginates	3,000

Max. allowable seaweed costs based on projected sales revenues for Pay Out Time 2, 5, 10 yrs



Scale biorefinery 330 kt/yr

= 110 km2 @ 30 ton/ha/yr

Estimates CAPEX, OPEX

1: Full Biorefinery: mannitol, fucoidan, furanics, fumaric acid, protein, K-"ore": 300-600 €

2: Extraction of alginate, fertilizer (K,P) and energy (AD + CHP): 650- 750 €

3: Simplified Biorefinery producing butanol and fertilizer: 150 - 250 € /ton d.w

Seaweed production cost

Type of cultvation system	Productivity		Costs		Reference:
	ton daf/ ha.yrr	ton d.w./ ha.yr	$ ton daf	$ (or €) / ton d.w.	
Chili: harvest of natural populations	-	-	-	250	Internet
Philippines: coastal cultivation; 'off-farm' price	-	-	-	80 - 160	Internet
Nearshore cultivation Macrocystis	34 50	57 83	67 42	40 25	[3]
Gracillaria/Laminaria line cultivation (offshore)	11 45	14 59	538 147	409 112	[3]
Tidal Flat farm Gracillaria/Ulva	11 23	14 30	44 28	33 21	[3]
Floating cultivation Sargassum	22 45	32 66	73 37	50 25	[3]

Ref [3]. Chynoweth, D.P. 2002. Review of biomethane from Marine Biomass. History, results and conclusions of the "US Marine Biomass Energy Program" (1968-1990). 194 pp.

Indication large scale production cost (design studies): 50 € (nearshore/floating) - 400 € (offshore) per ton dw. Verification required.

Ocean farm concept

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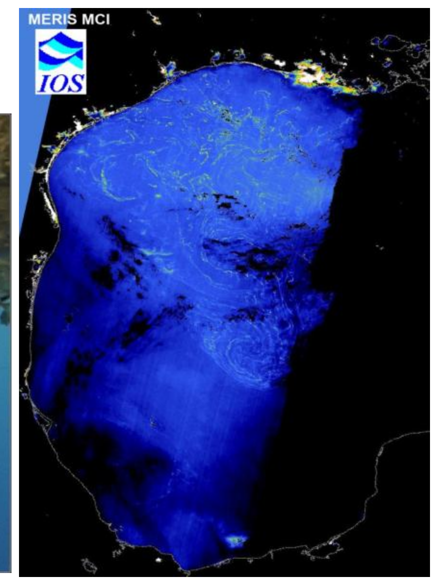
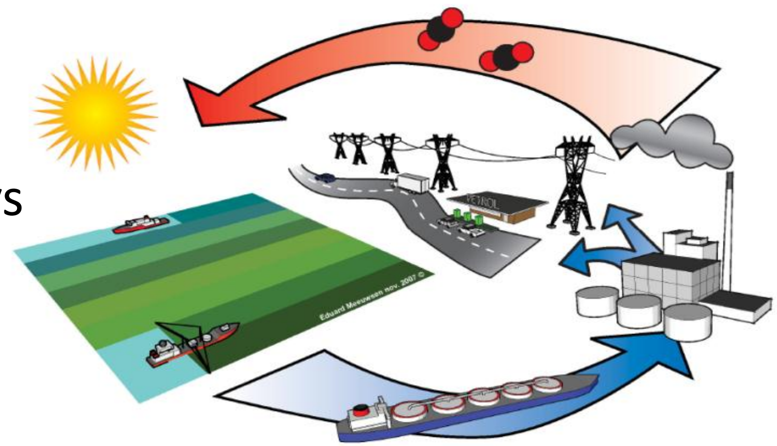
- Location: ocean gyres/ low current
- Seaweed *Sargassum natans*:
  - fast growing, floating, global occurrence;
  - uses nitrogen fixation by associated epiphyte or cyanobacteria (Philips et al, 1986)
  - good habitat for fish and many other species
  - can be monitored by satellite (MERIS)

A **spiral oceanic surface current** driven primarily by the global wind system and constrained by the continents surrounding the three ocean basins (Indian, Pacific, Atlantic).

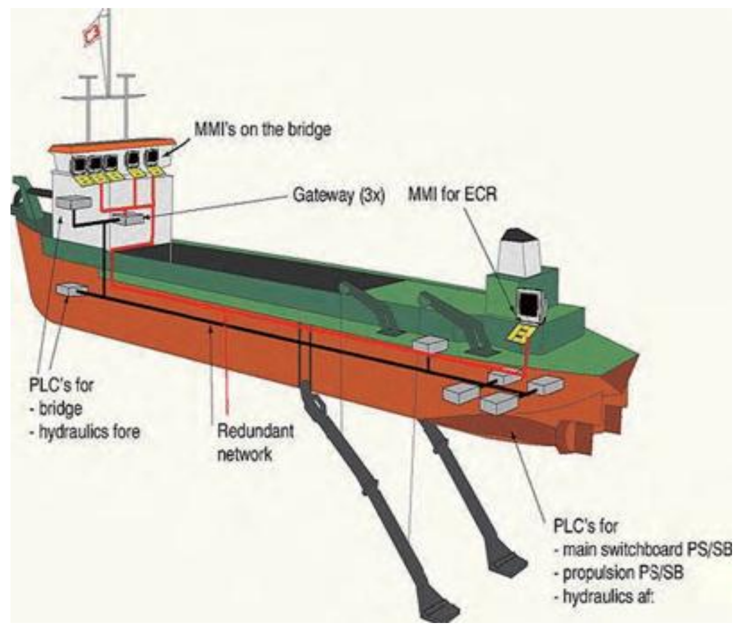


Ocean farm concept

- Farm location in gyre areas marked with buoys (ownership)
- Seeding with small fragments of *S. natans* combined with harvesting
- Selective fertilizer supply (no nitrogen), slow release
- Selective harvesting (no fish or turtles)
- Processing on shore (biorefinery)
- Ecological uncertainties: effects on marine ecosystem: Much more research is needed



Concept for offshore open ocean farming (Herfst, TU-Delft, 2008)



Cost estimate ethanol

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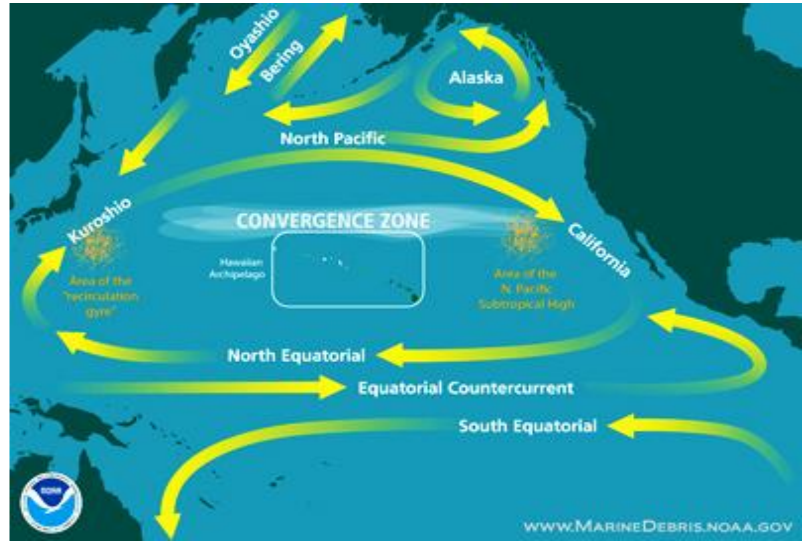
- Scale: one harvester\transporter Aframax size (80.000 ton)
- Assumed seaweed density: 10 ton/ha (dw)
- Harvesting capacity 3000 ton/hr (wet)
- Ship rent and fuel costs: 0,3 €/ton/day

	US-harbor (500 km)	Rotterdam (6000 km)
Biomass in harbor (dw)	12 €/ton	35 €/ton
Ethanol plant (on shore)	0,15 €/ltr	0,15 €/ltr
Total ethanol costs	**0,20 €/ltr**	**0,27 €/ltr**
Market value ethanol*	0,60 €/ltr	0,60 €/lr
Total per liter petrol eq	**0,29 €/ltr**	**0,40 €/ltr**
Market value petrol	0,50 €/ltr	0,50 €ltr

* 750 Euro/tonne ethanol

Seaweed to reduce the garbage patches

- Low density and small plastic particles (density 5 ton/km^2, 5 gram/m^2)
- Methods to collect the garbage are expensive
- Collection together with seaweed could be possible with little extra costs
- Approx. 0.25% of dry mass would be garbage



S. natans proteins compared with soy

Sargassum natans

- 6,6% (dw) proteins o.w.:
  - Methionine 2,3%
  - Lysine 4,5%
  - Threonine 3,8%

Source: Basil S. Kamel (1980)

Soy beans

- 36,5% proteins o.w.:
  - Methionine 1,4%
  - Lysine 7,4%
  - Threonine 4,9%

Ca. 5 ton dry *S. natans* could replace 1 ton soy beans for feed

Conclusions/outlook

- Seaweed cultivation offers a vast potential for CO_2 recycling, as a highly productive source of biobased chemicals, biofuels and feed.
- Seaweed cultivation in offshore wind parks offers multifunctional area use incl. potential combination with other aquaculture operations.
- Seaweed from open ocean farming could be
  - a promising source for biofuel production with low costs
  - a source of proteins for cattle and fish feed
  - seaweed harvesting could help reduce ocean garbage
- Many uncertainties, R&D required
  - Development of offshore cultivation systems
  - Nutrient supply/recycling
  - Harvesting and logistics
  - Processing
  - Environmental and socio-economic impacts.

Acknowledgements

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Contacts

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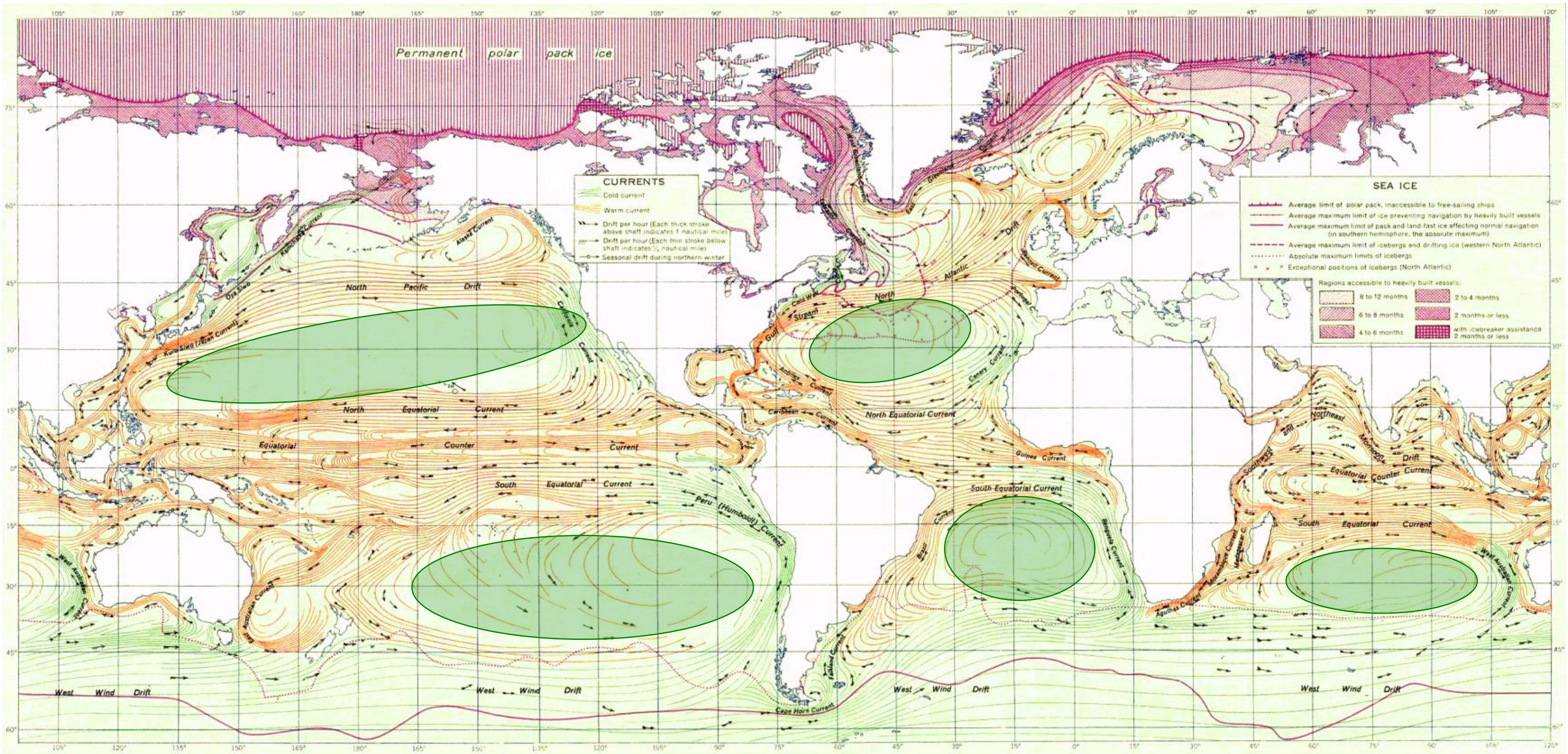
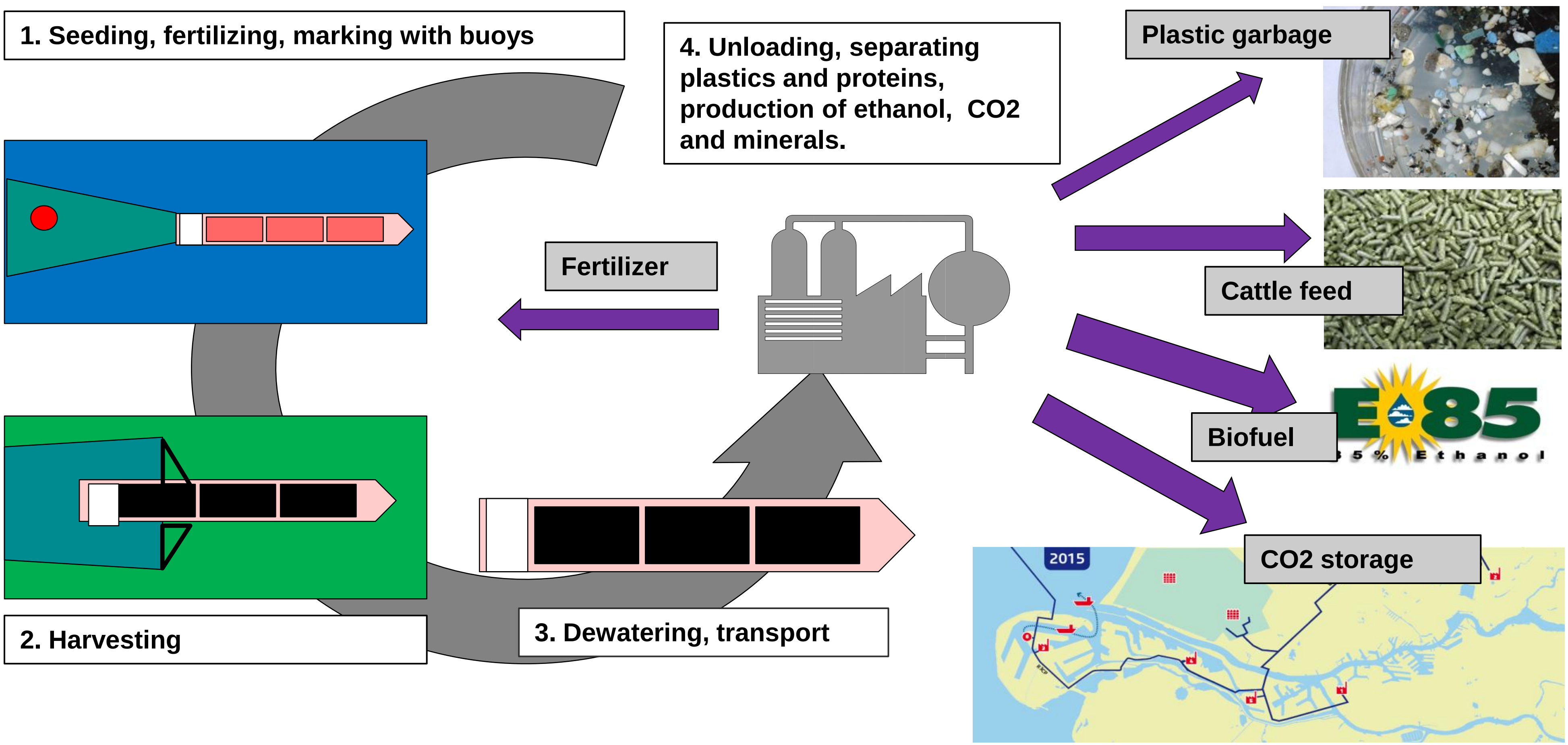
Ocean potential: >25.000.000 km²



- Current global agricultural crop area: 15.000.000 km2 (FAO, 2006)
- At 1000 ton/km2 (10 ton/ha) : 25.000 Mton seaweed biomass (375 EJ)

32 Gton CO_2 fixed, at 30% net CO_2 reduction: 9.6 Gton CO_2 avoided (vs Global total emission 29 Gton CO_2; transport: 6.5 Gton CO2

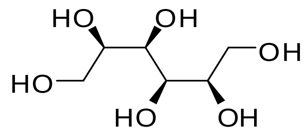
Ocean seaweed to fuel chain



Shell, AB Rotterdam deliver CO2 to OCAP > horticulture

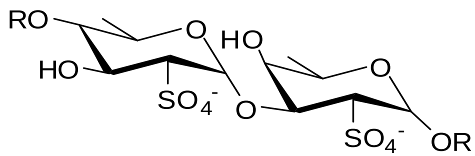
Brown seaweed carbohydrates

- Mannitol

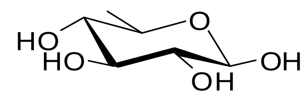


mannitol

- Fucoidan

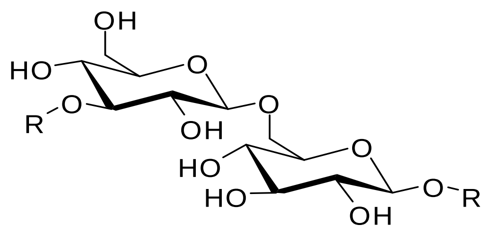


Fucoidan

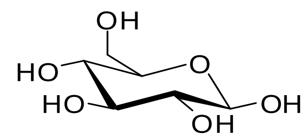


Fucose

- Laminarin

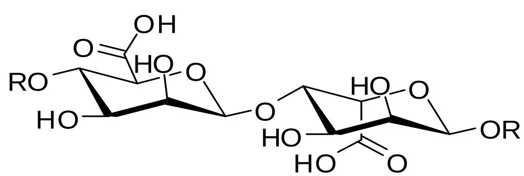


Laminarin

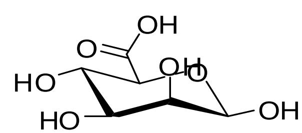


Glucose

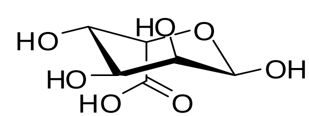
- Alginic acid



Alginic acid



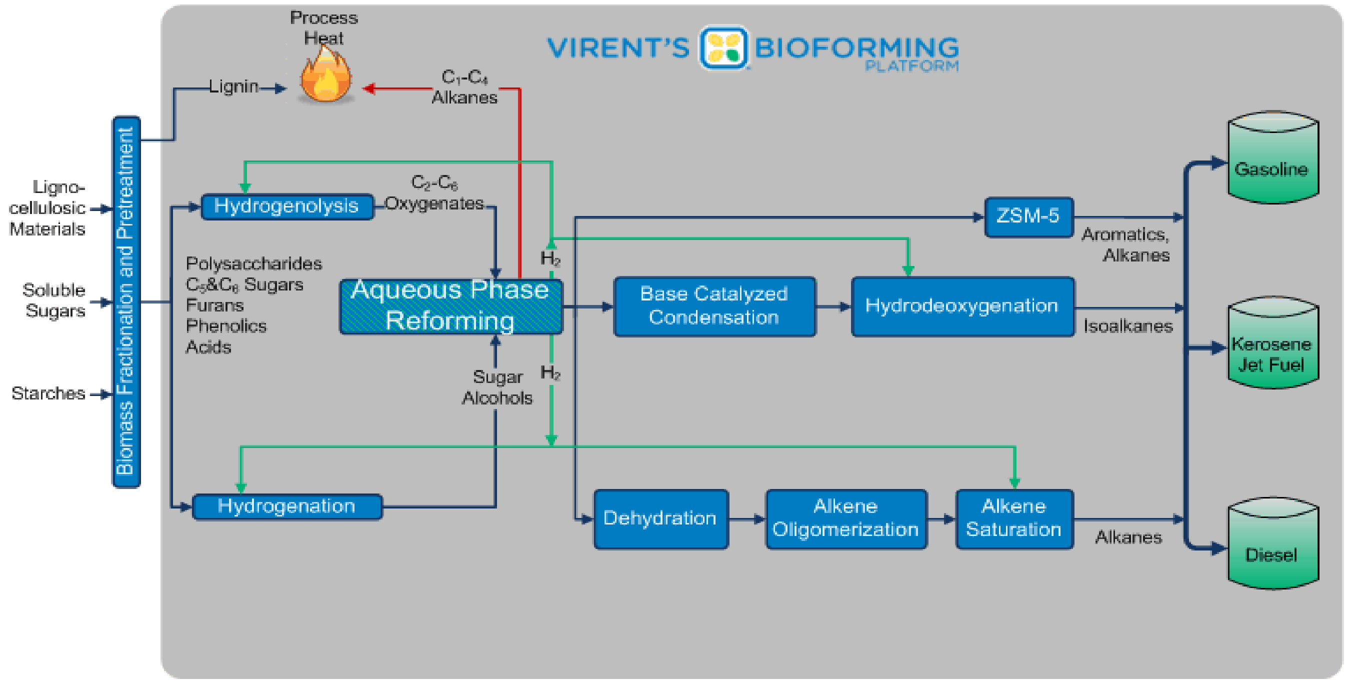
Mannuronate



Guluronate

Potential energy carriers from seaweed

- Ethanol, butanol from sugars (≥ 60 wt%) via fermentation
- Diesel and jet fuel via Aqueous Phase Reforming technology
- Bio crude via HTU
- Methane via anaerobic digestion



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