Perspectives of open ocean seaweed cultivation and seaweed biorefinery for large-scale production of biobased fuels and chemicals

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October 2012
ECN-L--12-055

Energy research Centre of the Netherlands

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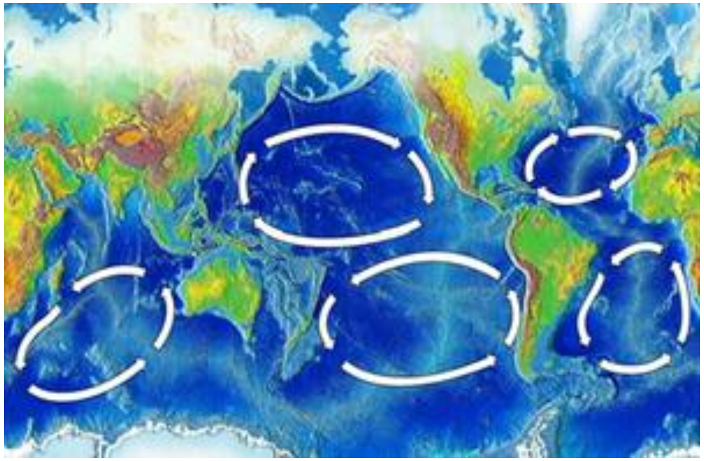
World Biofuels Markets, 13-15 March 2012, Rotterdam

Ocean farm concept ECN

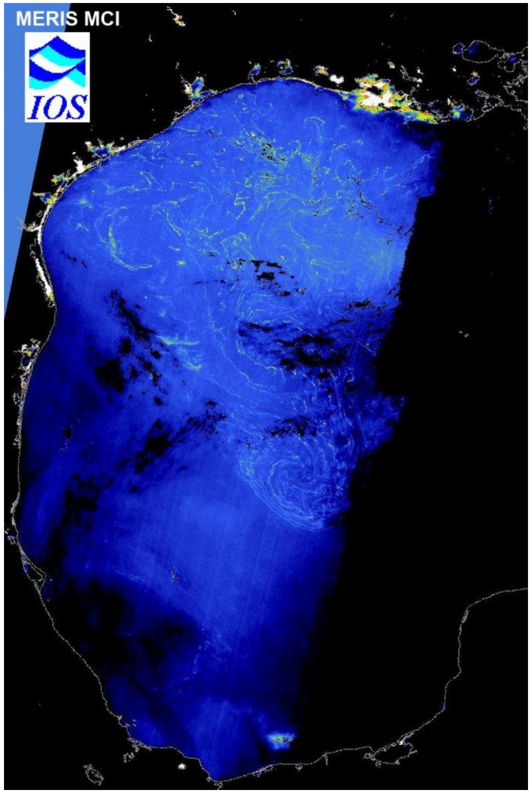
- Location: ocean gyres/ low current
- Sargasso seaweed *Sargassum natans* has attractive properties: (fast growing, floating, global occurrence; uses nitrogen fixation by an associated epiphyte or cyanobacteria (Philips et al, 1986)
- Large potential: >25.000.000 km2



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).

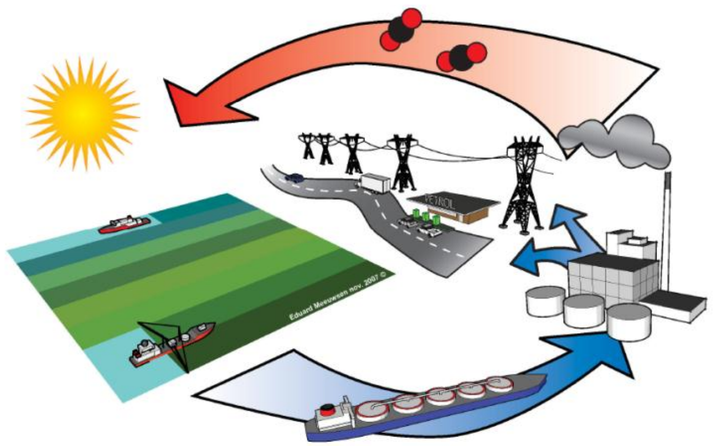
Sargassum natans

- *Sargassum* seaweed is now a pest (on shores)
- It forms also a good habitat for fish and many other species
- It can be monitored by satellite (MERIS)

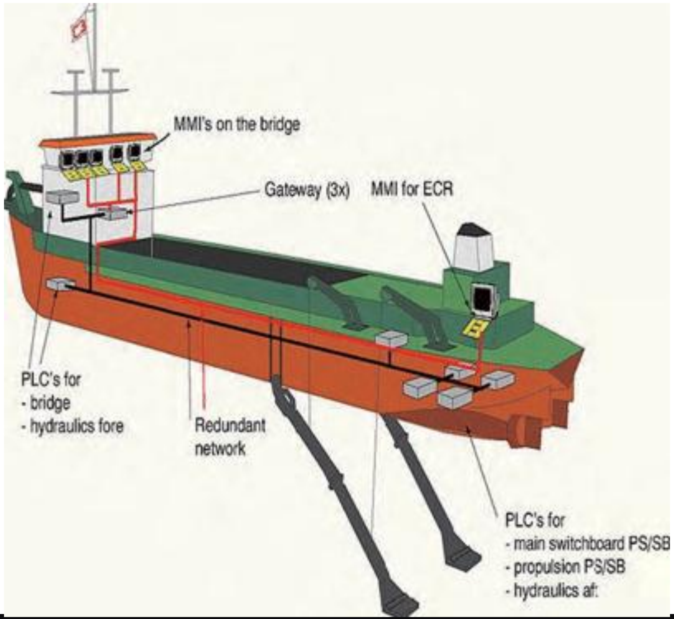


Ocean farm concept ECN

- 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

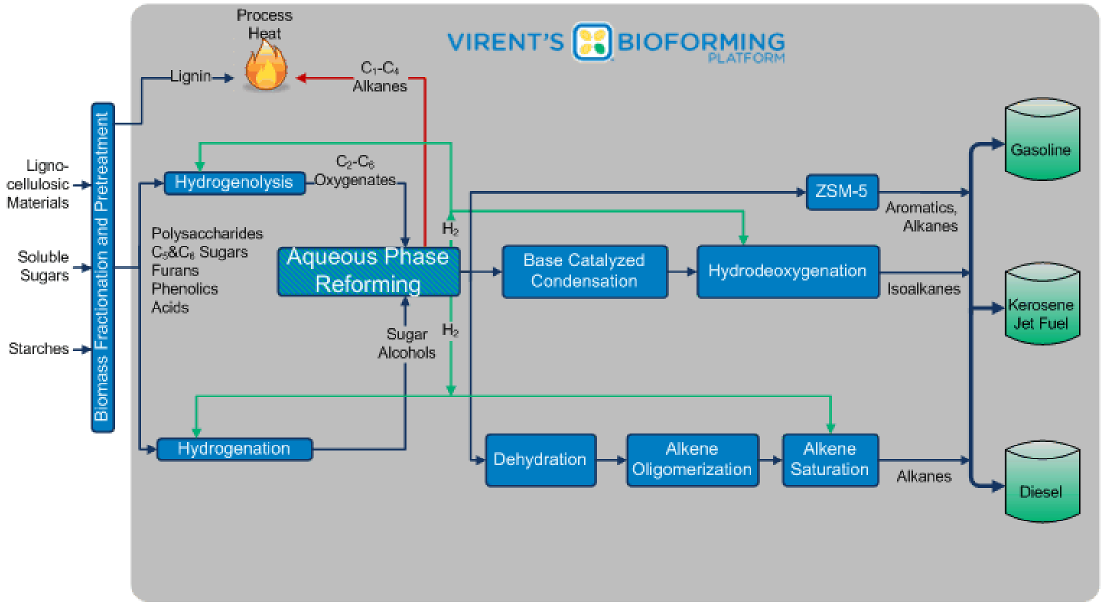


Concept for offshore open ocean farming (Herfst, TU-Delft, 2008)



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



Cost estimate (preliminary)

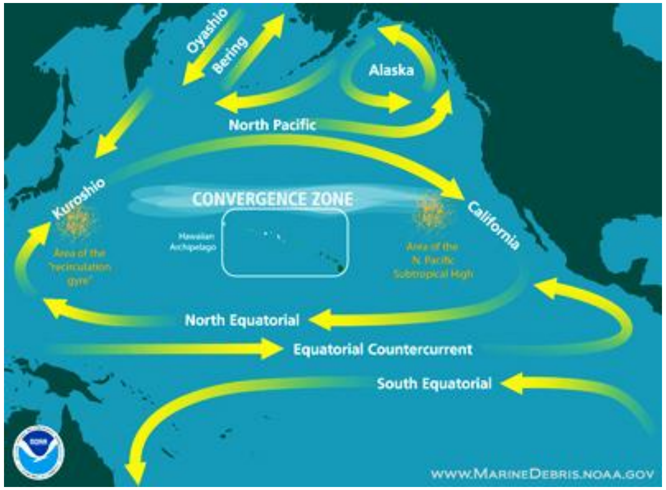
- Scale: one harvester\transporter Aframax size (80.000 ton)
- Assumed seaweed density: 10 ton/ha (dw)
- Harvesting capacity 3000 ton/hr (wet)
- Ship rent and fuel costs: 0,3 €/ton/day

	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 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 beans

Sargassum natans

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

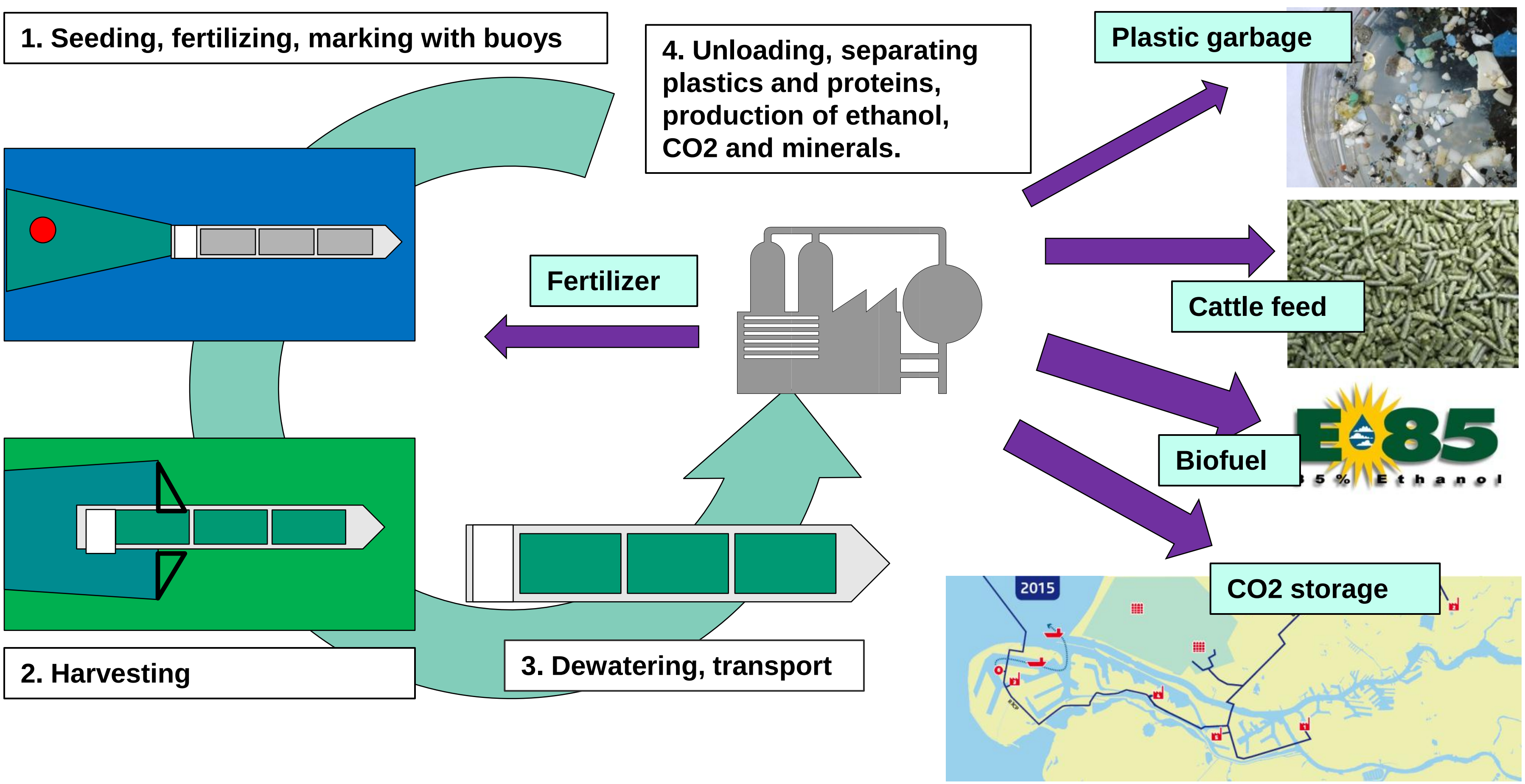
Source: Basil S. Kamel (1980)

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

Ocean seaweed to fuel chain



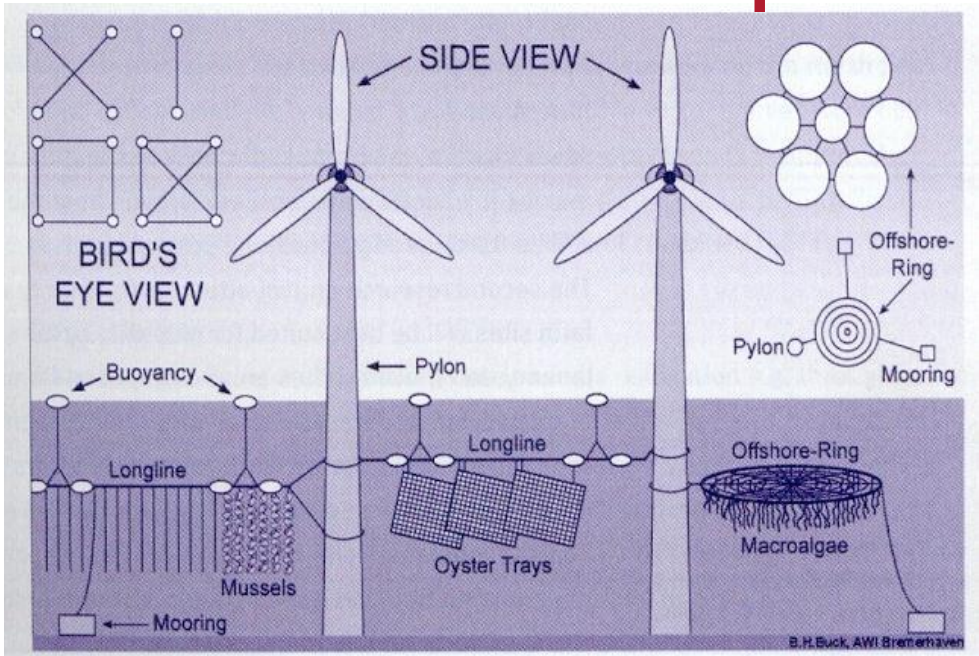
Shell, AB Rotterdam deliver CO2 to OCAP > horticulture

Summary open ocean farming

- Seaweed from ocean farming is a promising source for biofuel production with low costs and a large potential
- Seaweed could be a large source of proteins for cattle and fish feed
- Seaweed could help reduce ocean garbage and acidification
- Ecological benefits and risks need to balanced

Seaweed cultivation in offshore wind turbine parks

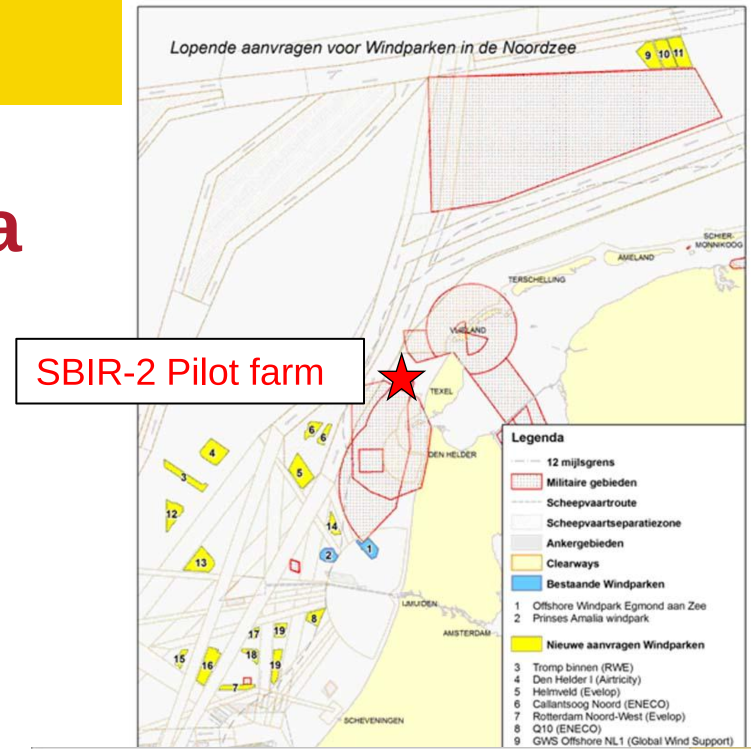
- Area closed for shipping
- Multifunctional use of area and offshore constructions
- Potential combination with other aquaculture e.g. mussel cultivation
- Joint O&M: personnel, vessels, equipment
- Synergy and cost benefits

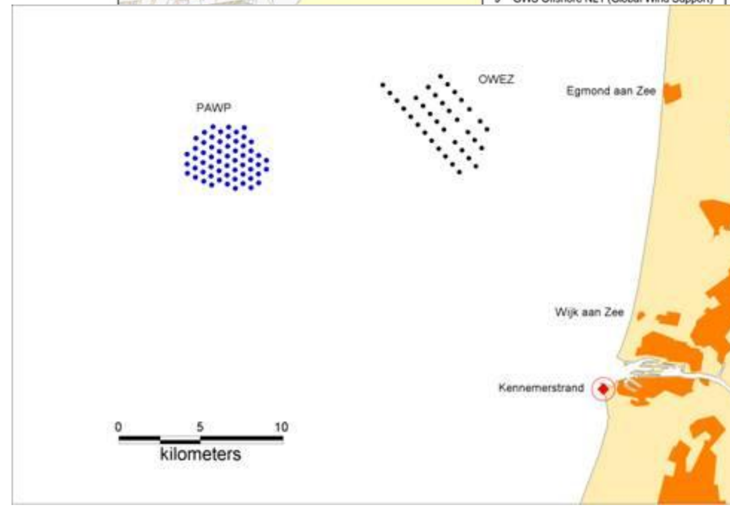


Source: Bela H. Buck, Alfred Wegener Institute, DE.

Seaweed at the North Sea

- 2 wind parks operational, 3 more planned/under construction.
- Ca. 100 KM2; Target: 6000 MW = 1000 km2
- Plans for combination seaweed in wind parks (Ecofys/Eneco/ECN)
- Construction must be stable in storms, high waves, current,..
- 0.5 Hectare experimental farms (Texel, Zeeland)
  - Test cultivation concepts
  - Test harvesting concepts
  - Product quality
  - Cultivate test quantities of native seaweeds





Seaweed species native to the North Sea

Lattissima saccharina

Laminaria digitata

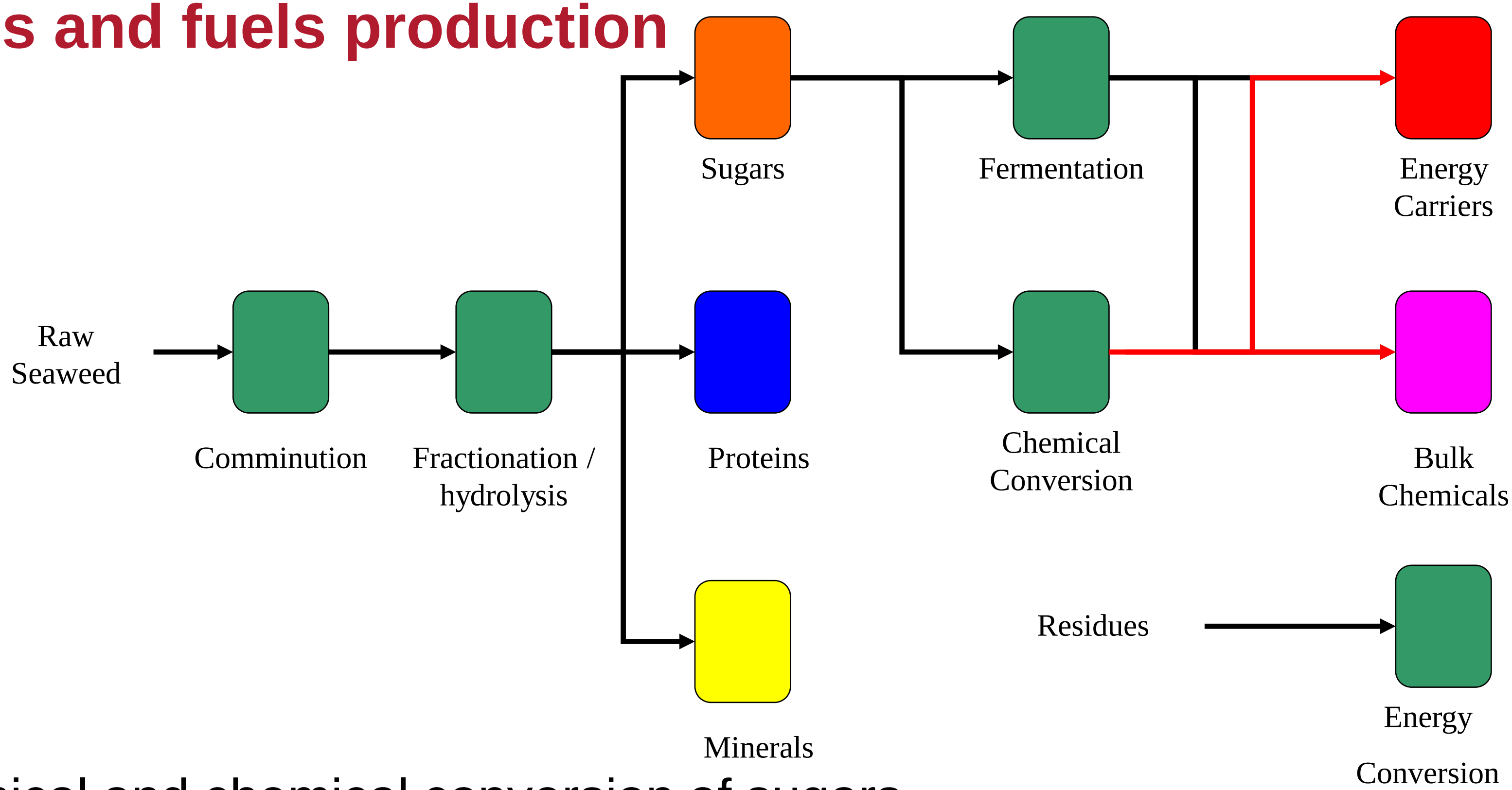
Laminaria hyperborea (Perez)

Ulva sp.

Alaria esculenta (Irish Seaweed Centre)

Palmaria palmata (AWI)

Aim: Development of biorefinery technologies for chemicals and fuels production



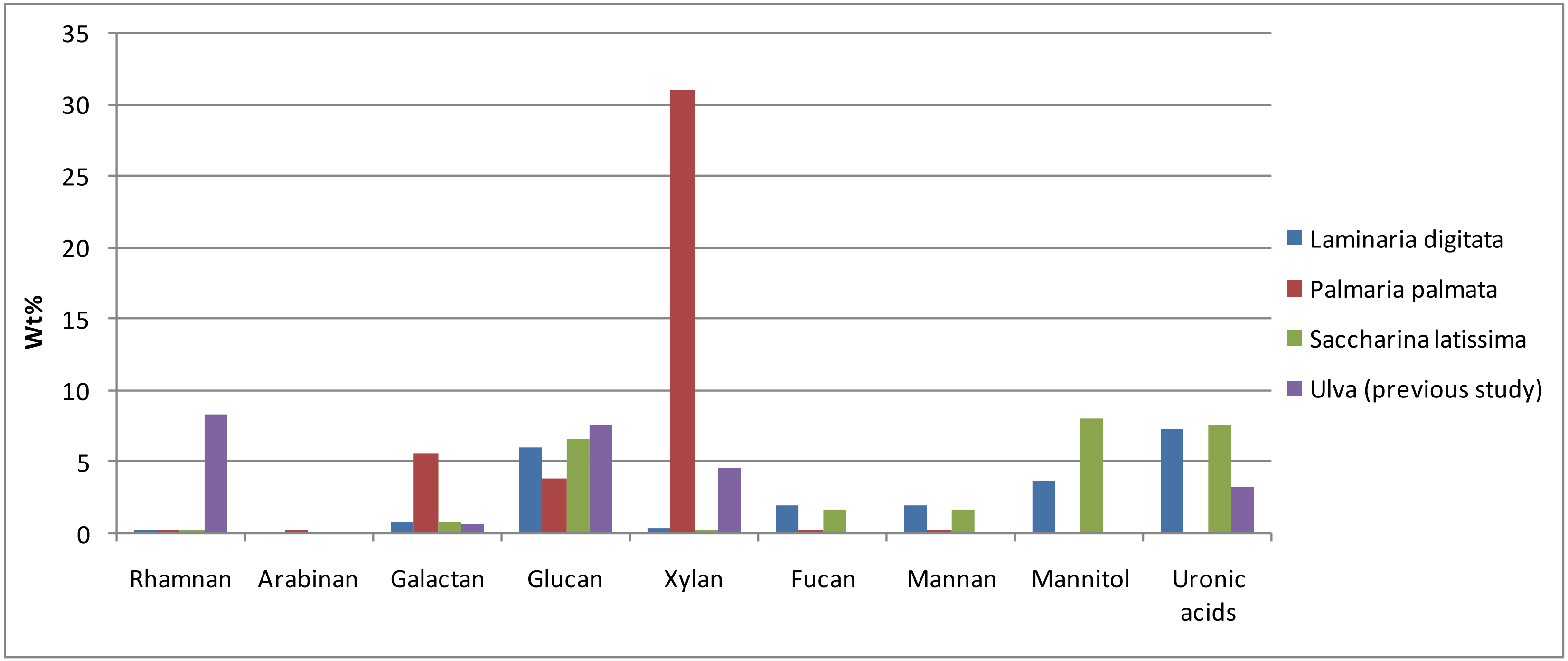
- Biochemical and chemical conversion of sugars
- Valorization remaining fractions: proteins, minerals, biogas
- Extraction of bio-actives, alginates, fucoidan,.. Not the focus
- Design, economic evaluation, LCA

Biomass characterization

basis for process development and selection of products/applications

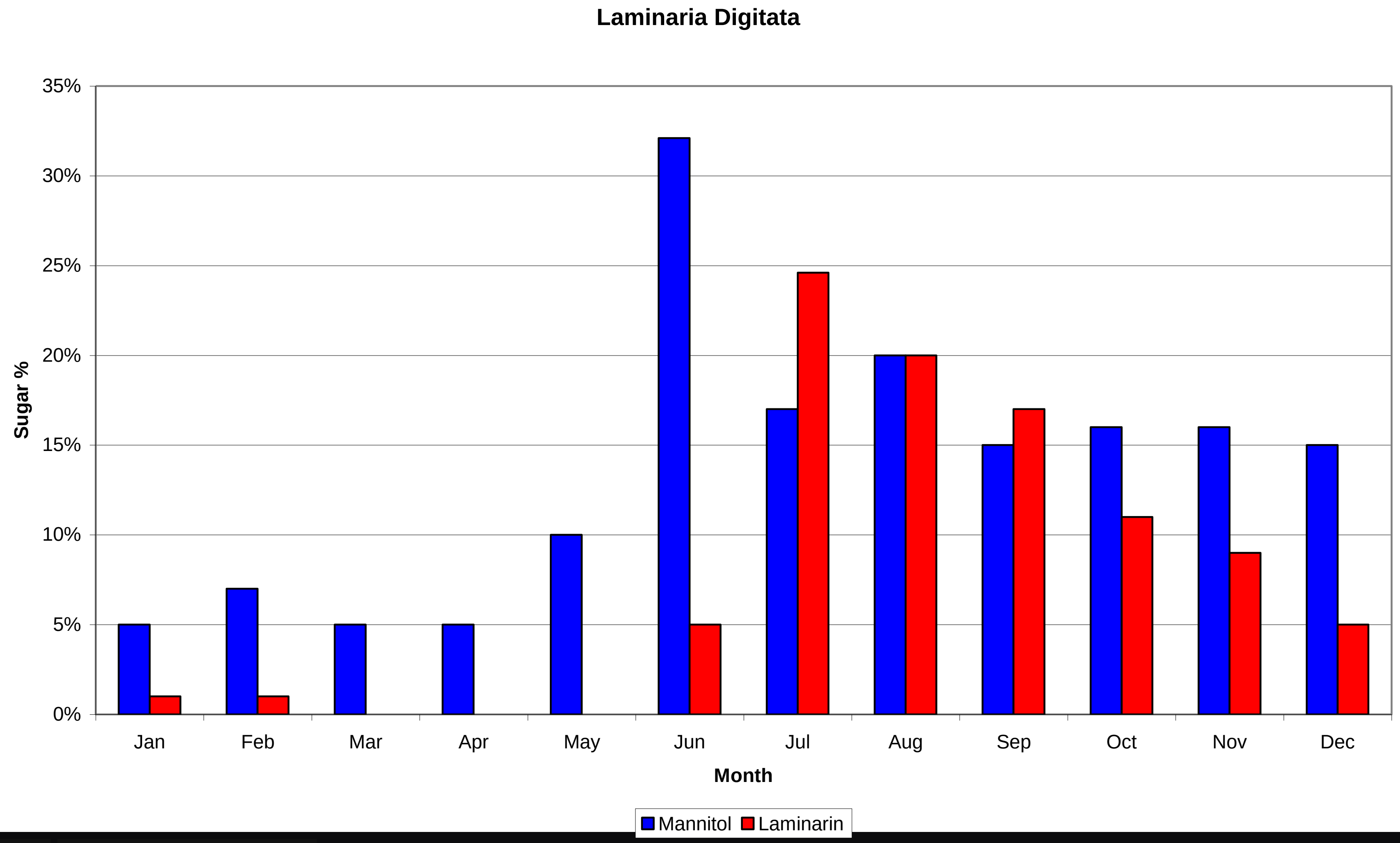
	Laminaria digitata	*Sargassum muticum*	*Saccharina latissima*	*Palmaria palmata*	*Ulva lactuca*
Harvest month	June	June	July	March	February
Sugars					
Total sugars, % d.m.	**14.5**	**7.8**	**17.6**	**40.5**	**11.3**
Glucose	5.9	2.2	6.6	3.8	5.4
Xylose	0.4	0.3	0.2	31.1	1.3
Fucose	1.9	1.1	1.6	0.0	0.0
Mannose	1.9	0.4	0.3	0.0	0.0
Arabinose	0.0	0.0	0.0	0.0	0.0
Galactose	0.7	1.0	0.8	5.5	0.5
Rhamnose	0.1	0.1	0.1	0.0	4.1
Mannitol	3.6	2.7	8.1	0.0	0.0
Total water extrac. % d.m.	25.2 (no mono-)	32.8 (mannitol)	47.9 (mannitol)	32.2(no mono-)	38.3 (no mono-)
EtOH/Toluene extract. % d.m.	3.4	7.9	6.3	6.3	2.6
EtOH extrac. % d.m.	1.3	2.5	3.3	2.0	0.2
Ash (900°C) % d.m.	22.8	22.9	25.0	9.9	18.2
Protein, % d.m. (Kjeldahl)	10.8	16.0	12.4	17.8	23.5

Carbohydrates

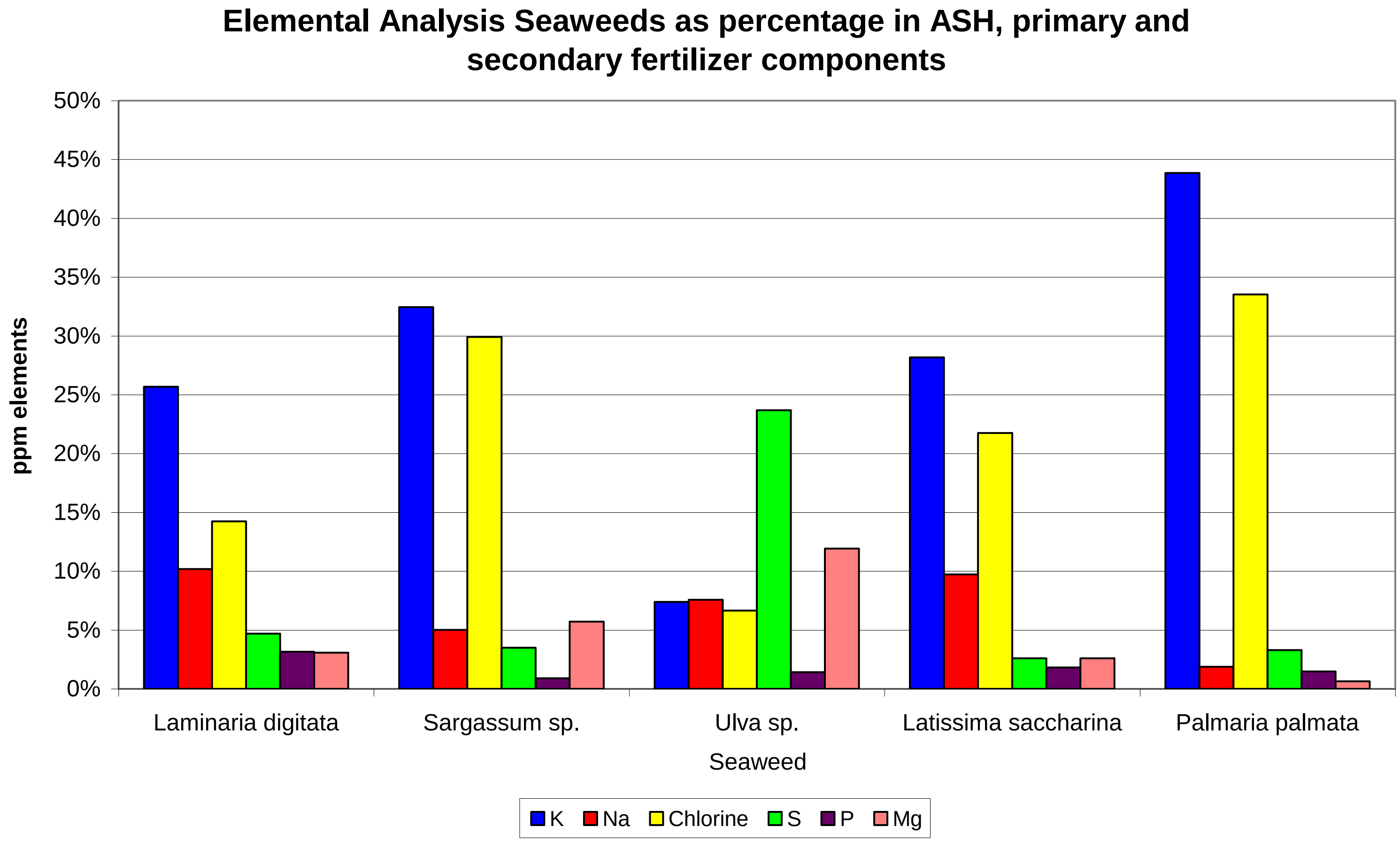


- Carbohydrate profile is highly species specific

Large seasonal variation

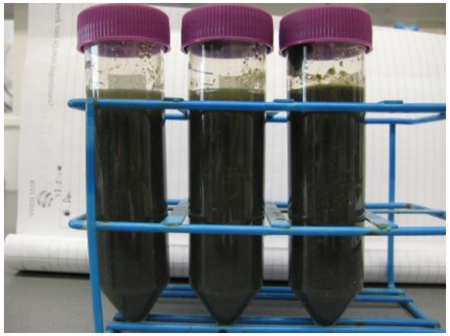


Minerals

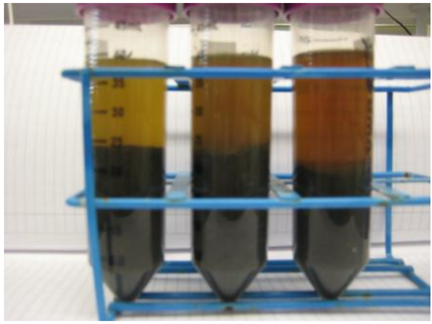


- Plus appreciable amounts of trace elements, incl. B, Mn, Fe, Zn, Cu, Mo, Se,..
- Fertilizer 'ore' or recycling to sea

Fractionation of Laminaria



Optional
Catalyst



Water +
Seaweed

T: 120-160 °C
t: 1-4 h
Liquid:Solid=1:10
Cat: 0-1 M H_2SO_4

Liquid

Solid

- After reaction, separation by centrifugation (10 min, 4000 rpm) and separation of the phases.

Results

- Near-complete liquefaction occurs at relatively mild conditions
- Fractionation requires (very) mild conditions to preserve biochemical structure and functionalities of biomass components
- Mannitol extraction from kelps possible under mild conditions.

Enzymatic hydrolysis

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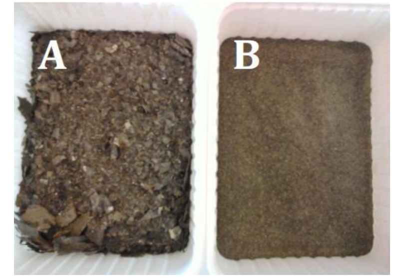
Hydrolysates of *Ulva, Palmaria* and *Saccharina* prepared by:

1) Water extraction
2) Enzymatic hydrolysis

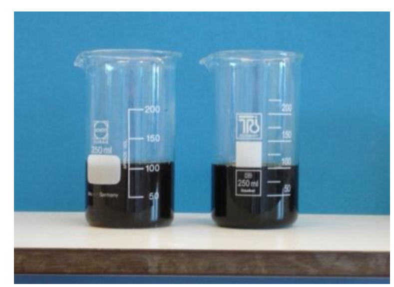


Dried, milled seaweed

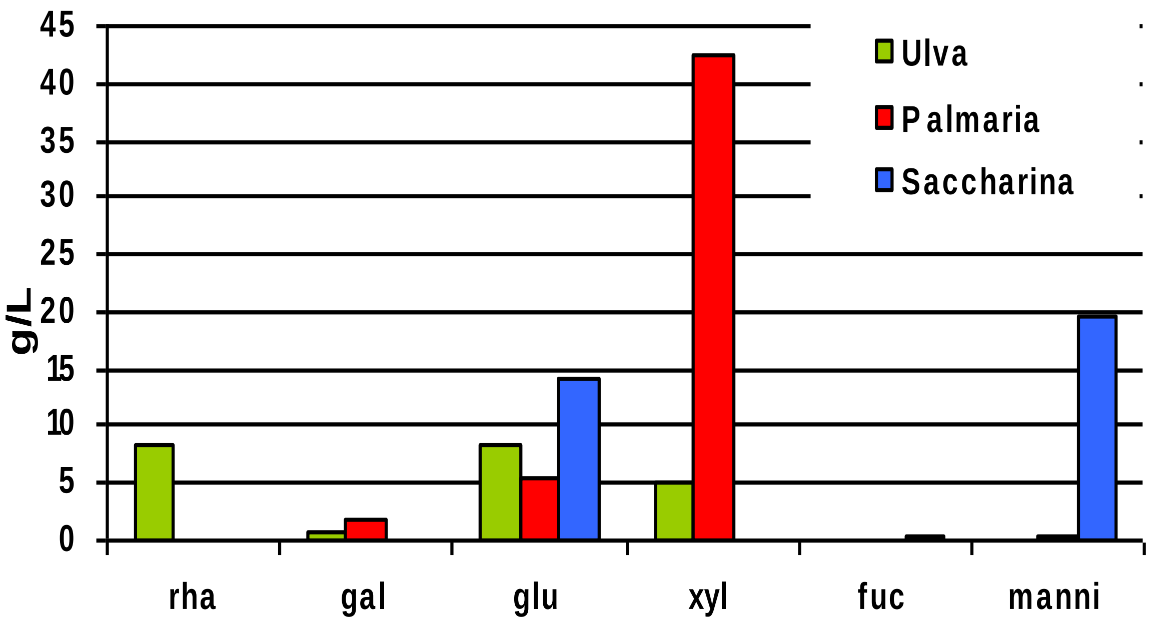
Water extraction

Enzymatic hydrolysis

Centrifugation



Seaweed hydrolysate



Sugar content of seaweed hydrolysates for fermentation

ABE fermentation (1)

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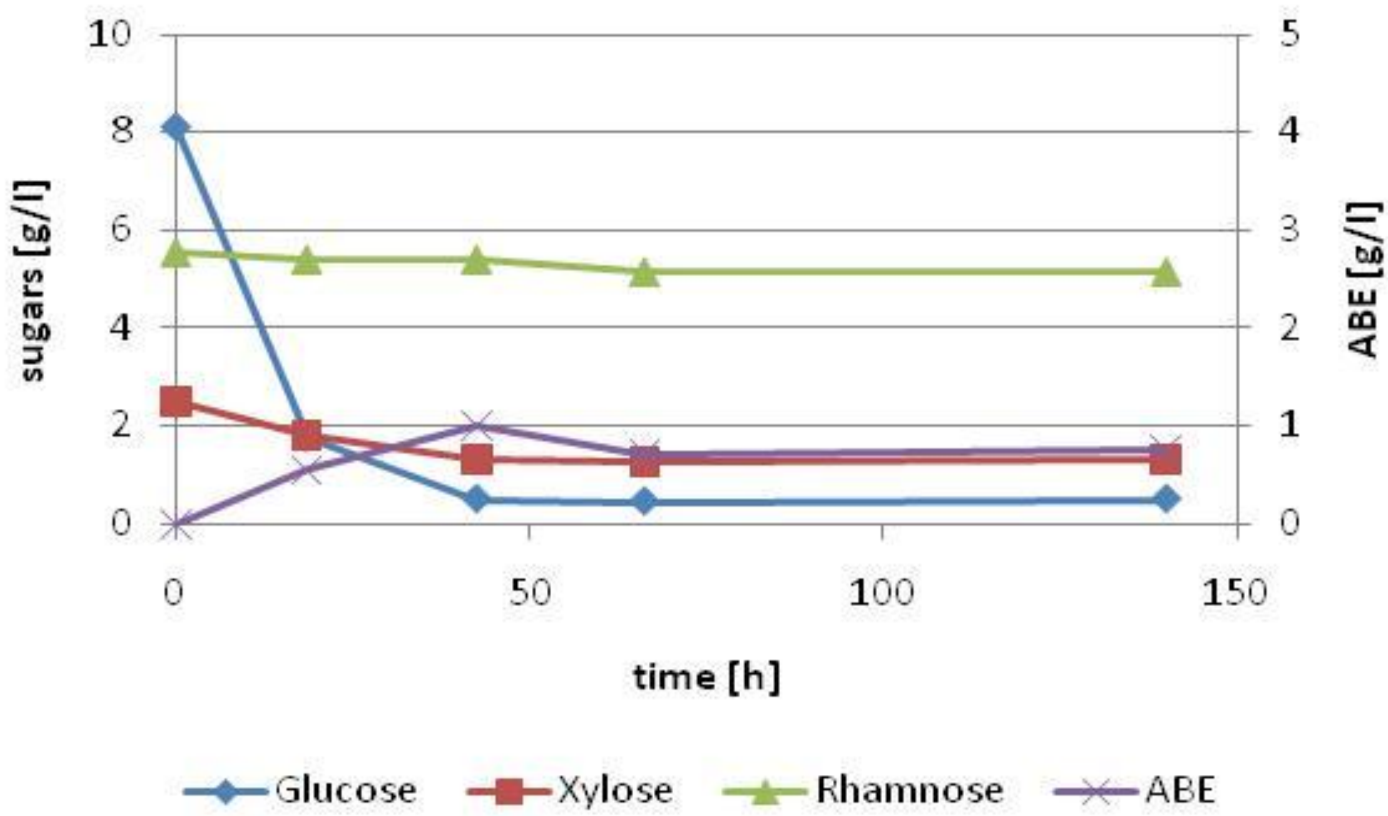
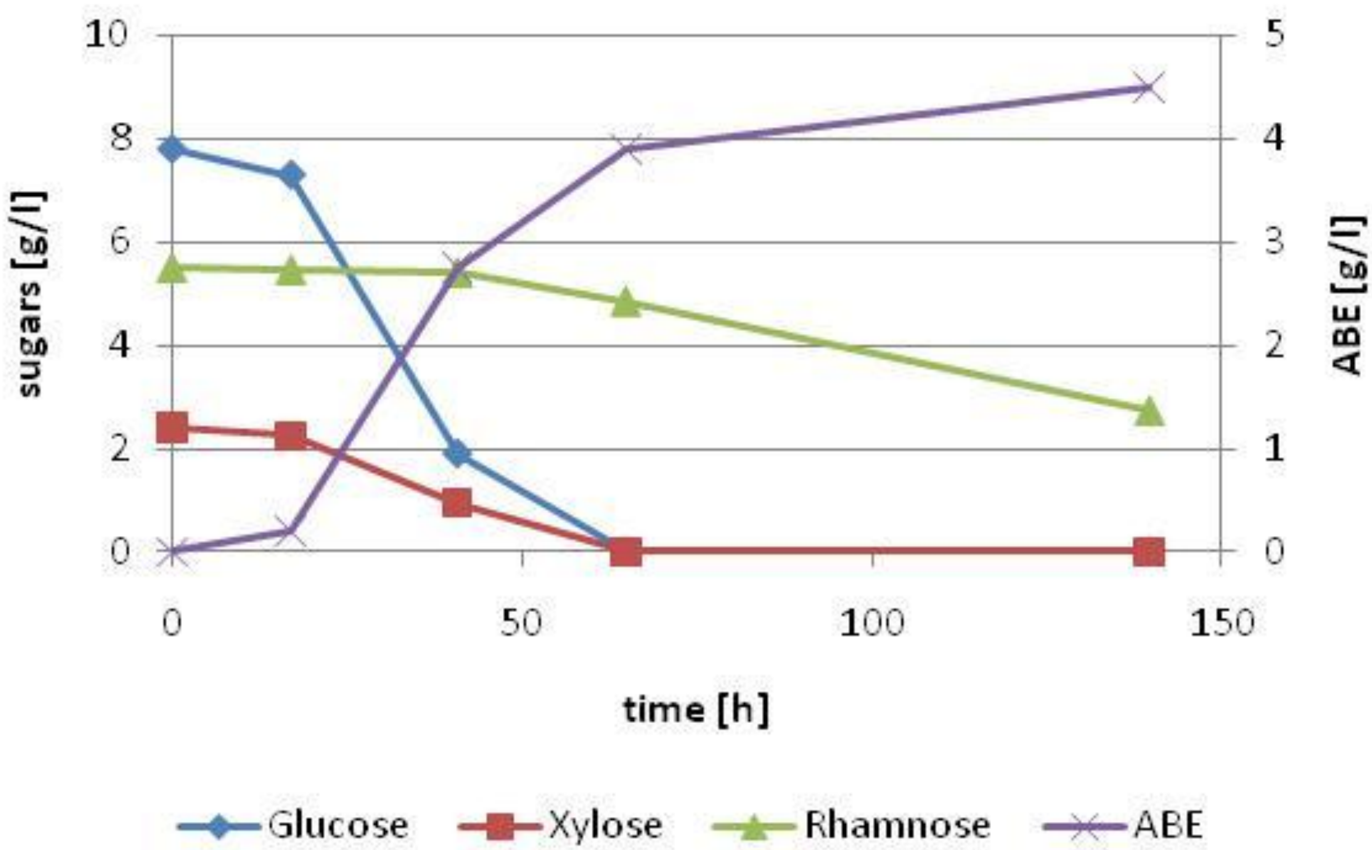


Fermentation of *Ulva lactuca* hydrolysate by *C. acetobutylicum* to acetone, butanol and ethanol (ABE)

ABE fermentation (2)

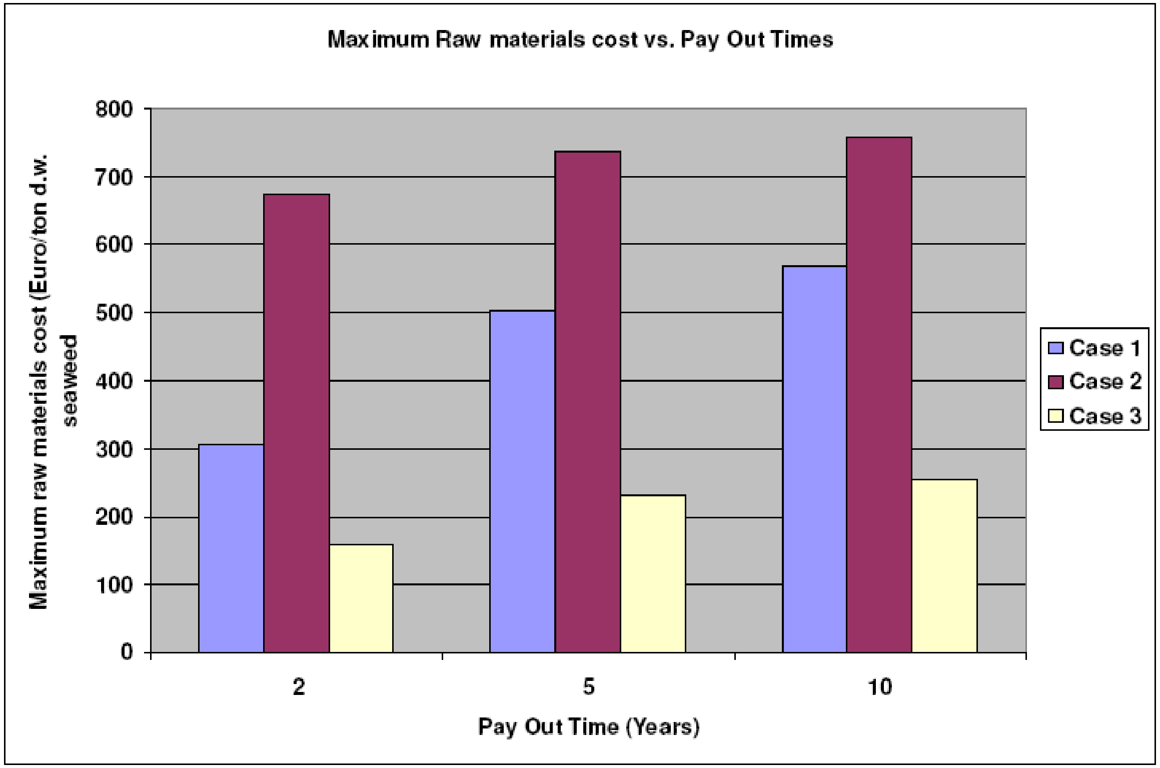


Fermentation of *Ulva lactuca* hydrolysate by ***C. Beijerinckii*** to acetone, butanol and ethanol (ABE):
Higher ABE productivity, rhamnose utilised as well.

Economics: Product spectrum

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

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

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

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

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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 (mostly from published design studies): **50 € (nearshore/floating) - 400 € (offshore) per ton dw.** **Verification required!**

Summary

- Four species of seaweeds biochemically characterized for biorefinery
- Mild fractionation required to preserve chemical structure.
- Seaweed carbohydrates can be hydrolyzed and fermented to ABE.
- Monetizing of all fractions is needed for viable biorefinery

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Acknowledgement

Project Seaweed biorefinery (2009-2013) supported by the Dept. of Economy, Agriculture and Innovation under project no. EOS LT 08027.

http://seaweed.biorefinery.nl

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Thank you for your attention!!

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