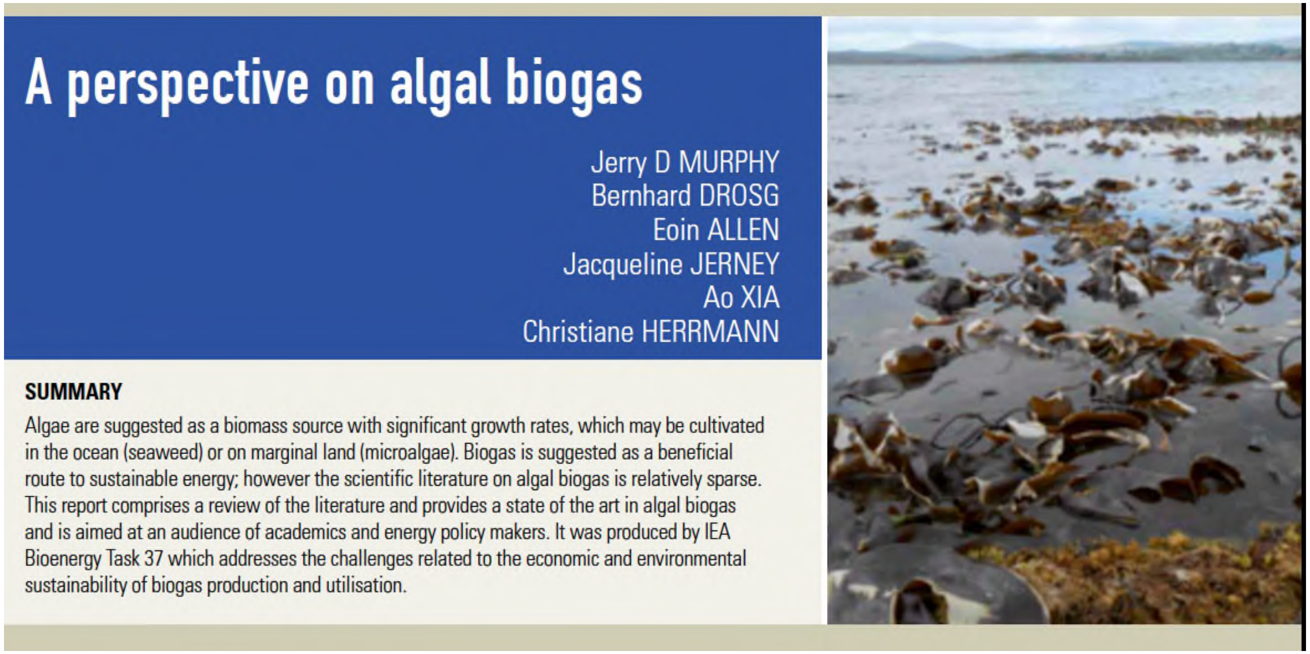
IEA Bioenergy

A Perspective on Algae Biogas



A perspective on algal biogas

Jerry D MURPHY
Bernhard DROSG
Eoin ALLEN
Jacqueline JERNEY
Ao XIA
Christiane HERRMANN

SUMMARY

Algae are suggested as a biomass source with significant growth rates, which may be cultivated in the ocean (seaweed) or on marginal land (microalgae). Biogas is suggested as a beneficial route to sustainable energy; however the scientific literature on algal biogas is relatively sparse. This report comprises a review of the literature and provides a state of the art in algal biogas and is aimed at an audience of academics and energy policy makers. It was produced by IEA Bioenergy Task 37 which addresses the challenges related to the economic and environmental sustainability of biogas production and utilisation.

Jerry D Murphy, Bernhard Drosg, Eoin Allen, Jacqueline Jerney, Ao Xia, Christiane Herrmann
International Energy Agency Bioenergy Conference
Berlin, Germany
27 & 28 October 2015

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Energy is not all about electricity

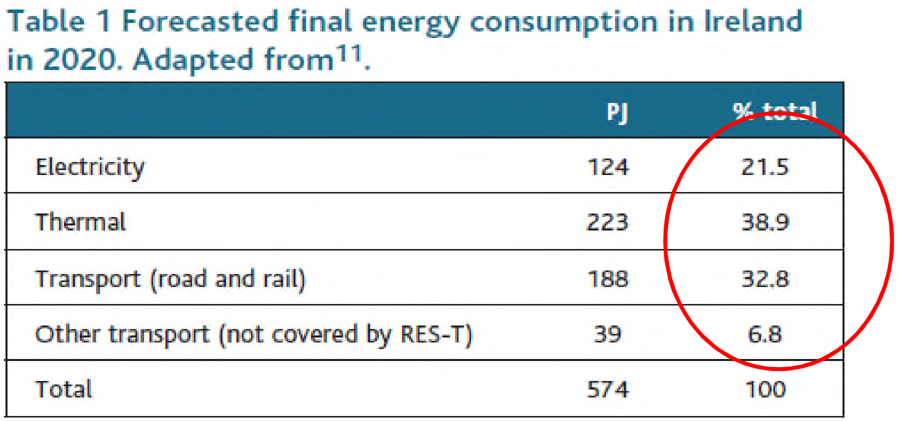

Table 1 Forecasted final energy consumption in Ireland in 2020. Adapted from[11].

	PJ	% total
Electricity	124	21.5
Thermal	223	38.9
Transport (road and rail)	188	32.8
Other transport (not covered by RES-T)	39	6.8
Total	574	100

Directive 2009/28/EC
(Renewable Energy Directive)

- Share of renewable energy sources in transport (RES-T) by 2020 at least 10%

- The share of biofuels from cereal and other starch rich crops, sugar and oil crops limited to 7% as of April 2015.

- Biofuels (from **(1) grasses (2) algae**, municipal solid waste, manures and residues) and **(3) gaseous fuels from non biological origin** shall be considered at 2 times energy content.

- **Also require Green Energy in Industry (FDI) and heating**

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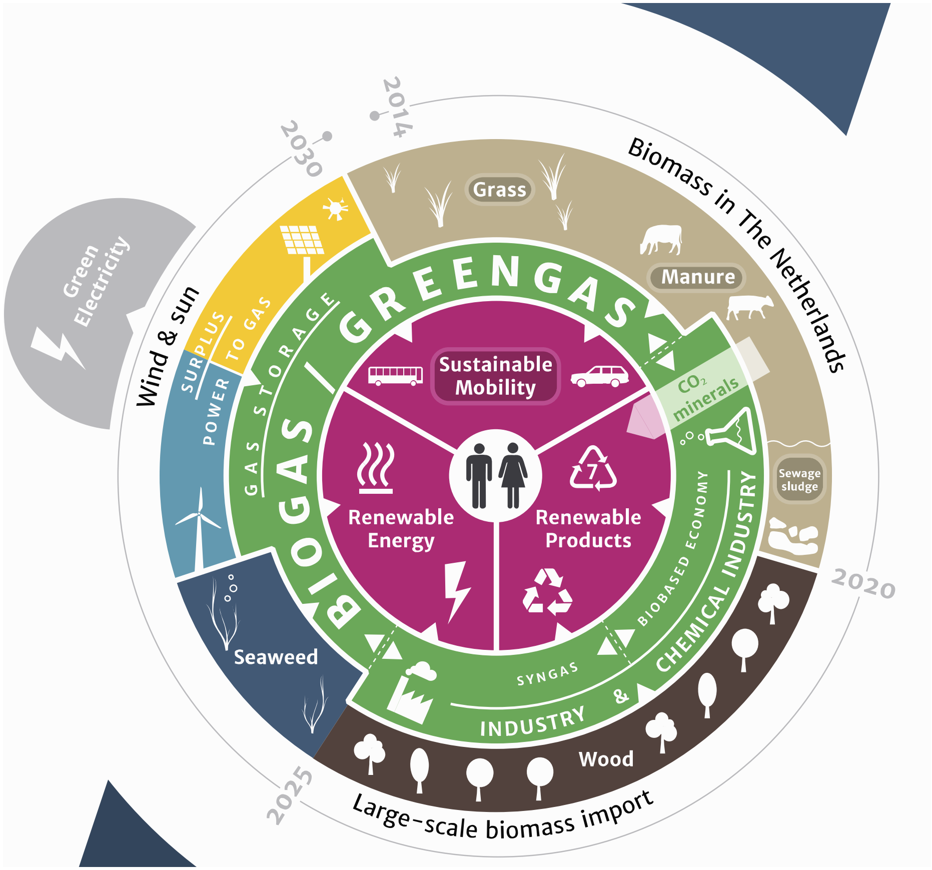
Green (Renewable) Gas



6 European gas grids have committed to 100% green gas in the gas grid by 2050

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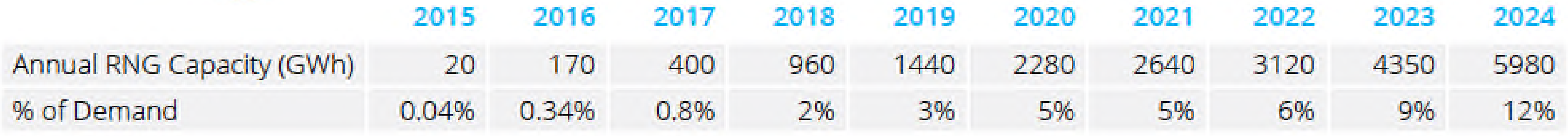
Green Gas in Ireland

Network Development Plan 2015

assessing future demand and supply position



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Annual RNG Capacity (GWh)	20	170	400	960	1440	2280	2640	3120	4350	5980
% of Demand	0.04%	0.34%	0.8%	2%	3%	5%	5%	6%	9%	12%

Major demand for Green Gas is FDI..Factories of the future will use green gas

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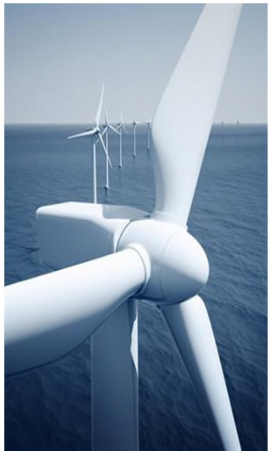

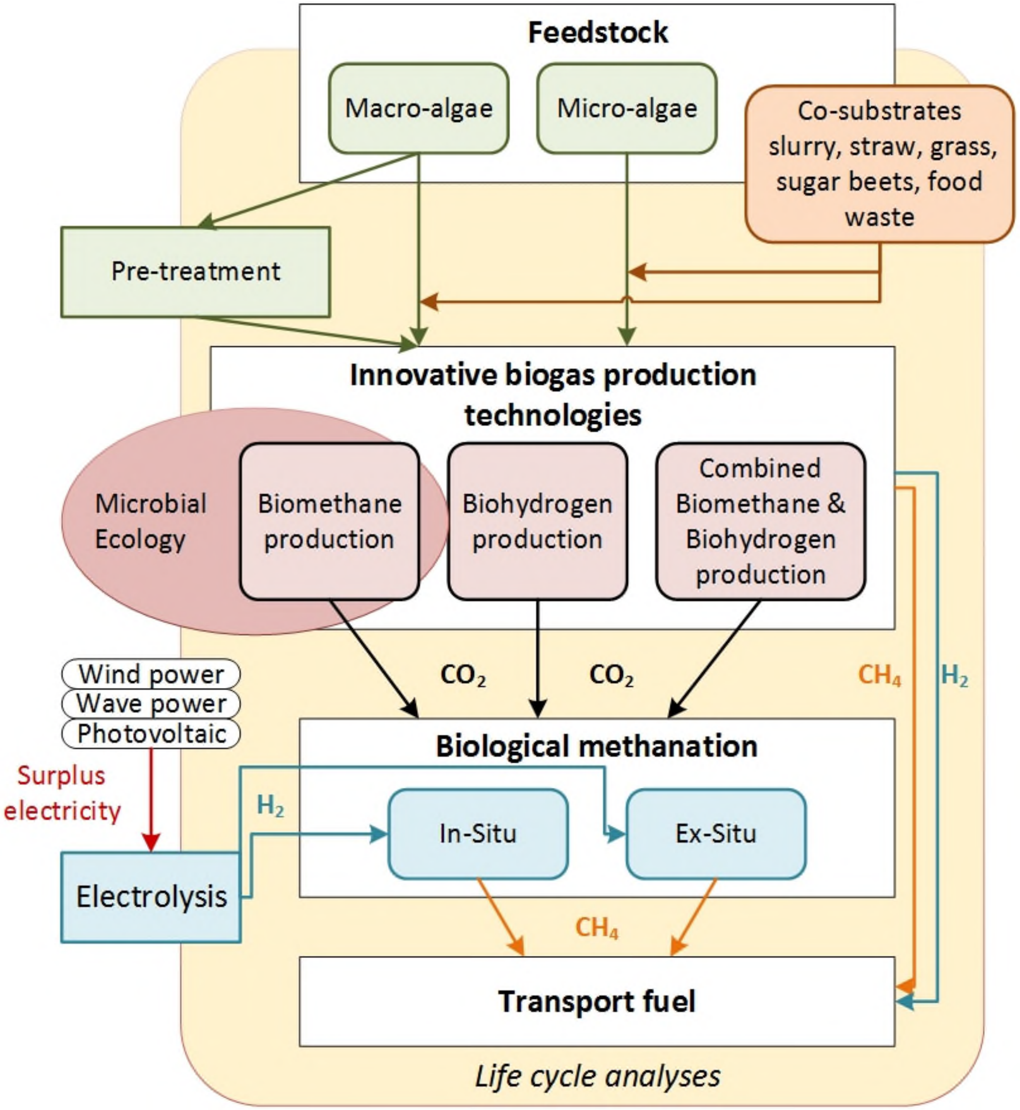

Feedstock

Macro-algae

Micro-algae

Co-substrates slurry, straw, grass, sugar beets, food waste

Pre-treatment

Innovative biogas production technologies

Microbial Ecology

Biomethane production

Biohydrogen production

Combined Biomethane & Biohydrogen production

CO_2

CO_2

CH_4

H_2

Wind power

Wave power

Photovoltaic

Surplus electricity

Electrolysis

H_2

Biological methanation

In-Situ

Ex-Situ

CH_4

Transport fuel

Life cycle analyses

Renewable Gas from marine sources

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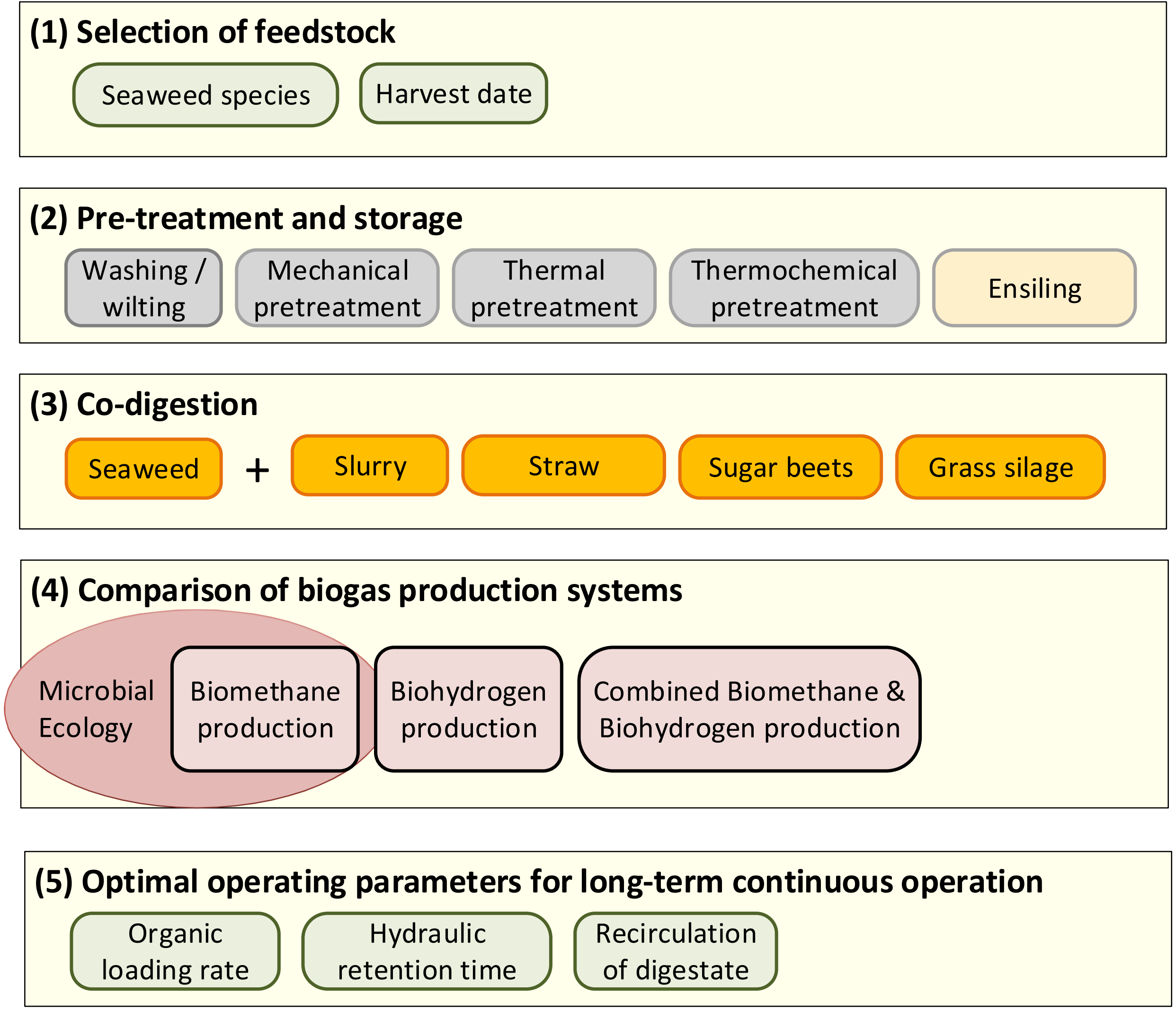
Seaweed as a source of renewable gas



(1) Selection of feedstock

- Seaweed species
- Harvest date

(2) Pre-treatment and storage

- Washing / wilting
- Mechanical pretreatment
- Thermal pretreatment
- Thermochemical pretreatment
- Ensiling

(3) Co-digestion

Seaweed + Slurry, Straw, Sugar beets, Grass silage

(4) Comparison of biogas production systems

- Microbial Ecology
- Biomethane production
- Biohydrogen production
- Combined Biomethane & Biohydrogen production

(5) Optimal operating parameters for long-term continuous operation

- Organic loading rate
- Hydraulic retention time
- Recirculation of digestate

Algal blooms: Green seaweed**,** *Ulva lactuca*

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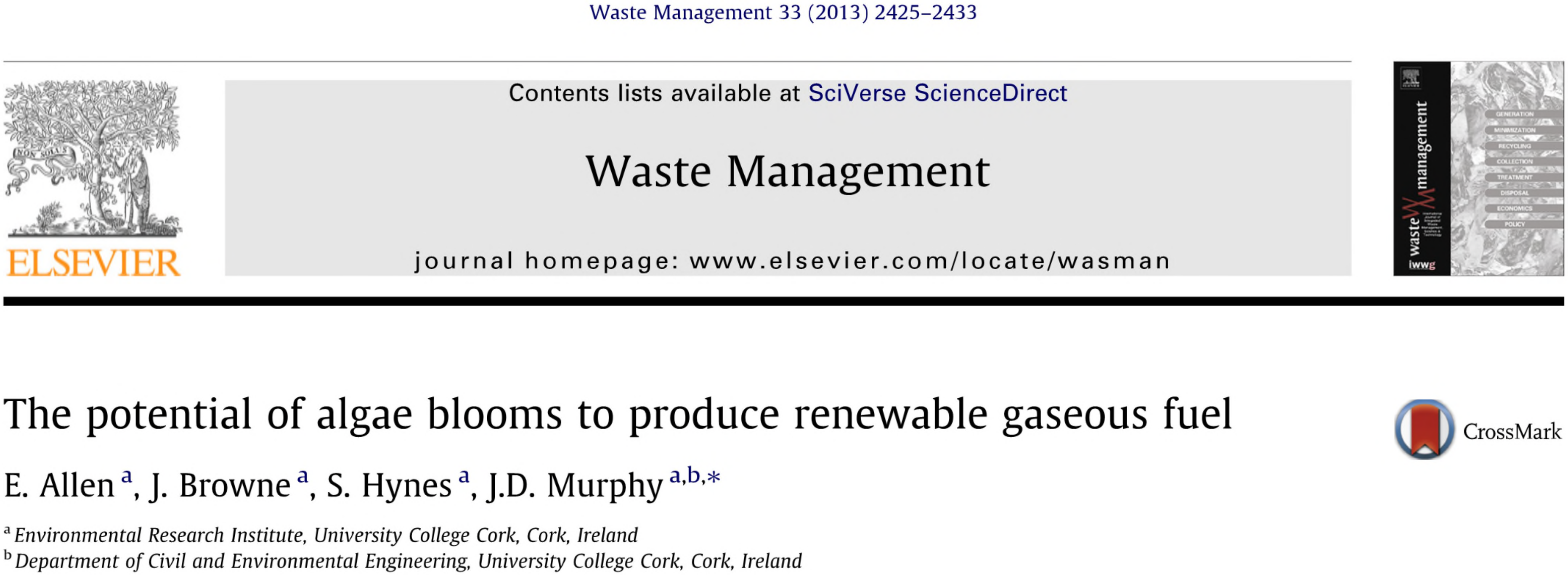

Waste Management 33 (2013) 2425–2433

Contents lists available at SciVerse ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

The potential of algae blooms to produce renewable gaseous fuel

E. Allen [a], J. Browne [a], S. Hynes [a], J.D. Murphy [a,b,*]

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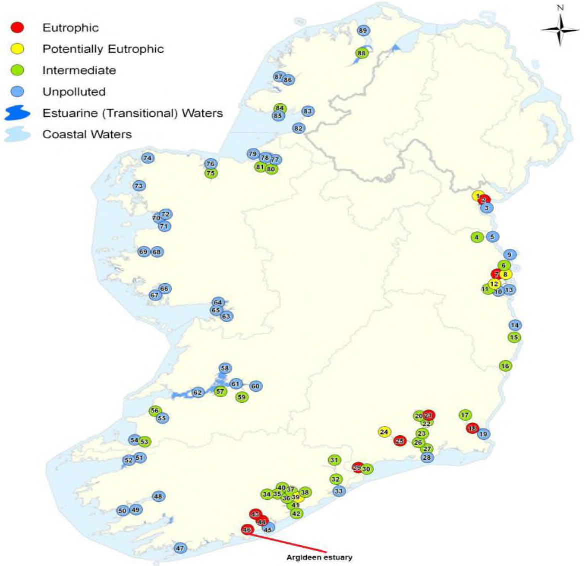
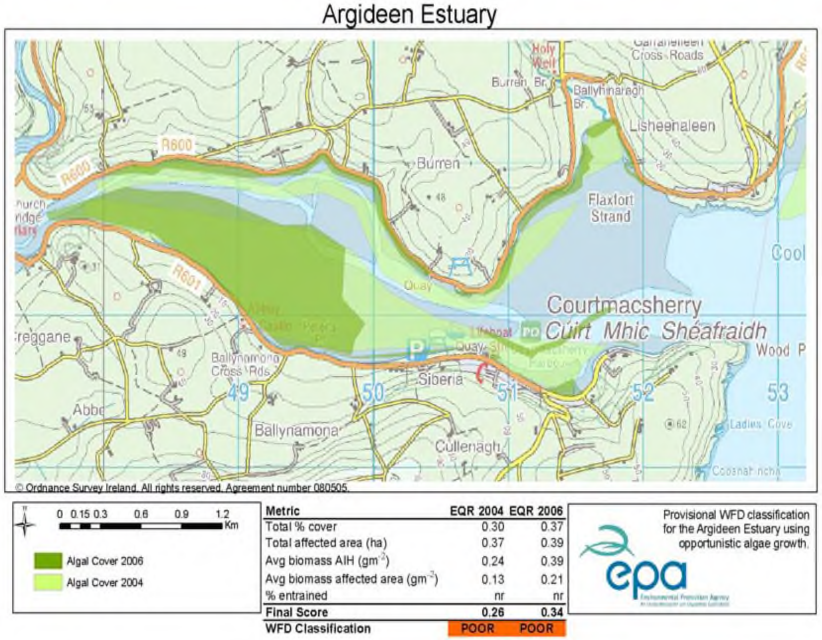
Green Seaweed



10,000 t DS/a arise in Argideen,

Sufficient to power 265 cars

100,000 t DS/a arise in Lannion Bay, Brittany



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Metric	EQR 2004	EQR 2006
Total % cover	0.30	0.37
Total affected area (ha)	0.37	0.39
Avg biomass AIH (gm^{-2})	0.24	0.39
Avg biomass affected area (gm^{-2})	0.13	0.21
% entrained	nr	nr
Final Score	**0.26**	**0.34**
WFD Classification	POOR	POOR

Provisional WFD classification for the Argideen Estuary using opportunistic algae growth.

Batch mono- and co-digestion of seaweed with slurry

Substrate	BMP yield ($L\ CH_4\ kg^{-1}\ VS$)	C:N ratio	Increased yield in co-digestion
Slurry	136	19.8	
Dried *U.lactuca*	226	7.1	
Fresh *U.lactuca*	205	9.1	
Co-digestion of U. lactuca:			
75% Fresh	220	11.8	+ 17.0%
50% Fresh	200	14.5	+ 17.0%
25% Fresh	183	17.1	+ 19.6%
75% Dried	210	10.3	+ 3.4%
50% Dried	193	13.5	+ 6.7%
25% Dried	186	16.6	+ 17.7%

Co-digestion of fresh and dried *U. lactuca* with dairy slurry in BMP tests: ratio of 25%, 50% and 75% seaweed (VS)

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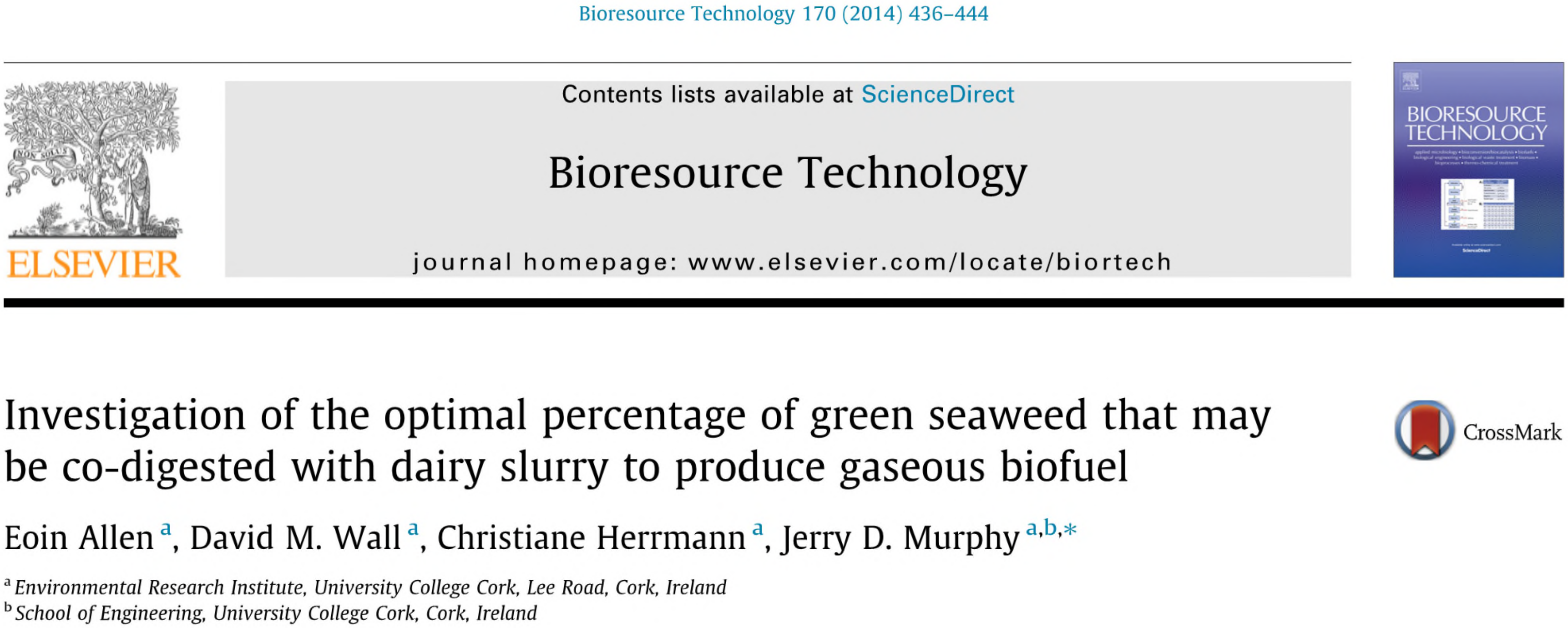

Bioresource Technology 170 (2014) 436–444

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Investigation of the optimal percentage of green seaweed that may be co-digested with dairy slurry to produce gaseous biofuel

Eoin Allen [a], David M. Wall [a], Christiane Herrmann [a], Jerry D. Murphy [a,b,*]

[a] Environmental Research Institute, University College Cork, Lee Road, Cork, Ireland
[b] School of Engineering, University College Cork, Cork, Ireland

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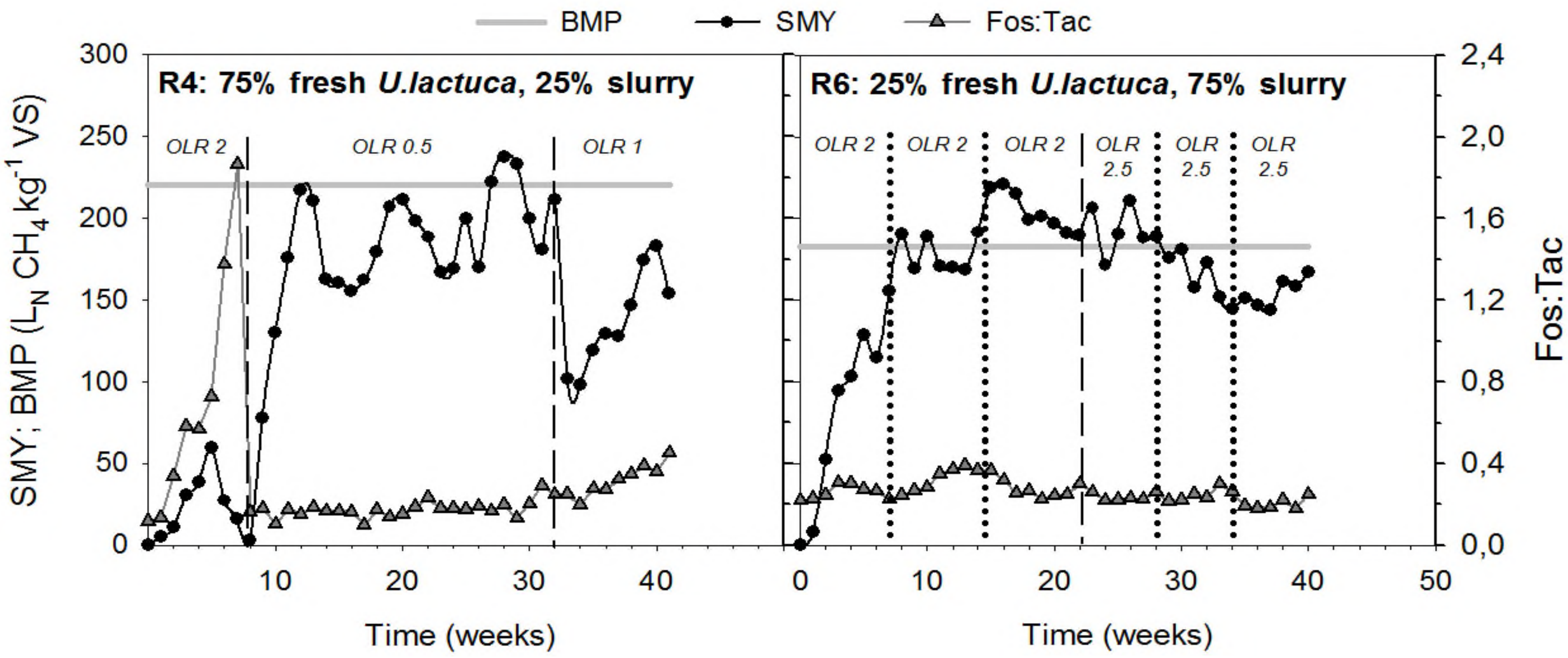
Higher Seaweed Input

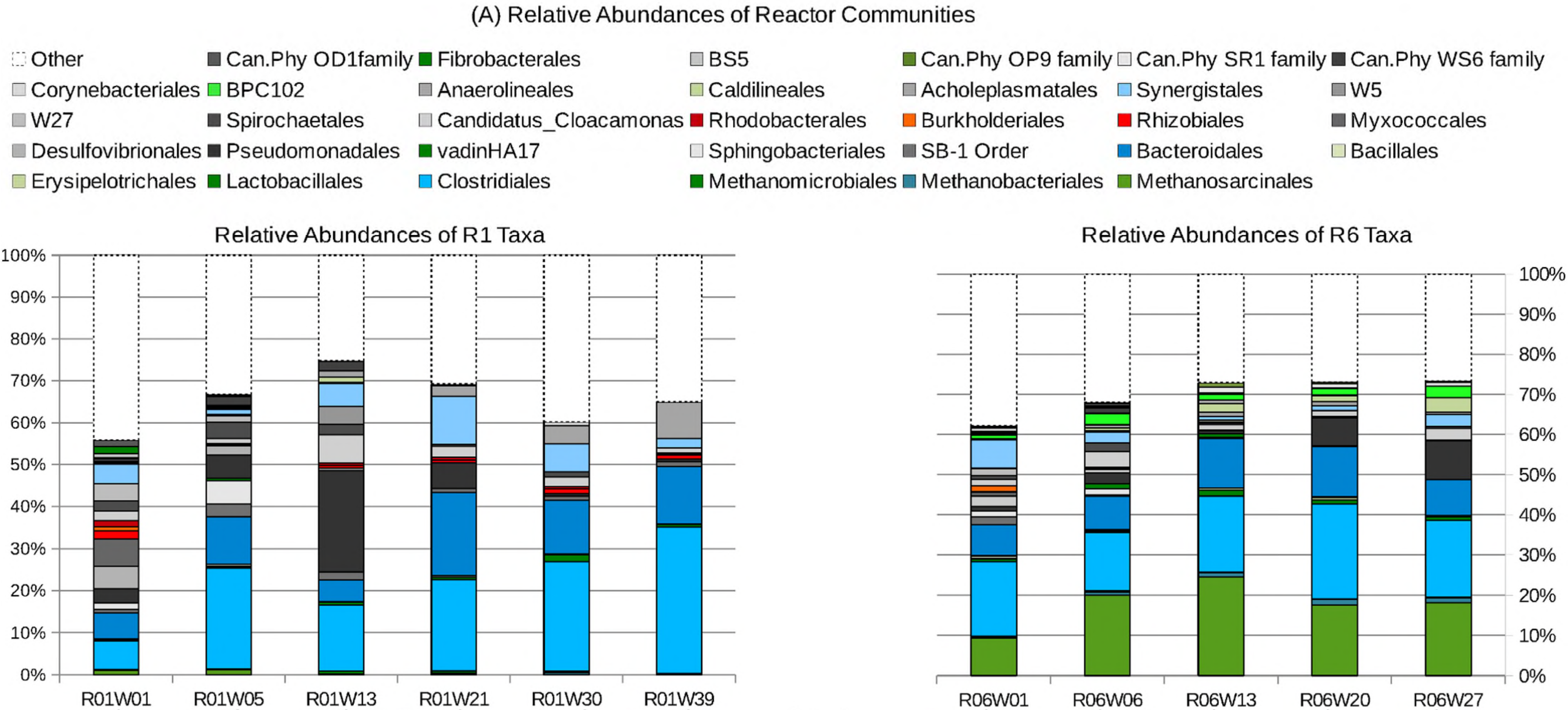
Higher Dairy Slurry Input

Long term co-digestion of Seaweed & Slurry



- optimum mix: 25% fresh *U. lactuca* and 75% dairy slurry by VS content
- levels in excess of 75% *U. lactuca* are not recommended
- optimum loading rate: 2.5 kg VS m^{-3} d^{-1}

Taxonomy of Ulva Digesters



High-Ulva Reactor: higher diversity; many marine-assoc. species; vanishing methanogens; 'dominating' species

Low-Ulva Reactor: large methanogen population (10-25%) converting acetic acid; species evenly distributed

Alan DW Dobson; Jamie A Fitzgerald; Eoin Allen; David M Wall; Stephen A Jackson; Jerry D Murphy (2015) Methanosarcina play an important role in Anaerobic co-digestion of the Seaweed Ulva lactuca: Metagenomics structure and predicted metabolism of functional microbial communities. PLOS ONE (submitted August 2015).

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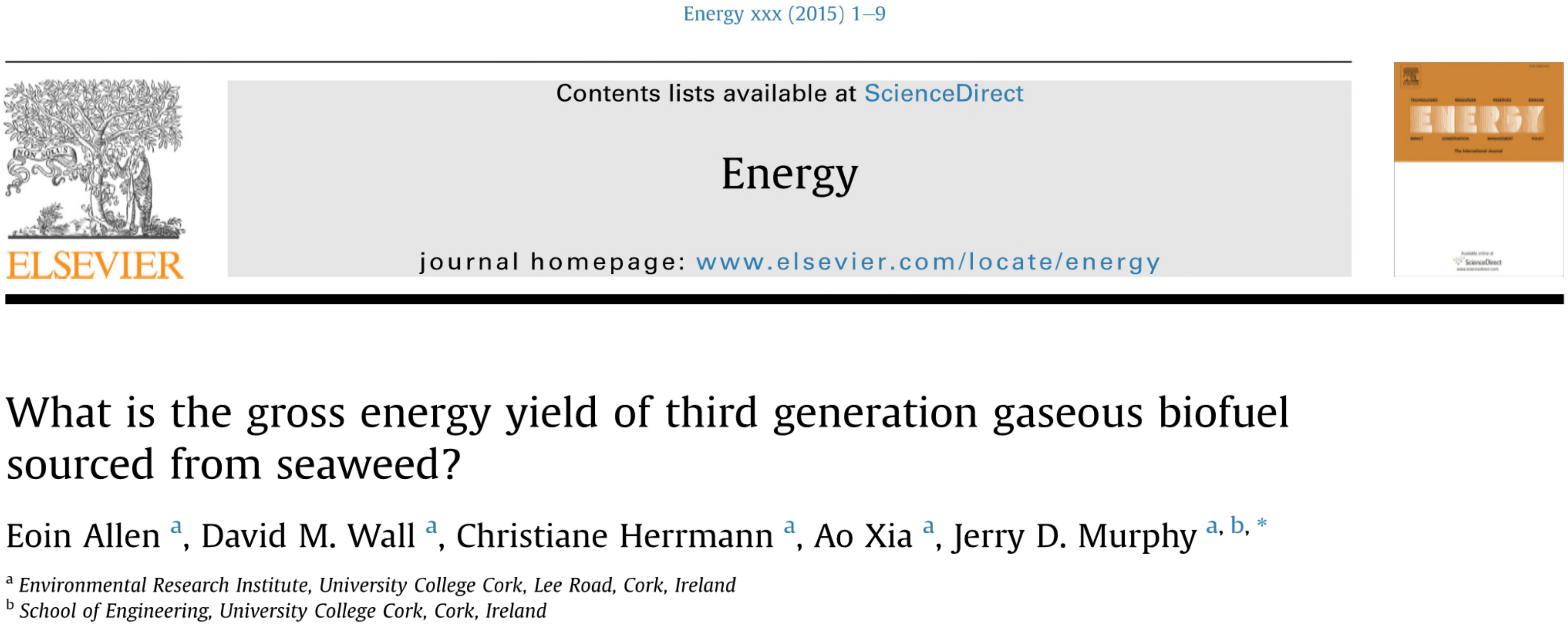
Energy Yield of brown seaweeds



Energy xxx (2015) 1–9

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

What is the gross energy yield of third generation gaseous biofuel sourced from seaweed?

Eoin Allen [a], David M. Wall [a], Christiane Herrmann [a], Ao Xia [a], Jerry D. Murphy [a, b, *]

[a] *Environmental Research Institute, University College Cork, Lee Road, Cork, Ireland*
[b] *School of Engineering, University College Cork, Cork, Ireland*

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Brown Seaweed in Roaring Water Bay

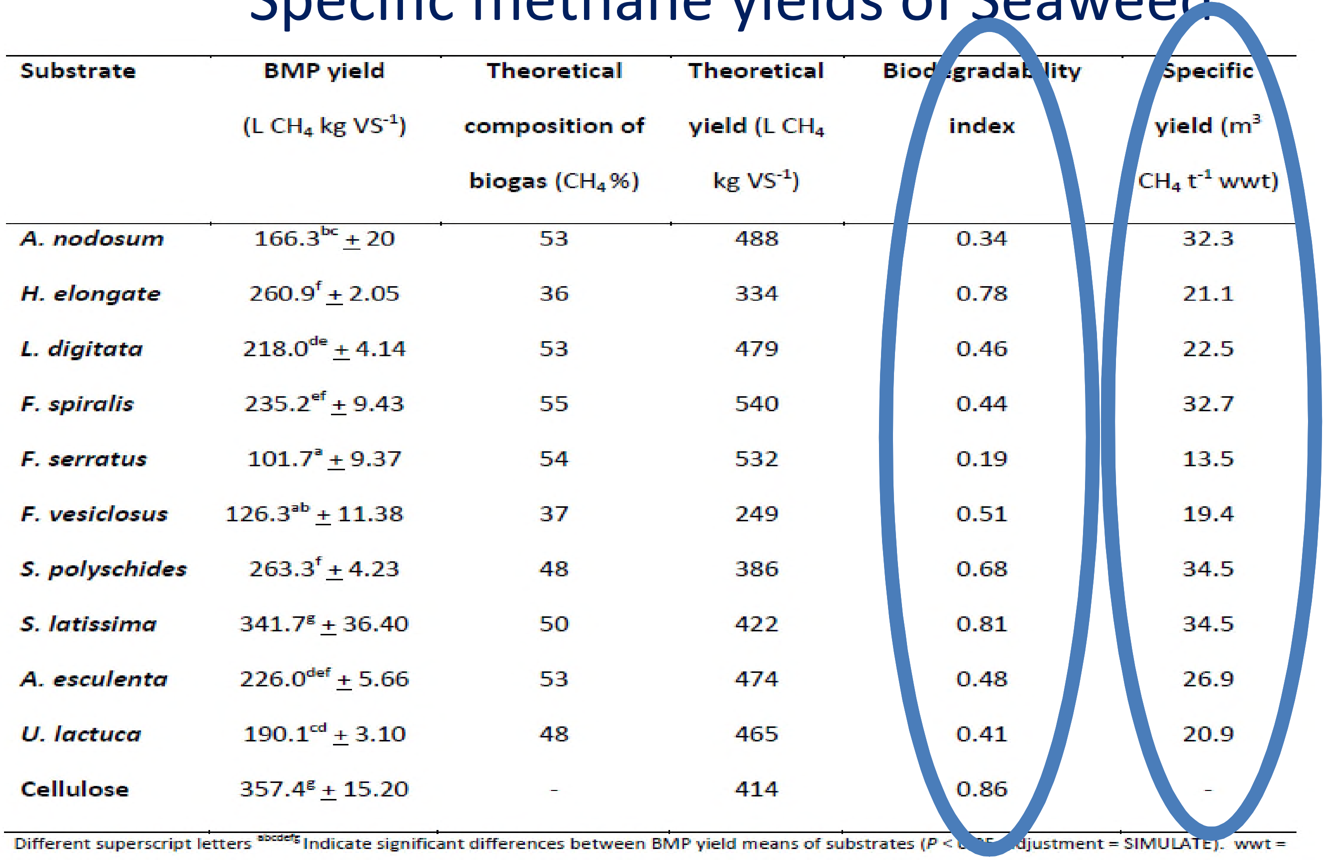
Ascophyllum nodosum

Saccharina latissima

Laminaria digitata

Fucus serratus

Specific methane yields of Seaweed



Substrate	BMP yield (L CH_4 kg VS^{-1})	Theoretical composition of biogas (CH_4 %)	Theoretical yield (L CH_4 kg VS^{-1})	Biodegradability index	Specific yield (m^3 CH_4 t^{-1} wwt)
A. nodosum	$166.3^{bc} \pm 20$	53	488	0.34	32.3
H. elongate	$260.9^{f} \pm 2.05$	36	334	0.78	21.1
L. digitata	$218.0^{de} \pm 4.14$	53	479	0.46	22.5
F. spiralis	$235.2^{ef} \pm 9.43$	55	540	0.44	32.7
F. serratus	$101.7^{a} \pm 9.37$	54	532	0.19	13.5
F. vesiclosus	$126.3^{ab} \pm 11.38$	37	249	0.51	19.4
S. polyschides	$263.3^{f} \pm 4.23$	48	386	0.68	34.5
S. latissima	$341.7^{g} \pm 36.40$	50	422	0.81	34.5
A. esculenta	$226.0^{def} \pm 5.66$	53	474	0.48	26.9
U. lactuca	$190.1^{cd} \pm 3.10$	48	465	0.41	20.9
Cellulose	$357.4^{g} \pm 15.20$	-	414	0.86	-

Different superscript letters ^{abcdefg} Indicate significant differences between BMP yield means of substrates ($P <$ [illegible] adjustment = SIMULATE). wwt = wet weight.

Table 2. Biomethane production for seaweed using results of BMP analysis and theoretical analysis.

Energy yield per hectare of Seaweed

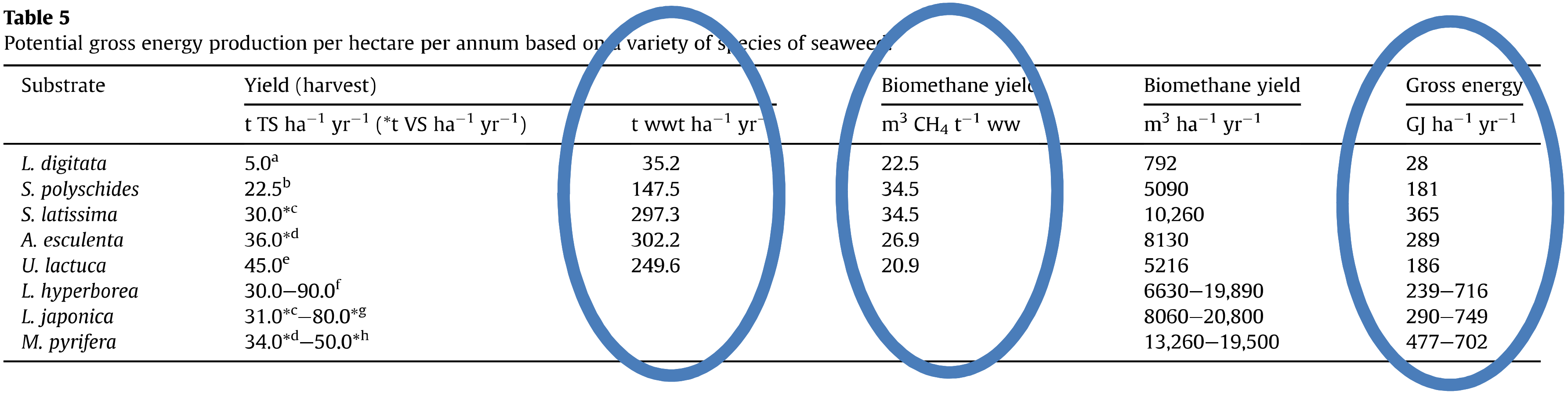


Table 5

Potential gross energy production per hectare per annum based on a variety of species of seaweed.

Substrate	Yield (harvest)		Biomethane yield	Biomethane yield	Gross energy
	t TS ha^{-1} yr^{-1} (*t VS ha^{-1} yr^{-1})	t wwt ha^{-1} yr^{-1}	m^3 CH$_4$ t^{-1} ww	m^3 ha^{-1} yr^{-1}	GJ ha^{-1} yr^{-1}
L. digitata	5.0[a]	35.2	22.5	792	28
S. polyschides	22.5[b]	147.5	34.5	5090	181
S. latissima	30.0*[c]	297.3	34.5	10,260	365
A. esculenta	36.0*[d]	302.2	26.9	8130	289
U. lactuca	45.0[e]	249.6	20.9	5216	186
L. hyperborea	30.0–90.0[f]			6630–19,890	239–716
L. japonica	31.0*[c]–80.0*[g]			8060–20,800	290–749
M. pyrifera	34.0*[d]–50.0*[h]			13,260–19,500	477–702

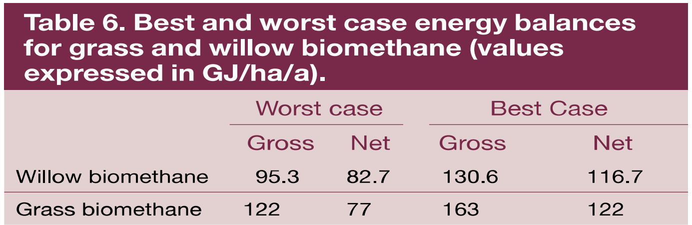


Table 6. Best and worst case energy balances for grass and willow biomethane (values expressed in GJ/ha/a).

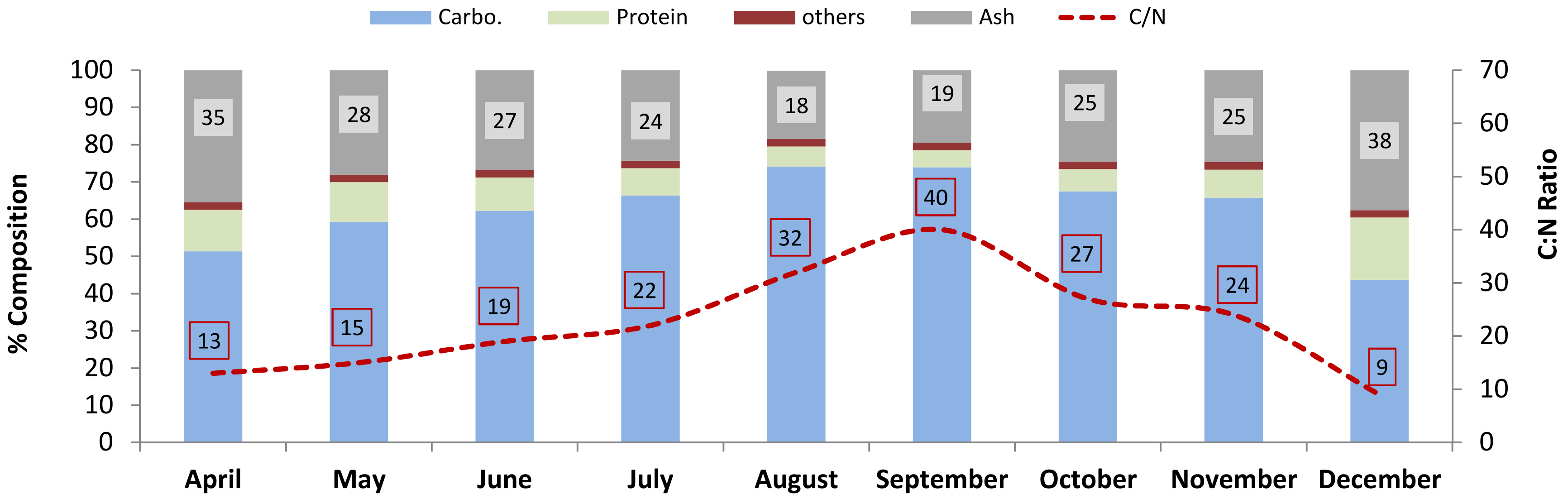
	Worst case		Best Case	
	Gross	Net	Gross	Net
Willow biomethane	95.3	82.7	130.6	116.7
Grass biomethane	122	77	163	122

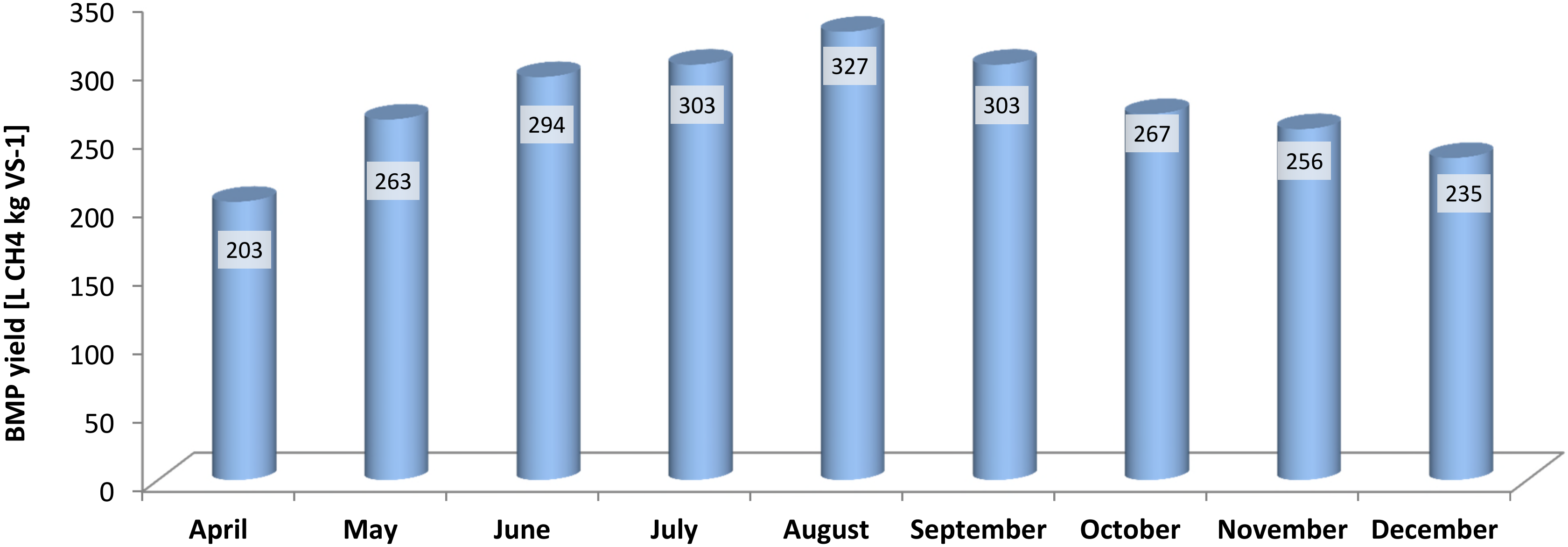
Seasonal variation in chemical composition (*L. digitata*)

	Proximate Analysis					Ultimate Analysis				
	MC %	**TS %**	**VS %**	**VS% TS**	**Ash %**	**C %**	**H %**	**N %**	**O %**	**C:N**
January	89	11	7	61	39	26	3	4	28	7
February	89	11	7	64	36	26	4	4	30	7
March	90	10	6	67	33	30	4	4	29	8
April	86	14	9	65	35	30	4	2	28	13
May	88	12	9	73	28	32	5	2	33	15
June	86	14	10	73	27	34	5	2	32	19
July	86	14	11	77	24	33	5	2	37	22
August	**80**	**20**	**16**	**82**	**18**	37	6	1	38	**32**
September	81	19	16	82	19	37	5	1	39	40
October	84	16	12	76	25	33	5	1	37	27
November	85	15	11	75	25	37	5	2	32	24
December	**92**	**8**	**5**	**60**	**38**	31	4	3	21	**9**

Muhammad, R.T., Ao, X., Murphy, J.D. (2015). Seasonal variation and biomethane potential of Irish brown seaweeds, ***Bioresource Technology*** to be submitted Nov, 2015

Seasonal variation in biochemical composition
L. digitata





Integrated Multi-trophic aquaculture

Aquaculture contributed 24 million tonnes of algae in 2012

Aquaculture contributed 66.6 million tonnes of fish in 2012, 42 % of global production.

Carbon footprint is 10 times less than for beef per unit of energy in food

Integrated multi-trophic aquaculture can reduce pollution through co-culture of seaweed and mussels that utilise waste disposed from fish.

A model is investigated which would provide 1.25% of energy in transport in the EU from seaweed. This would involve annual production of 168Mt of seaweed (in excess of present world harvest) integrated with 13Mt of farmed salmon.

The model proposes 2603 anaerobic digesters, each treating 64,500 t/a of *Saccharina latissima* in coastal digesters

JACOB, A., XIA, A., GUNNING, D., BURNELL, G., MURPHY, J.D., Is it beneficial to associate a seaweed biofuel industry with Integrated Multi-trophic Aquaculture? International Conference on Environmental Science and Development (submitted)

Cultivating Seaweed

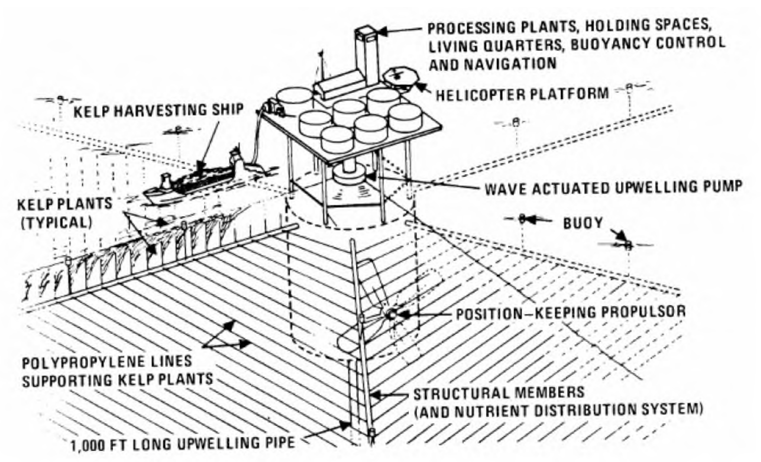
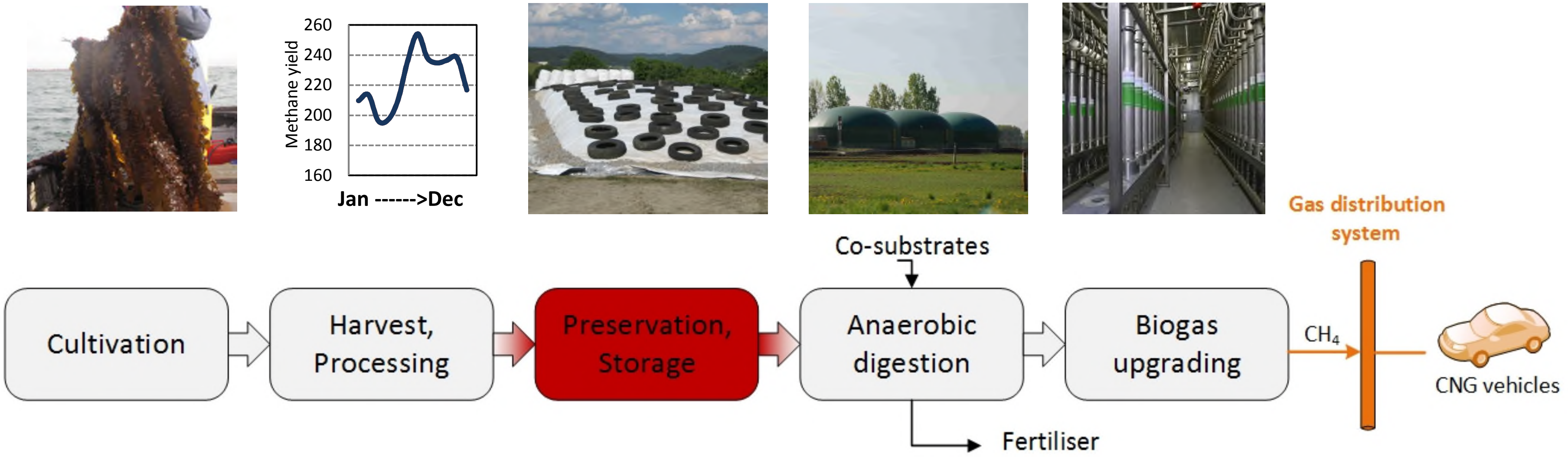


Figure 1. Conceptual design of 405 ha (1,000 acre) ocean food and energy farm unit. (Leese 1976) Source: David Chynoweth.

Position adjacent to fish farms
Increased yields of seaweed as compared to pristine waters
Clean water of excess nutrients
Harvest when yield is highest

Ensiling of seaweed- *Background*



Cultivation → Harvest, Processing → Preservation, Storage → Anaerobic digestion → Biogas upgrading

Co-substrates

Fertiliser

CH_4

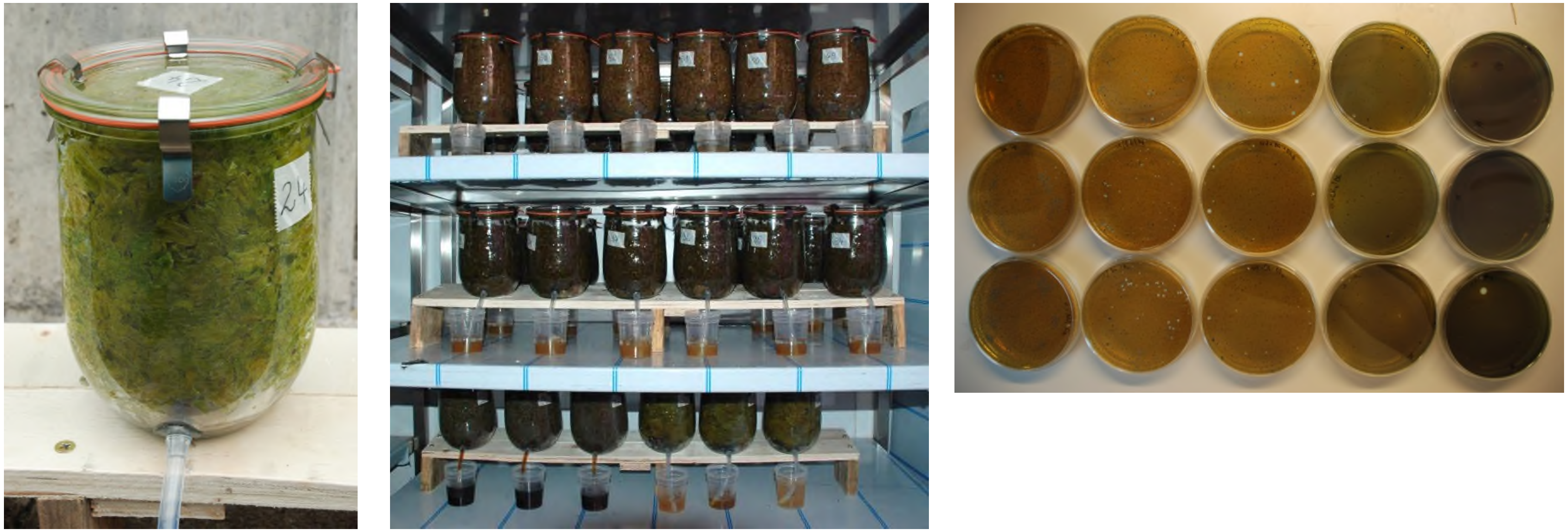
Gas distribution system

CNG vehicles

Ensiling of seaweed

Experimental approach:

- Ensiling of 5 seaweed species: *U. lactuca, A. nodosum, L. digitata, S. polyschides, S. latissima*
- Ensiling in 1-Litre lab scale silos, collection of silage effluent
- Time course experiments: storage duration 2, 4, 7, 14, 90 days at 20°C
- Analyses of ensilability, products of silage fermentation, counts of lactic acid bacteria, biomethane potential



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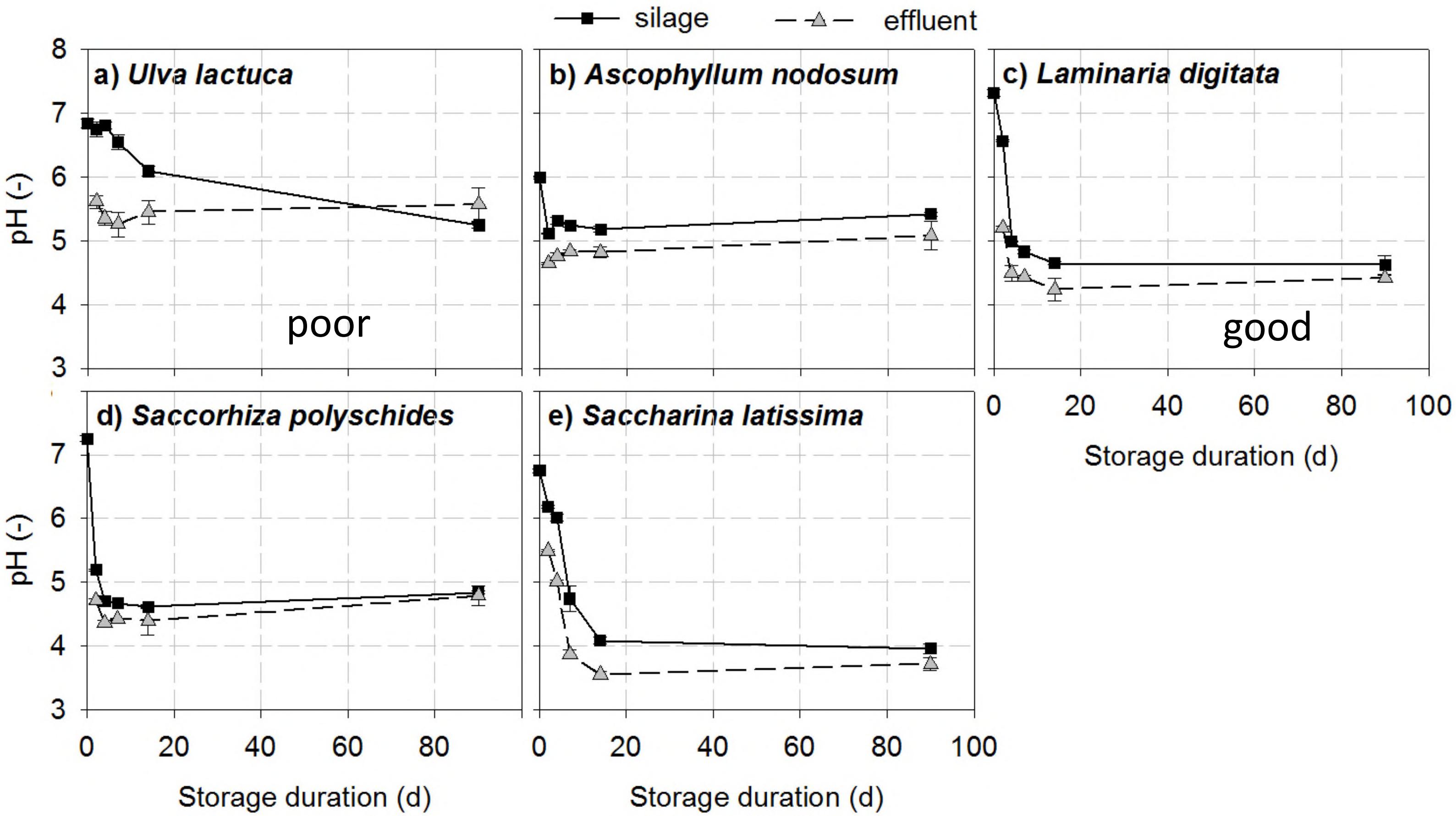
Ensiling of seaweed- *Results*



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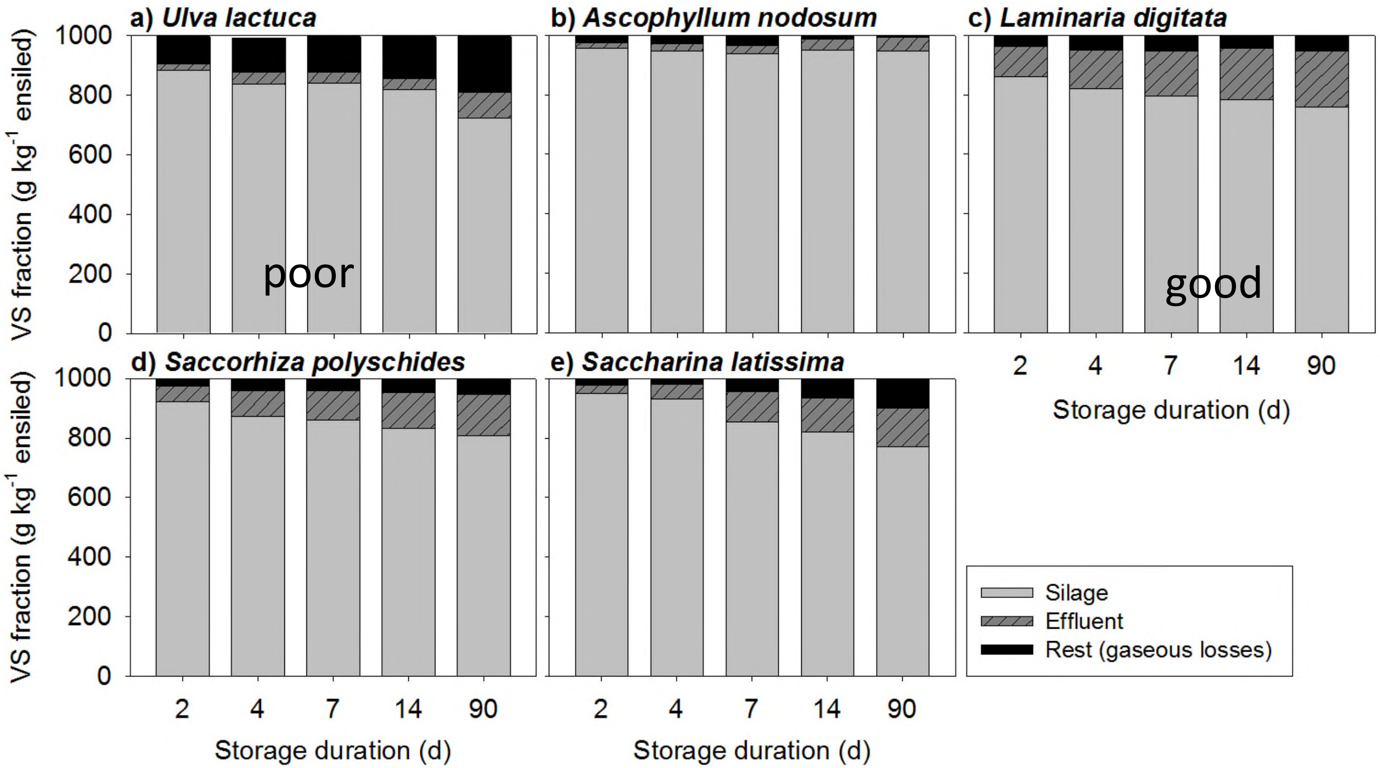
Ensiling of macro-algae - *Results*



- Gaseous storage losses 0.3 – 19% after 90 days of storage, dependent on seaweed species
- Large amounts of effluent released – up to 28% of the ensiled biomass (FM) after 90 days of storage

Ensiling of seaweed - *Results*

Seaweed species	**Storage**	**BMP yield (L kg^{-1} VS$_{added}$)**	**BMP yield (L kg^{-1} VS$_{orig}$)**
U. lactuca	Fresh	247.2^{gh}	247.2^{c}
	Silage	314.1^{de}	255.8^{cd}
	Effluent	220.3^{hi}	
A. nodosum	Fresh	185.7^{i}	185.7^{e}
	Silage	239.3^{gh}	236.7^{d}
	Effluent	218.3^{hi}	
L. digitata	Fresh	340.8^{bcd}	340.8^{ab}
	Silage	371.4^{b}	353.8^{ab}
	Effluent	376.1^{b}	
S. polyschides	Fresh	358.8^{bc}	358.8^{a}
	Silage	294.9^{ef}	276.8^{c}
	Effluent	273.1^{fg}	
S. latissima	Fresh	329.5^{cde}	329.5^{b}
	Silage	353.4^{bc}	329.8^{b}
	Effluent	422.5^{a}	

- No losses in methane yield occurred during 90 day storage for 4 of 5 seaweed species
- Collection and use of silage effluent is imperative to avoid methane losses

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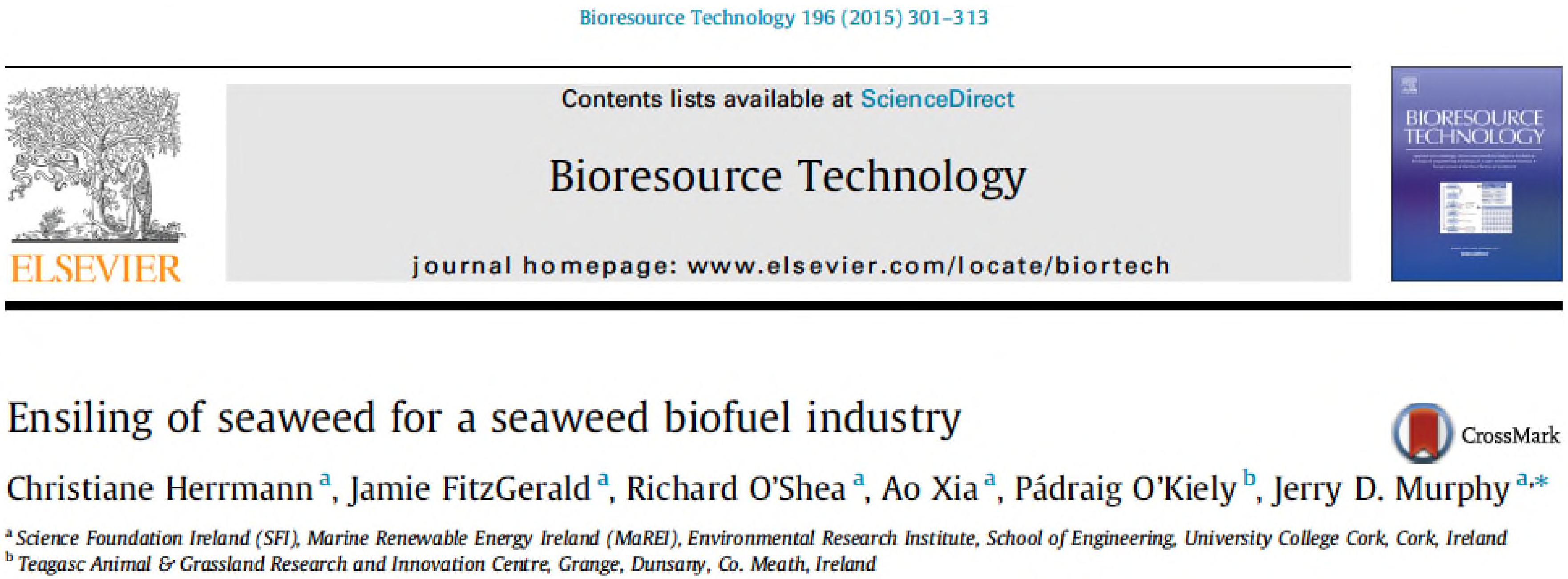

Bioresource Technology 196 (2015) 301–313

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

ELSEVIER

Ensiling of seaweed for a seaweed biofuel industry

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[a] *Science Foundation Ireland (SFI), Marine Renewable Energy Ireland (MaREI), Environmental Research Institute, School of Engineering, University College Cork, Cork, Ireland*

[b] *Teagasc Animal & Grassland Research and Innovation Centre, Grange, Dunsany, Co. Meath, Ireland*

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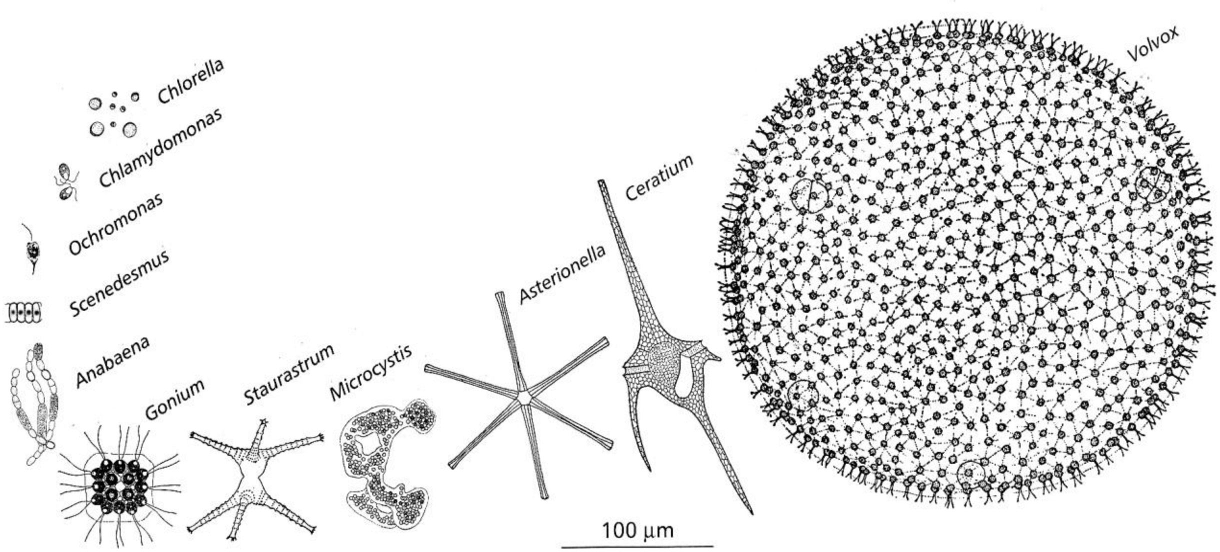
Microalgal biogas

IEA Bioenergy

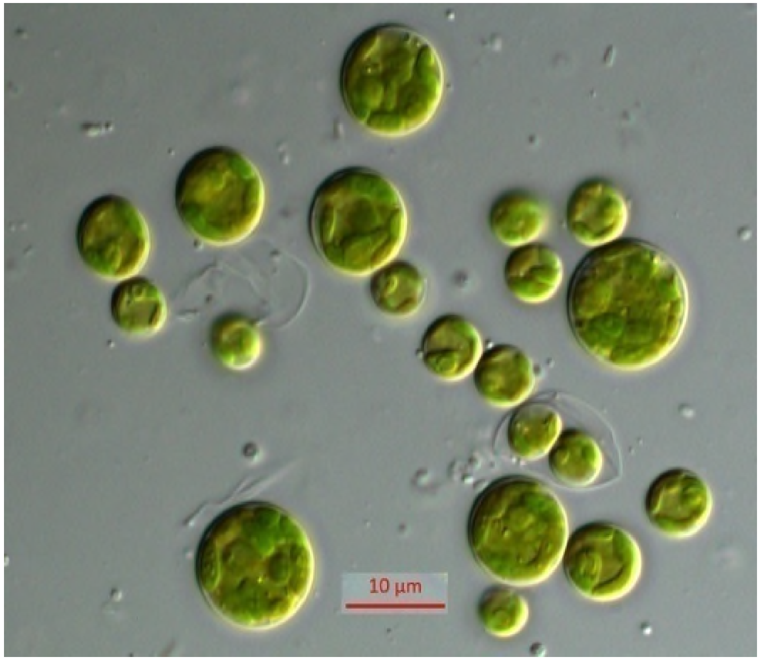
bioenergy2020+

What are microalgae?

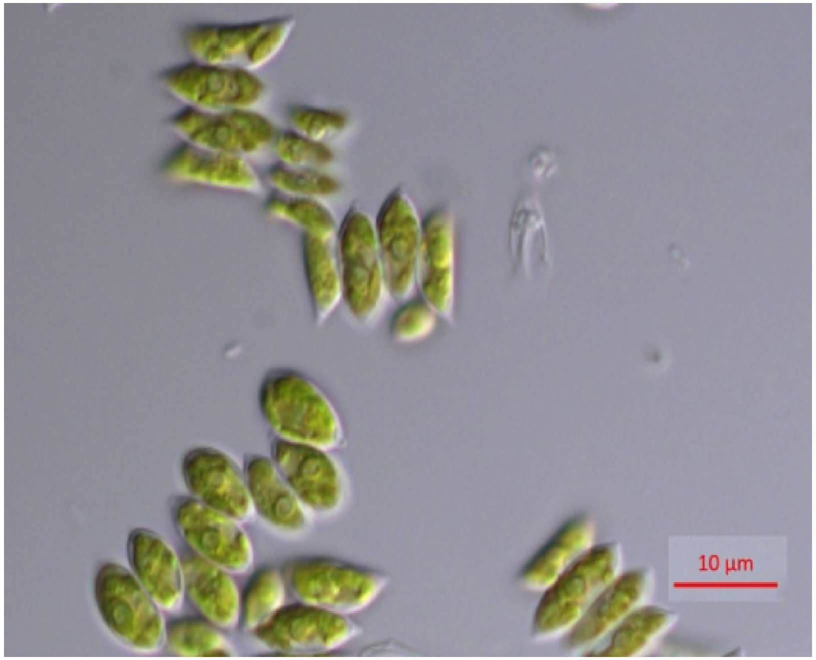
- … are the precursors of higher land plants
- … the main reason for present oxygen levels in the atmosphere
- … due to oxygenic photosynthesis
- … extremely diverse group



Common strains

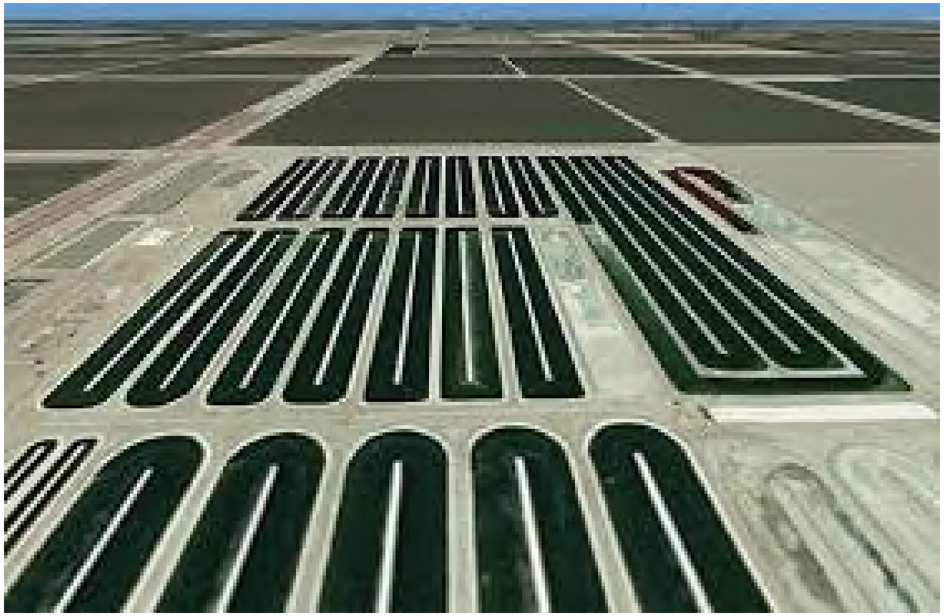


Chlorella sp.



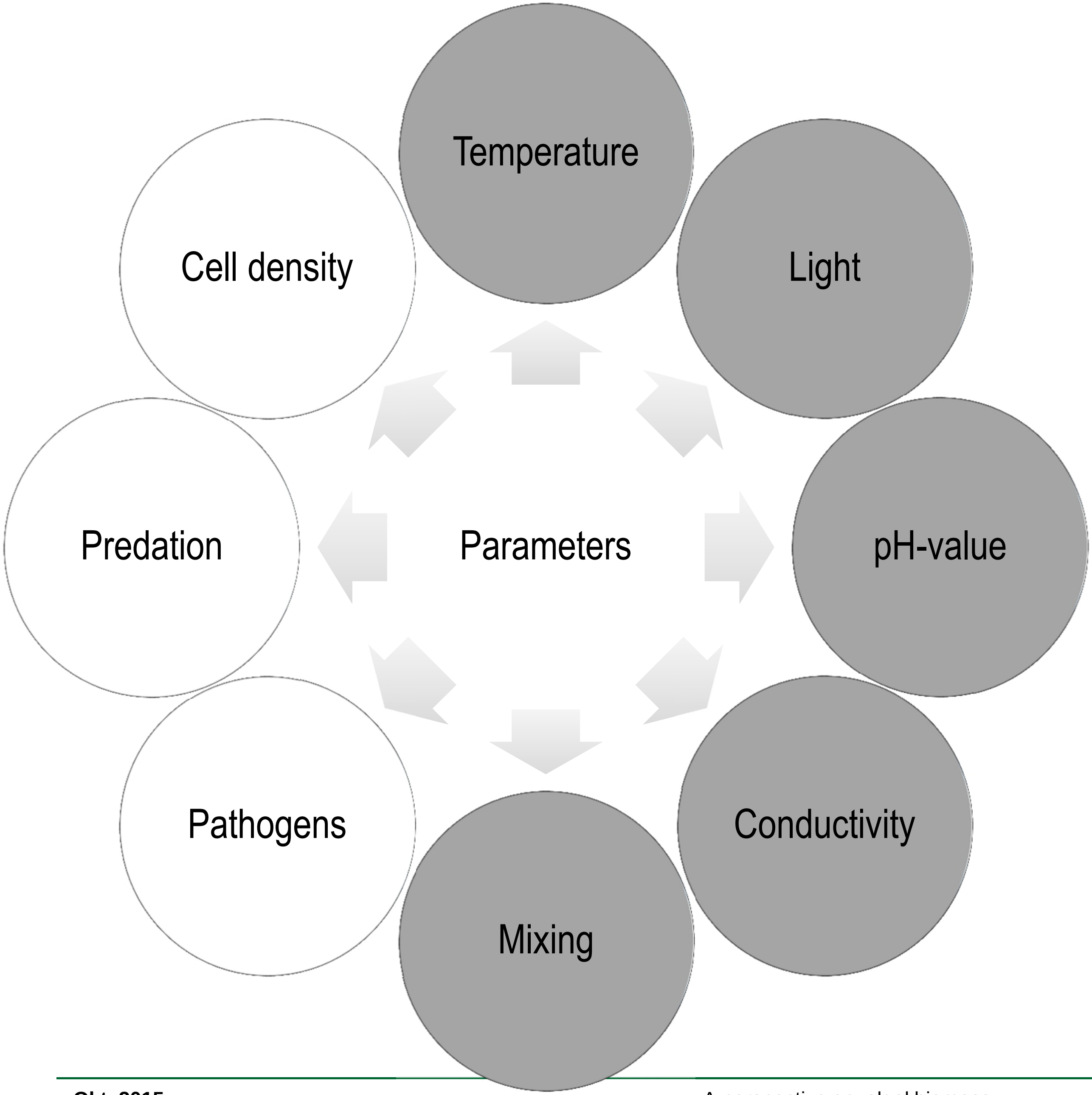
Scenedesmus sp.

Cultivation systems



Open systems

Closed systems



Relevant abiotic (filled spheres) and biotic (empty spheres) parameters for microalgae cultivation

Challenges in cultivation:

Photoinhibition
Photolimitation
Oxygeninhibition

Estimated world algae biomass production

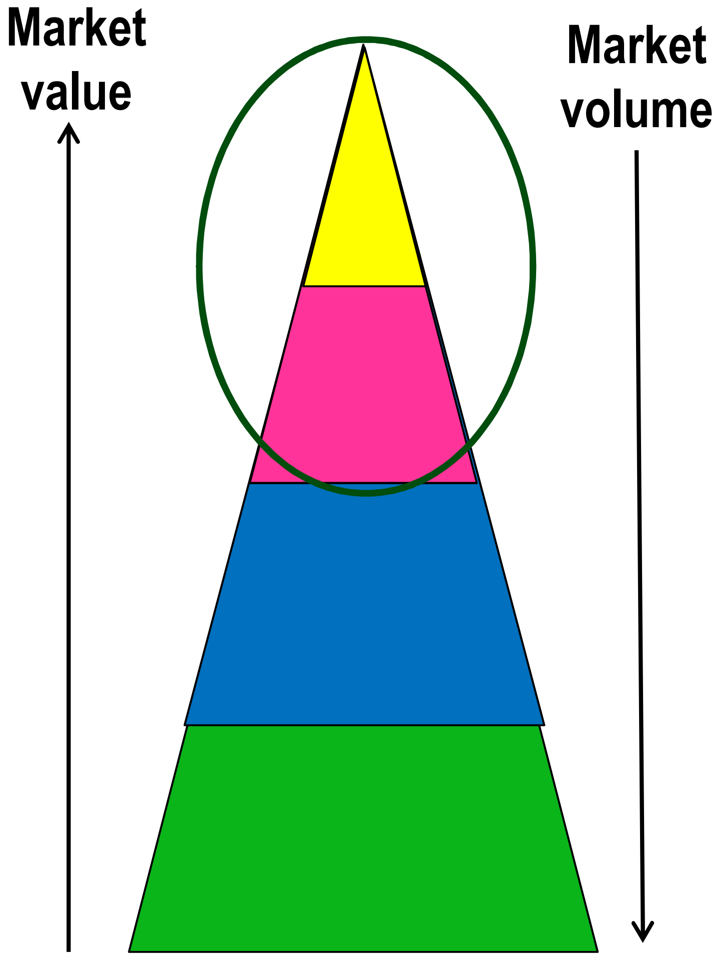
Algae	Production (t dry matter/year)
Spirulina	10,000
Chlorella	4,000
Dunaliella	1,000
Haematococcus	200

Source: Benemann, 2013, *Microalgae for biofuels and animal feeds*. Energies, 6(11), 5869-5886.

Current Market prices of algal biomass

Micro-algae	Main Producers	Application and product	Price [€]
***Spirulina* sp.**	China, India, USA, Myanmar, Japan	Human nutrition Animal nutrition Cosmetics	36 kg^{-1}
***Chlorella* sp.**	Taiwan, Germany, Japan	Human nutrition Cosmetics	36 kg^{-1}
		Aquaculture	50 L^{-1}
Dunaliella salina	Australia, Israel, USA, Japan	Human nutrition Cosmetics ß-carotene	215 - 2150 kg^{-1}
Aphanizomenon flos-aquae	USA	Human nutrition	
Haematococcus pluvialis	USA, India, Israel	Aquaculture	50 L^{-1}
		Astaxanthin	7150 kg^{-1}

Current algae markets



- Pharmaceutical products
- Cosmetics
- Food additives
- Feed additives
- Chemicals
- Bulk chemicals
- Energy

Biogas as conversion technology

Advantages:

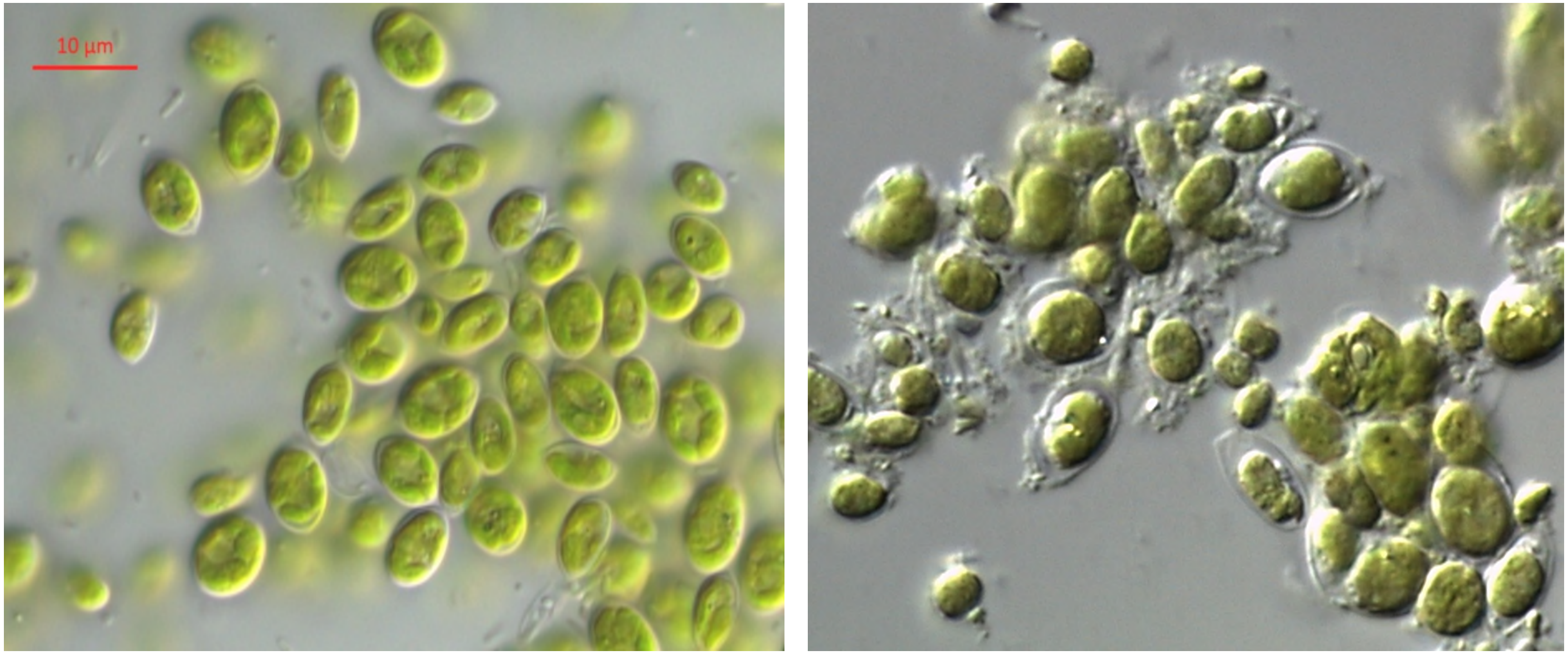
- No pure cultures necessary (cheaper production)
- No specific product needs to be produced (e.g. Triglycerides in biodiesel
- Suitable as well for entire algal biomass or residue after extraction of high value product

Disadvantages:

- Some algae have thick cell walls (especially robust strains)
  → pretreatment necessary
- High protein content can lead to ammonia inhibition

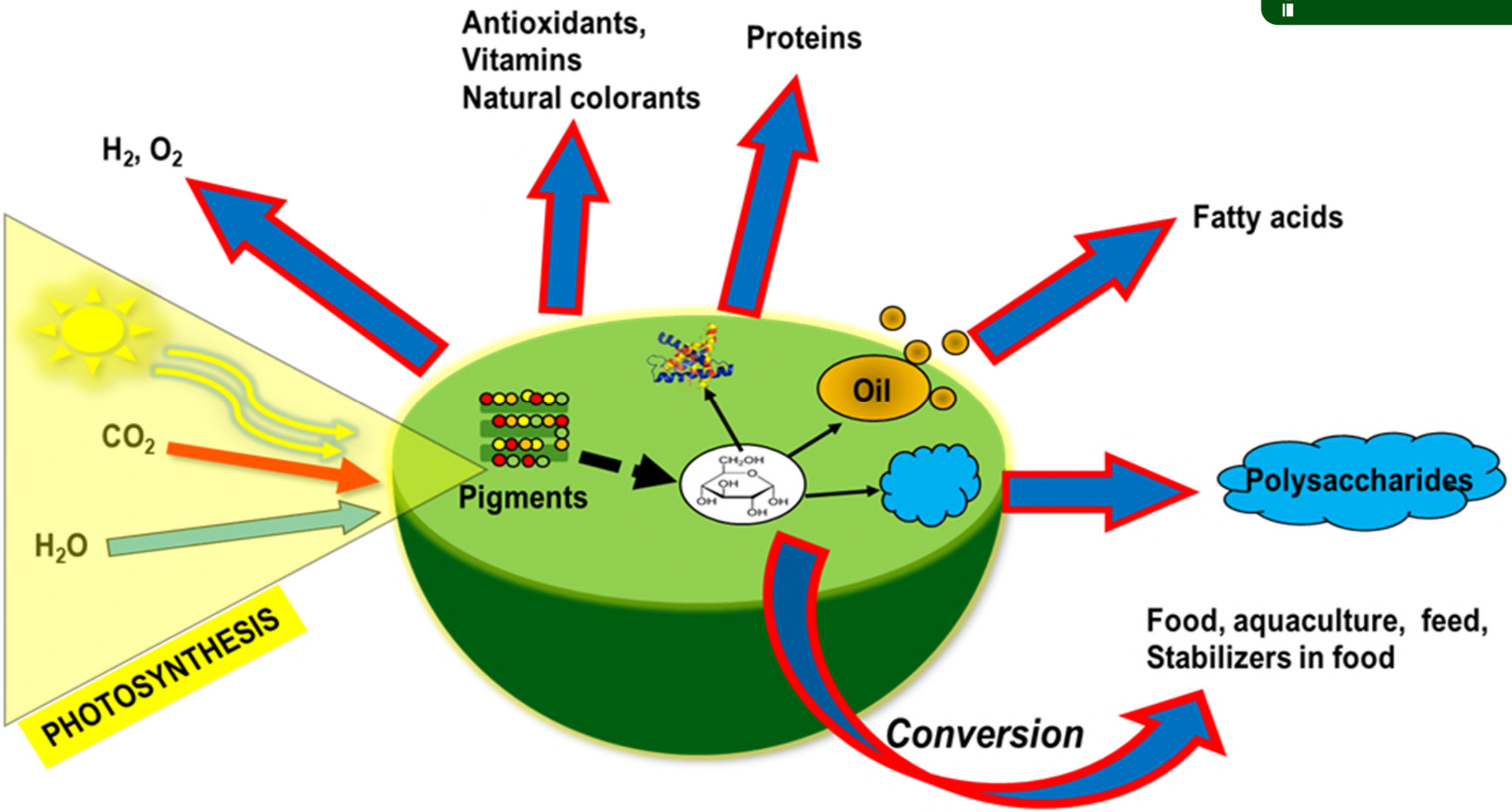
  → dilution

Pretreatment of microalgae



***Chlorella vulgaris* before (left) and after (right) ultrasound pre-treatment**

A more probable approach – The microalgae biorefinery



→ Residues of microalgae are treated in a biogas plant

Further synergies of microalgae and biogas

- Digestate utilisation

→ Digestate from biogas plants is suitable as nutrient media for algae (at least for some strains)

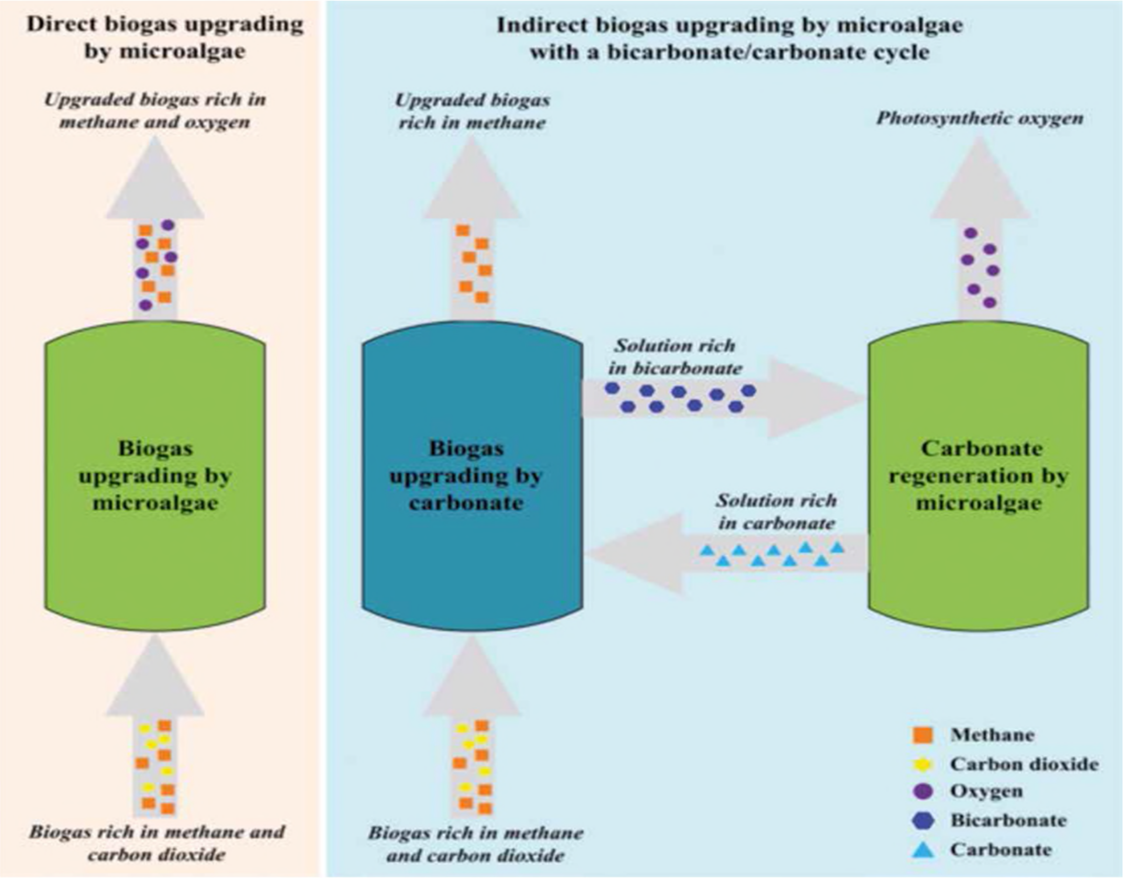
- Utilisation of CO_2

→ Flue gas from combustion of biogas has a comparable high CO_2-content

→ CO_2-rich offgas from biogas upgrading

- Utilisation of waste heat

Use of micro-algae to upgrade biogas



→ Niche applications such as use of micro-algae to biogas upgrading

Conclusions

- **Seaweed biogas**

→ Cast seaweed has significant potential if considered unpleasant.

→ Digest residues associated with extraction of products from seaweed.

→ Cultivation may be advantagous if combined with fish farms for improvement of marine environments.

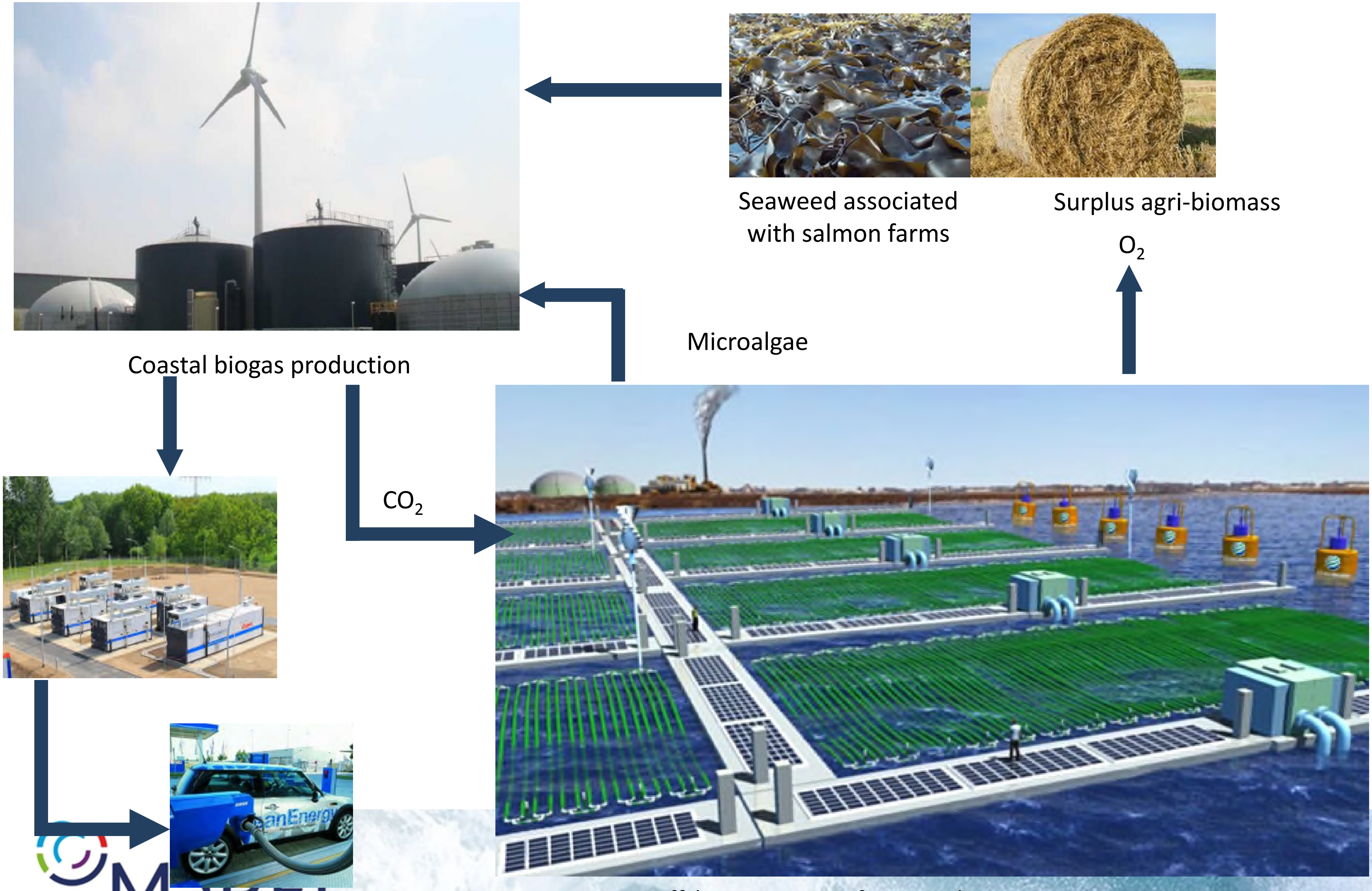
- **Micro-algal biogas**

→ Large scale capture of carbon from fossil fuel power plants is unrealistic at present; the technology requires very high carbon fines

→ Innovative applications associated with bioenergy systems

→ Optimum systems will involve cascading biorefinerys

Coastal biogas production and offshore biogas upgrading system



Seaweed associated with salmon farms

Surplus agri-biomass

O_2

Coastal biogas production

Microalgae

CO_2

Offshore capture of CO2 and wastewater treatment

Offshore Membrane Enclosures for Growing Algae (OMEGA) system, http://www.nasa.gov/centers/ames/research/OMEGA/index.html

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