State of Technology Review on Algae Bioenergy

An IEA Bioenergy Task 39-led Inter-Task Strategic Project

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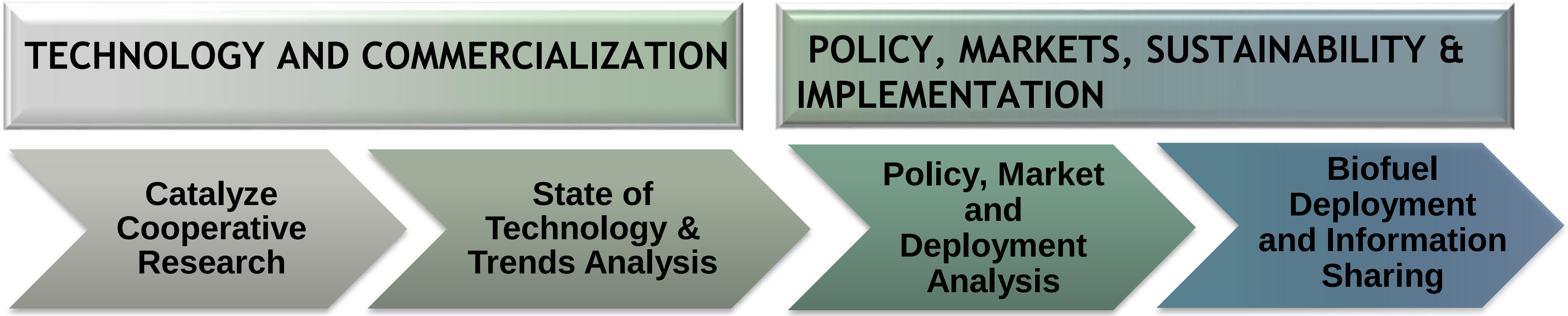
Task 39
IEA Bioenergy

IEA Bioenergy Task 39 - Objectives

- Facilitate commercialization of conventional and advanced liquid biofuels

- An international collaboration between participating countries
  - Analyze policy, markets and sustainable biofuel implementation
  - Focus on Technical and Policy issues
  - Catalyze cooperative research and development
  - Ensure information dissemination & outreach with stakeholders



TECHNOLOGY AND COMMERCIALIZATION

POLICY, MARKETS, SUSTAINABILITY & IMPLEMENTATION

Catalyze Cooperative Research

State of Technology & Trends Analysis

Policy, Market and Deployment Analysis

Biofuel Deployment and Information Sharing

IEA Bioenergy Task 39
Liquid biofuels focus
14 member countries 2016-2018
www.Task39.org

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Update Report on Status and Potential for Algal Biofuels/Bioenergy Production

- **An Inter-Task strategic project** to update and expand on Task 39's 2010 report on the status and prospects for algal-based liquid biofuels
- **Scope broadened to include macroalgae, thermochemical pathways, non-liquid fuel biorefinery products and sustainability**
- Task 39-led collaboration between IEA Bioenergy Tasks 34 (pyrolysis), 37 (biogas), 38 (LCA), 39 (liquid fuels) and 42 (biorefineries)
- **Project leader**: Dr. Lieve Laurens (NREL)
- Critical review of recent literature, **158 pages with >475 references, includes summary of global research operations and >400 companies** focused on commercial applications
- **Completed extensive peer review**, addressed 450 comments and final version will be published/accessible by Jan 30, 2017

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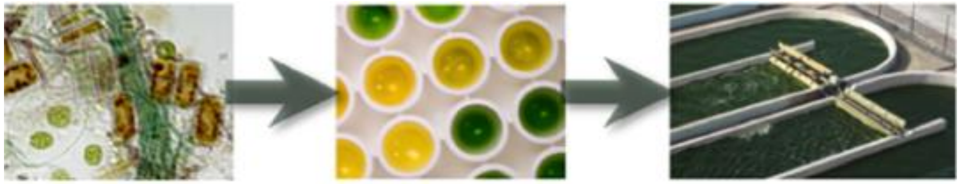

Project Participants' & Contributions

Name	Task	Country	Affiliation	Section contributions
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J.D. McMillan	Task 39	USA	NREL	ES, 1, 2, 10, 11
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- ***Broad contributions from IEA Bioenergy Executive Committee and Task members, spanning 5 tasks (34, 37, 38, 39, 42) and 8 countries***

2017 State of Technology Review - Algae Bioenergy

2016 State of Technology Review – Algae Bioenergy

An IEA Bioenergy Inter-Task Strategic Project

Image of climate simulating photobioreactor growing microalgae under controlled light, CO_2 and temperature, image by Dennis Schoeder, NREL (#25528)

IEA Bioenergy

Report Structure

1. Introduction
2. International Activities Advancing
3. Algae for Bioenergy
4. Technology routes overview
5. Biochemical processes
6. Thermochemical processes
7. Biorefineries and bioproducts
8. Techno-economic analysis
9. Sustainability/life cycle analysis
10. Biogas from macroalgae
11. Other products from macroalgae
12. Conclusions & recommendations

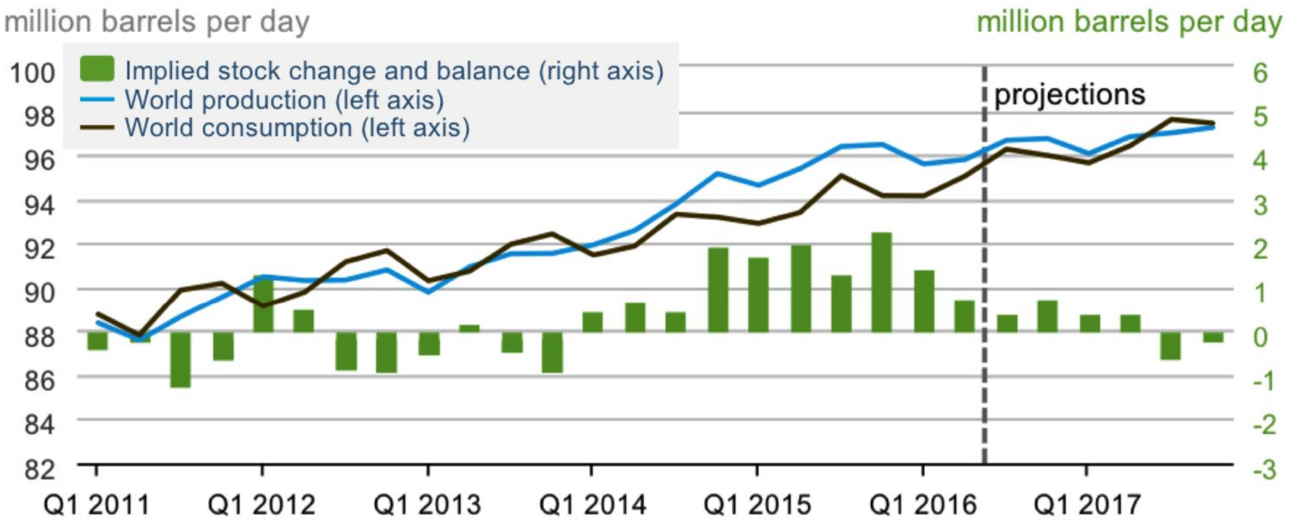
Appendix A: Suggested std LCA input metrics

Appendix B: R&D and Commercial Groups

Global Fuel Use and Petrochemical Markets

- The on-going decline in petroleum and natural gas prices coupled with a lack of carbon pricing are challenging the ability for algal routes to be cost-competitive for production of liquid fuels and other bioenergy products

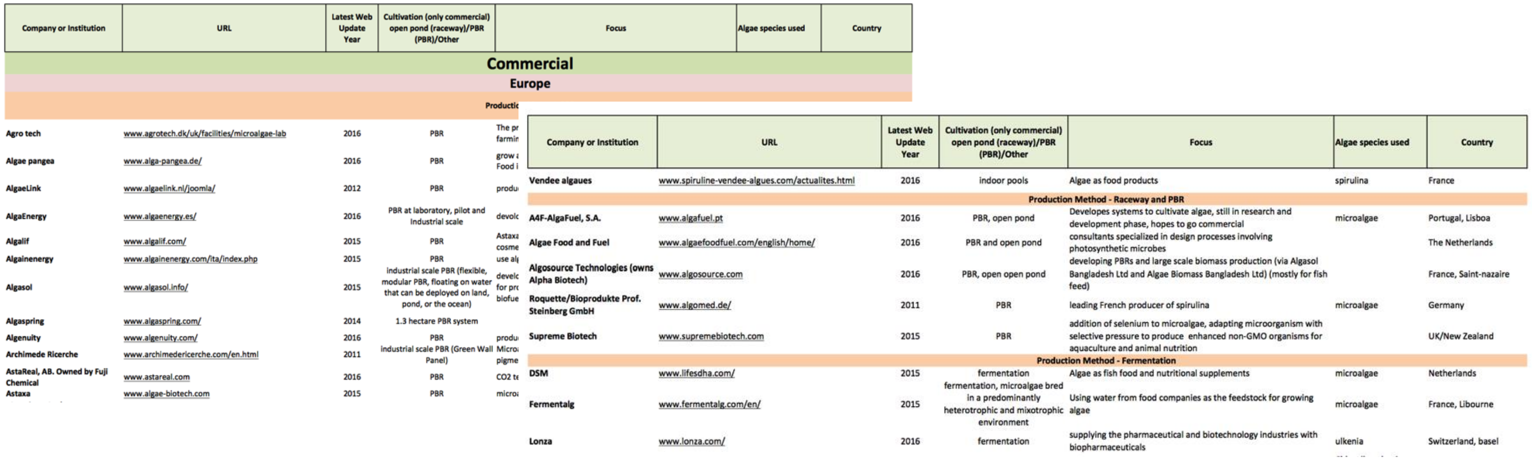
➢*Macroeconomic conditions will prohibit economically viable algae-based fuel production in the near- to mid-term*



EIA, Energy Outlook, September 2016

Global Industrial Development of Algae Technologies

- The algae-based products industry is expanding rapidly for higher value (non-fuel/energy) products, providing near term opportunities (bioenergy production in a biorefinery context, as a coproduct) but also increased competition for algal products markets and suitable land for siting facilities

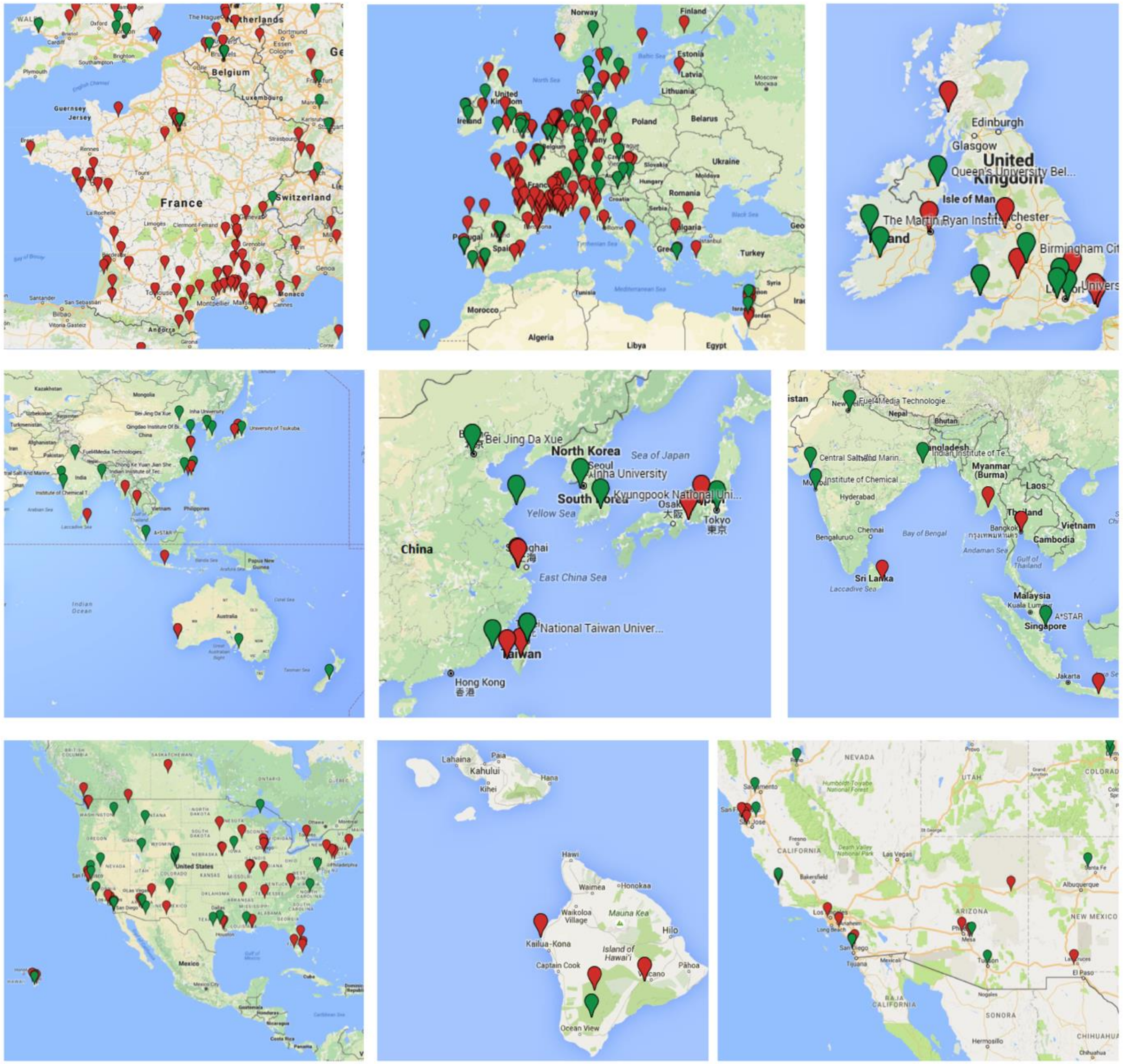


Company or Institution	URL	Latest Web Update Year	Cultivation (only commercial) open pond (raceway)/PBR (PBR)/Other	Focus	Algae species used	Country
Commercial						
Europe						
Productio						
Agro tech	www.agrotech.dk/uk/facilities/microalgae-lab	2016	PBR	The pr farmin		
Algae pangea	www.alga-pangea.de/	2016	PBR	grow a Food i		
AlgaeLink	www.algaelink.nl/joomla/	2012	PBR	produ		
AlgaEnergy	www.algaenergy.es/	2016	PBR at laboratory, pilot and Industrial scale	devolc		
Algalif	www.algalif.com/	2015	PBR	Astaxa cosme		
Algainenergy	www.algainenergy.com/ita/index.php	2015	PBR	use alg		
Algasol	www.algasol.info/	2015	industrial scale PBR (flexible, modular PBR, floating on water that can be deployed on land, pond, or the ocean)	develc for prc biofue		
Algaspring	www.algaspring.com/	2014	1.3 hectare PBR system			
Algenuity	www.algenuity.com/	2016	PBR	produ		
Archimede Ricerche	www.archimedericerche.com/en.html	2011	industrial scale PBR (Green Wall Panel)	Micro pigme		
AstaReal, AB. Owned by Fuji Chemical	www.astareal.com	2016	PBR	CO2 te		
Astaxa	www.algae-biotech.com	2015	PBR	micro		

Company or Institution	URL	Latest Web Update Year	Cultivation (only commercial) open pond (raceway)/PBR (PBR)/Other	Focus	Algae species used	Country
Vendee algaues	www.spiruline-vendee-algues.com/actualites.html	2016	indoor pools	Algae as food products	spirulina	France
Production Method - Raceway and PBR						
A4F-AlgaFuel, S.A.	www.algafuel.pt	2016	PBR, open pond	Developes systems to cultivate algae, still in research and development phase, hopes to go commercial	microalgae	Portugal, Lisboa
Algae Food and Fuel	www.algaefoodfuel.com/english/home/	2016	PBR and open pond	consultants specialized in design processes involving photosynthetic microbes		The Netherlands
Algosource Technologies (owns Alpha Biotech)	www.algosource.com	2016	PBR, open open pond	developing PBRs and large scale biomass production (via Algasol Bangladesh Ltd and Algae Biomass Bangladesh Ltd) (mostly for fish feed)		France, Saint-nazaire
Roquette/Bioprodukte Prof. Steinberg GmbH	www.algomed.de/	2011	PBR	leading French producer of spirulina	microalgae	Germany
Supreme Biotech	www.supremebiotech.com	2015	PBR	addition of selenium to microalgae, adapting microorganism with selective pressure to produce enhanced non-GMO organisms for aquaculture and animal nutrition		UK/New Zealand
Production Method - Fermentation						
DSM	www.lifesdha.com/	2015	fermentation	Algae as fish food and nutritional supplements	microalgae	Netherlands
Fermentalg	www.fermentalg.com/en/	2015	fermentation, microalgae bred in a predominantly heterotrophic and mixotrophic environment	Using water from food companies as the feedstock for growing algae	microalgae	France, Libourne
Lonza	www.lonza.com/	2016	fermentation	supplying the pharmaceutical and biotechnology industries with biopharmaceuticals	ulkenia	Switzerland, basel

Table 2-1: Summary of commercial and research operations working towards commodity algae-based products globally, separated by region.

	Total	Europe	North America	Asia	Oceania	Middle East
Commercial	306	166	105	26	2	7
PBR	50	32	14	1	N/A	3
Raceway	50	32	11	4	1	2
Combined PBR and Raceway	12	5	7	N/A	N/A	N/A
Fermentation	13	4	5	4	N/A	N/A
Unknown cultivation method	160	85	55	17	1	2
Suppliers	21	8	13	N/A	N/A	N/A
Research	94	50	27	9	5	3
Total	400	216	132	35	7	10
Shut operations	50	28	22	N/A	N/A	N/A



- Strong global industrial development reflects many partnerships of governments and industry groups to support early R&D
- A subset of the 400 world-wide current and past algae commercial operations are summarized

Figure 2-2: Overview of global commercial and research operations; red pins represent commercial operations, green pins research/demonstration projects

Algae Productivity

- Algae exhibit high photosynthetic efficiency and high yields (~**55 tonnes ha^{-1} yr^{-1}**), roughly twice that of productive terrestrial plants, and thus remain an attractive target for bioenergy applications

- Resources (water, land, sunlight) and nutrients (N, P) remain key issues for economic and environmental sustainability; integration with wastewater treatment provides nearer-term opportunities

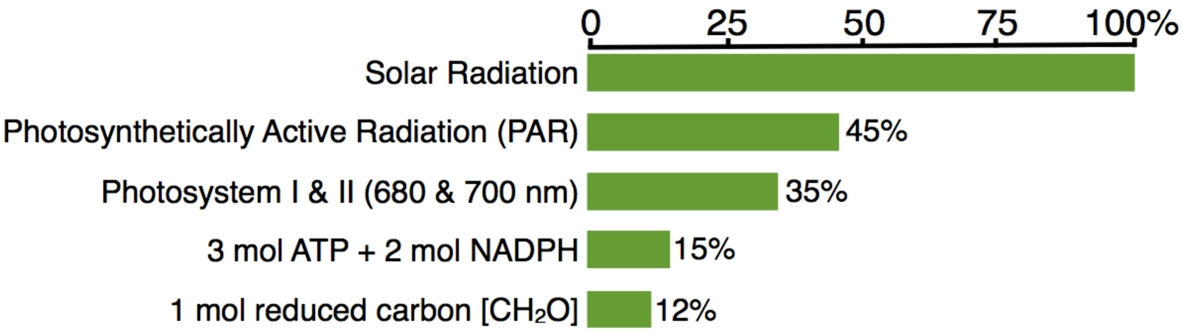
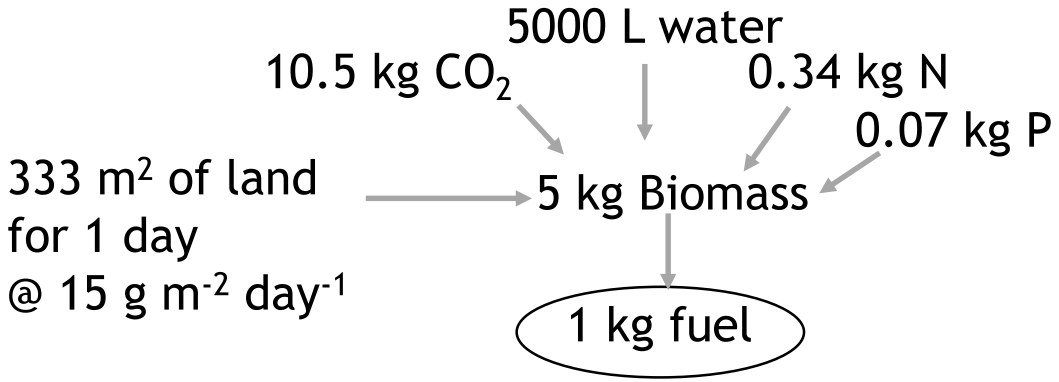


Figure 3-4 : Stepwise loss of energy during photosynthetic assimilation of inorganic carbon to reduced carbohydrate



5000 L water

10.5 kg CO_2

0.34 kg N

0.07 kg P

333 m^2 of land
for 1 day
@ 15 g m^{-2} day^{-1}

5 kg Biomass

1 kg fuel

Approximate inputs to produce 1 kg of algal-based biofuel. Developed from information presented in section 3.4.

- Up to 12% theoretical efficiency on solar radiation; observed efficiencies 2-3%; further potential to improve
- Growth rates are 10-30 g m^{-2} day^{-1}, depending on location and cultivation system, with realistic algal oil content of 12-20%
- Oil and biomass productivity inverse relationship is main target of strain engineering to increase biofuel yields
- Algae cultivation is resource intensive, requires extensive recycling of nutrients post extraction/conversion, or co-locating with wastewater facilities

Conversion Technologies

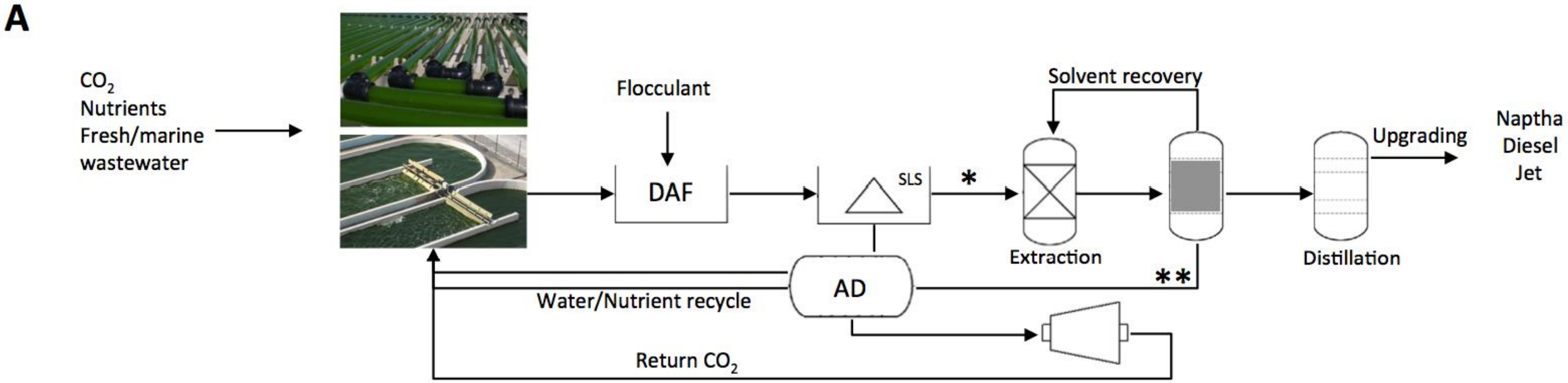


Figure 4-1 : Major algae conversion pathways under development: (A) base-case algal lipid extraction and upgrading (ALU) approach. DAF = dissolved air flotation, SLS = solid liquid separation, AD = anaerobic digestion, HTL = hydrothermal liquefaction, CHG = catalytic hydrothermal gasification.

- Hundreds of permutations of process operations are described in the literature
- The report classifies approaches into 3 major categories:
  - **i) Lipids-only**
  - **ii) Whole algal biomass non-destructive fractionation**
  - **iii) Thermochemical hydrothermal liquefaction**

Fractionation

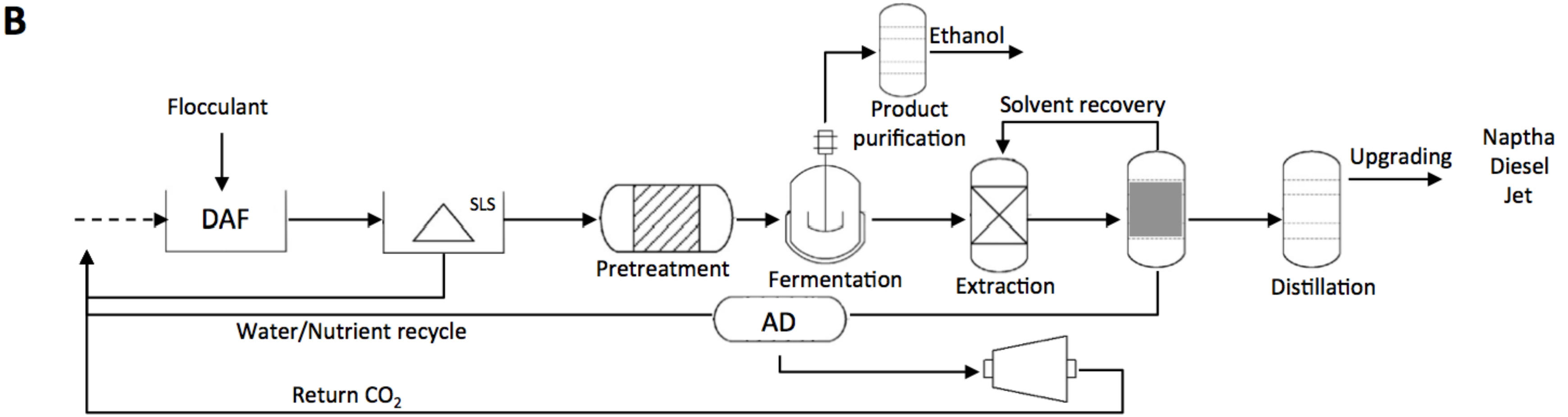


Figure 4-1 : Major algae conversion pathways under development: (B) Current base-case of combined algal processing (CAP) pathway where bioenergy-products are derived from both carbohydrate and lipid fractions. DAF = dissolved air flotation, SLS = solid liquid separation, AD = anaerobic digestion, HTL = hydrothermal liquefaction, CHG = catalytic hydrothermal gasification.

- Fractionation refers to dilute acid pretreatment of algal biomass slurry (15-20%), generating a sugar stream from carbohydrates, and extractable lipids for upgrading with a protein-enriched residue
- Combined Algal Processing (CAP) maximizes the valorization of different components in the biomass, but respective yields are highly dependent on the composition
- Nutrients can be recycled from aqueous AD effluent or protein fermentation after digest of the protein rich residue

Hydrothermal Liquefaction

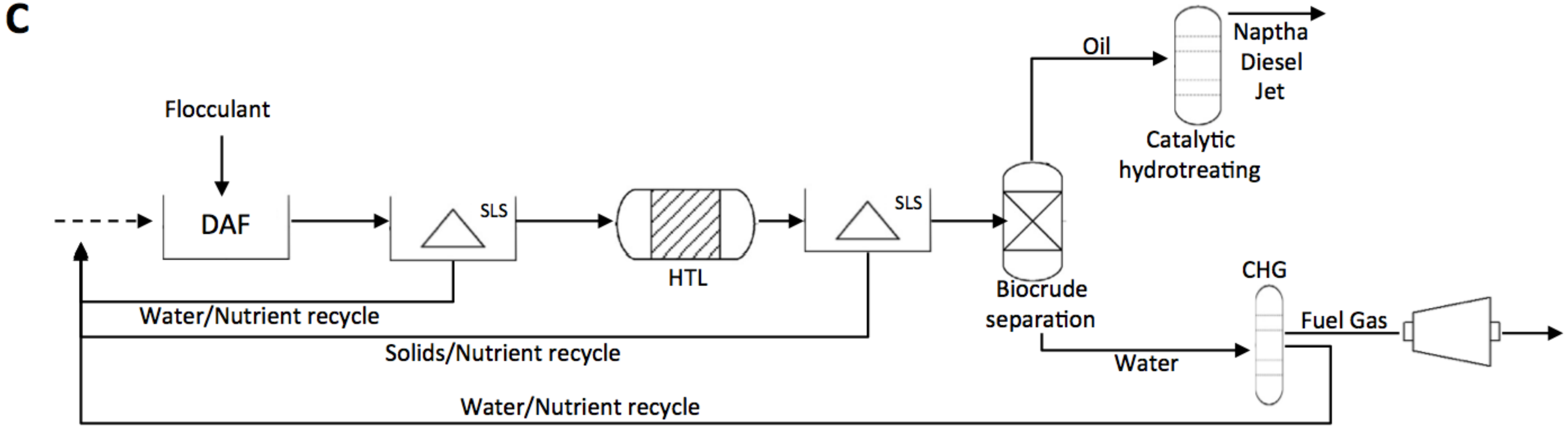


Figure 4-1 : Major algae conversion pathways under development (C) Hydrothermal liquefaction process as described and modeled Acronyms: DAF = dissolved air flotation, SLS = solid liquid separation, AD = anaerobic digestion, HTL = hydrothermal liquefaction, CHG = catalytic hydrothermal gasification.

- HTL consists of slurry (15-25 wt%) in a hot reactor, after which, aqueous, biocrude and solid phases are separated
- The addition of biomass pretreatment, conversion pH or catalysts impacts the yield and quality of biocrude
- Biocrude yields are dependent on biochemical make up of the cells; e.g. non-lipid components can add 5-25% to the yield
- In dilute form, the aqueous phase can serve as a source of nutrients for recycle or microbial growth

Biogas production from microalgae

- Anaerobic Digestion (AD) of microalgae has been demonstrated with whole biomass and biomass residue after extraction
- Yields are dependent on biomass composition
- Biomass pretreatment may be necessary to maximize the CH_4 yields
- Challenges with post-extraction AD is ensuring bioavailability of the carbon in a high N:C ratio of the biomass

Species	Temp. [°C]	Biogas prod. [L/kg VS]	CH_4 prod. [L/kg VS]	CH_4 content [%]
Arthrospira platensis	-	481 ± 14	293	61
Chlamydomonas reinhardtii	-	587 ± 9	387	66
Chlorella kessleri	-	335 ± 8	218	65
Chlorella vulgaris	28-31	-	310-350	68-75
Dunaliella salina	-	505 ± 25	323	64
Dunaliela	35	-	420	-
Euglena gracilis		485 ± 3	325	67
Nanochloropsis sp.	38	388	312	80.5
Scenedesmus obliquuus	-	287 ± 10	178	62
Anthrospira sp.	35	-	320-310	-
	38	556	424	76.3
Anthrospira maxima	35	-	190-340	-
Mixed algae sludge (*Clorella-Scenedesmus*)	35-50	-	170-320	62-64
	50	500	NS	-
	35	405	NS	-
	45	611	NS	-
	35	-	100-140	-
	38	420	310	73.9

Table 4-1 : Methane and biogas production yields from different microalgal species measured by BMP tests

Biorefineries and Bioproducts from Algae

- Recent technology developments facilitate the use of all algal biomass components; algal-based biofuels production is no longer focused on valorizing only/primarily the lipid fraction
- Composition of products in biomass and market size needs to be aligned when algae farms are scaled to >2000 ha

	Total	All Livestock	Poultry	Pig	Ruminant	Aquaculture
Production (10^6 Tonnes)	980	939	439	256	196	41
Percentage	100%	96%	45%	27%	20%	4%
China (10^6 Tonnes)	183	158.2	65	85	8.2	18
USA (10^6 Tonnes)	173	146	82	24	40	11

Table 6-2 : Sumary of global feed market sizes, separated by application

Feedstock	Wt %	Product	Market size (T)
Fatty acids	10-45%	Hydrocarbon fuel products	5,000,000
Omega-3-fatty acids	3-6%	Polyols	11,000,000
	3-6%	Polyurethane	11,000,000
	3-6%	Nutraceuticals	22,000
Hydroxy fatty acids	~1%	Surfactants, fuel additives	3,500,000
Branched chain fatty acids	~1%	Surfactants, fuel additives	3,500,000
Fatty alcohols	~1%	Surfactants, fuel additives	3,500,000
Sterols	2-4%	Surfactants/emulsifiers	2,000,000
	2-4%	Hydrocarbon fuel products	5,000,000
	2-4%	Phytosterol nutra/pharmaceuticals	25,000
Phytol	3-4%	Raw material for vitamin E, fragrance	1
	3-4%	Surfactants, fuel additives	3,500,000
Polar lipids	10-35%	Ethanolamine	600,000
	10-35%	Phosphatidylcholine, phosphoinositol and phosphatidyl ethanolamine (lecithin)[†]	20,000-30,000
Glycerol	2-6%	Di-acids for nylon production	2,500,000
	2-6%	Feed, pharmaceuticals	25,000
Fermentable sugars (glucose, mannose)	10-45%	Polylactic acid (PLA) polymers	300,000
	10-45%	Di-acids (e.g. adipic acid)	2,500,000
	10-45%	Ethanol	68,000,000
Mannitol	3-6%	Polyether polyols	2,300,000
Alginate	~3-5%	Alginate additives	12,000
Starch	5-40%	Polysaccharide-derived bioplastics[°]	2,000,000
Protein	19-40%	Thermoplastics	5,000,000
Amino acids/peptides	19-20%	Polyurethane	11,000,000
Amino acids/peptides	19-20%	Biobutanol, mixed alcohol fuels	40,000,000

Table 6-1 : Bioderived products from algae biochemical components, shown as wt% of dry biomass, based on literature data

Sustainability considerations

- *The quantity of water (whether fresh water or saline water) required for algae cultivation and the quantity of freshwater addition and water purge to maintain the appropriate water chemistry.*
- *Supply of the key nutrients for algal growth—nitrogen, phosphorus, and* CO_2 *needs to be ensured to not impact global supplies*
- *Appropriate land area with suitable climate and slope, near water and nutrient sources*
- *Energy return on investment* (EROI). Algal biofuel production would have to produce sufficiently more energy than is required in cultivation and fuel conversion to be sustainable.
- *GHG emissions over the life cycle of algal biofuels*. Algal biofuel production would have to produce a GHG benefit relative to other fuel options such as fossil fuels. Estimates of life-cycle GHG emissions of algal biofuels span a wide range, and depend on many factors including the source of CO_2 and the disposition of bio-products.

National Academies of Science, National Research Council report, 2012

Economic drivers

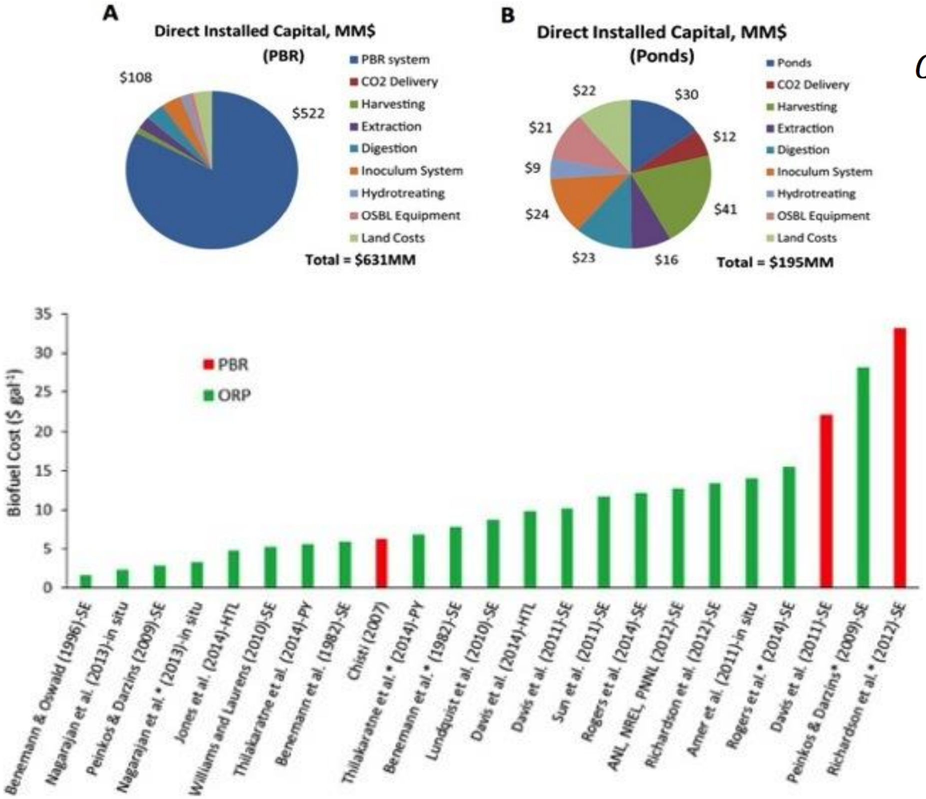


Figure 7-4: Techno-economic assessment results color-coded by growth platform and conversion technology. Studies span reported approaches, including SE-solvent extraction, HTL-hydrothermal liquefaction, PY-pyrolysis (from reference 320)

$$C_{production} = \sum_i C_{capital,i} + \left(\sum_j C_{operating,j} - \sum_k V_{bio-products,k} \right)$$

- Single biggest barrier to market deployment remains the high cost of cultivating and harvesting algal biomass
- There are **two challenges** and steps remaining regarding TEA of cultivation of microalgae:
  i) **harmonization and standardization of the models, assumptions and methodologies;** and ii) **accessibility to pilot and demonstration experimental data from different locations to permit model validation**

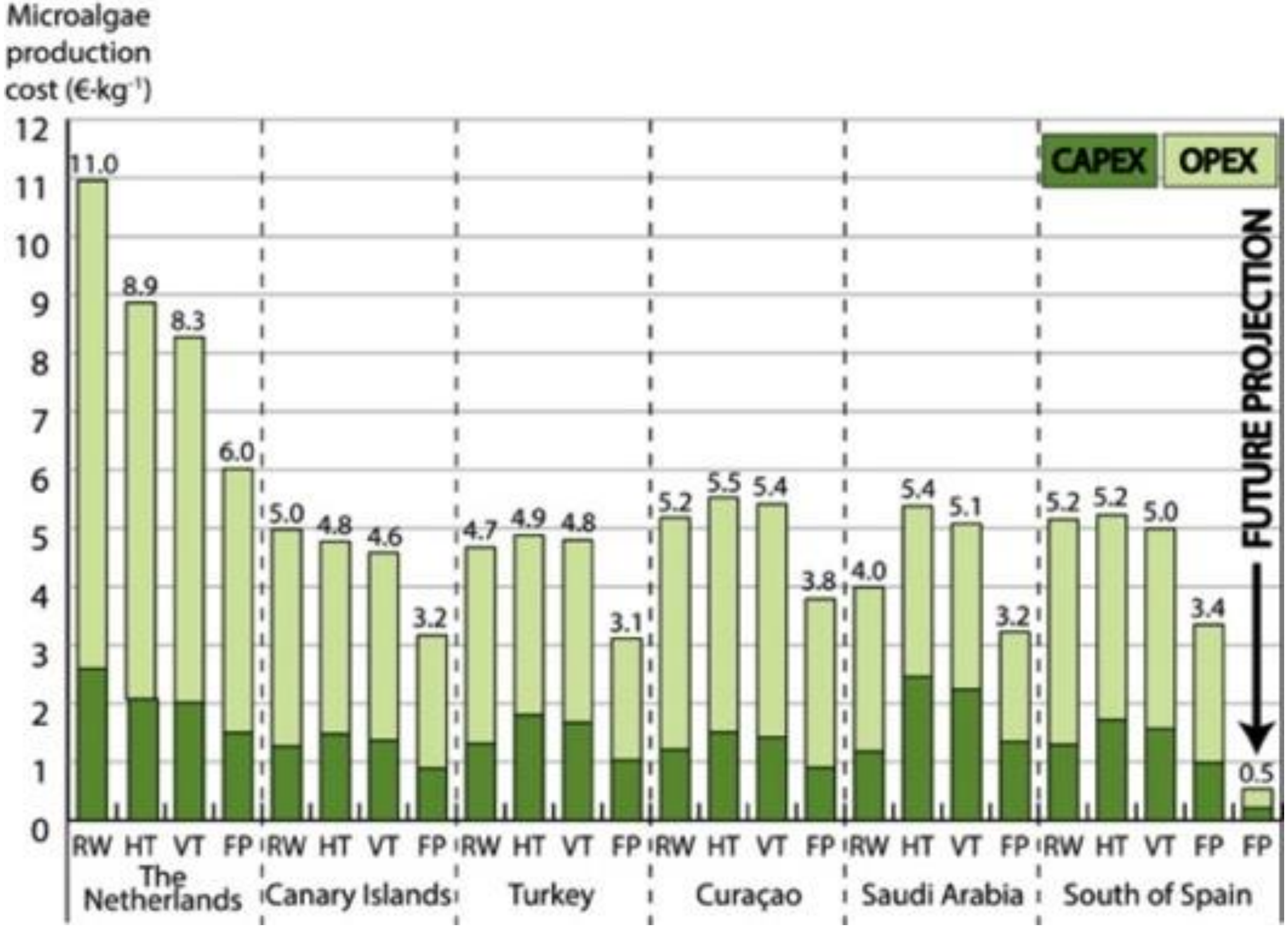


Figure 7-5: Projected biomass production costs (cultivation and harvesting) in the studied locations for current scenarios and future projection for southern Spain. Costs are the sum of CAPEX and OPEX. RW: raceway pond; HT: horizontal tubular photobioreactor; VT: vertically stacked horizontal tubular photobioreactor; FP: flat panels photobioreactor (from reference 308).

- Calculations using one TEA model applied to algae productivity estimated at 6 different locations show a 3.5-fold range in estimated costs of production, (3.1 – 11.0 € kg^{-1})

- All of these projected costs are 6-10-fold higher than what is considered to be economically viable for fuel production

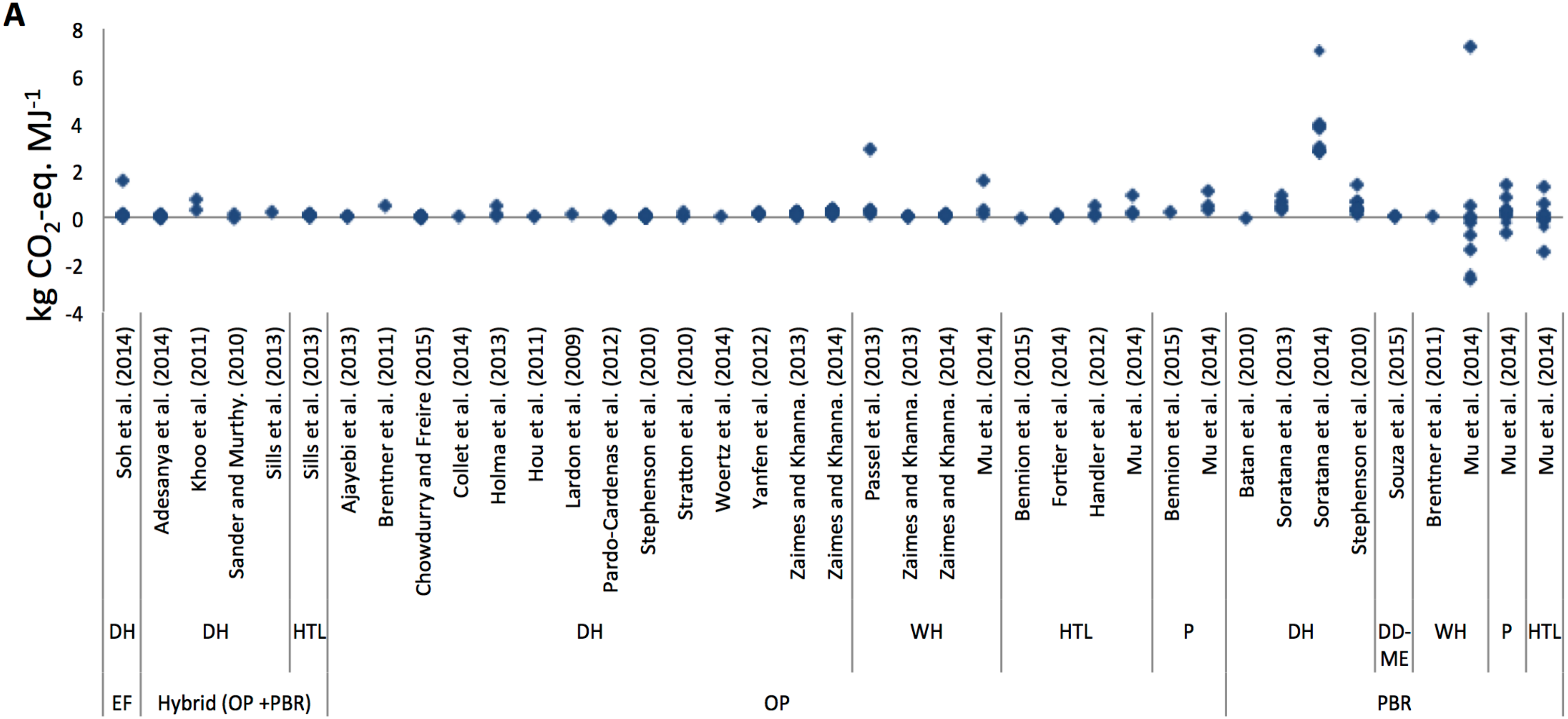


Figure 8-2A: GHG intensity of microalgae biodiesel production in reviewed studies. Abbreviations: DH - Dry extraction with hexane; EF - Erlenmeyer flasks; HTL - Hydrothermal liquefaction; WH - Wet extraction with hexane; P - Pyrolysis; DD-ME -Dry extraction with dimethylether; OP - Open pond; PBR – Photobioreactor.

- Large range in net CO_2 per MJ biofuel produced (-2.6-7.3 kg CO_2eq MJ^{-1})
- LCA modeling choices are major driver, as are processing differences
- A standardized/harmonized approach is needed for LCA/TEA modeling

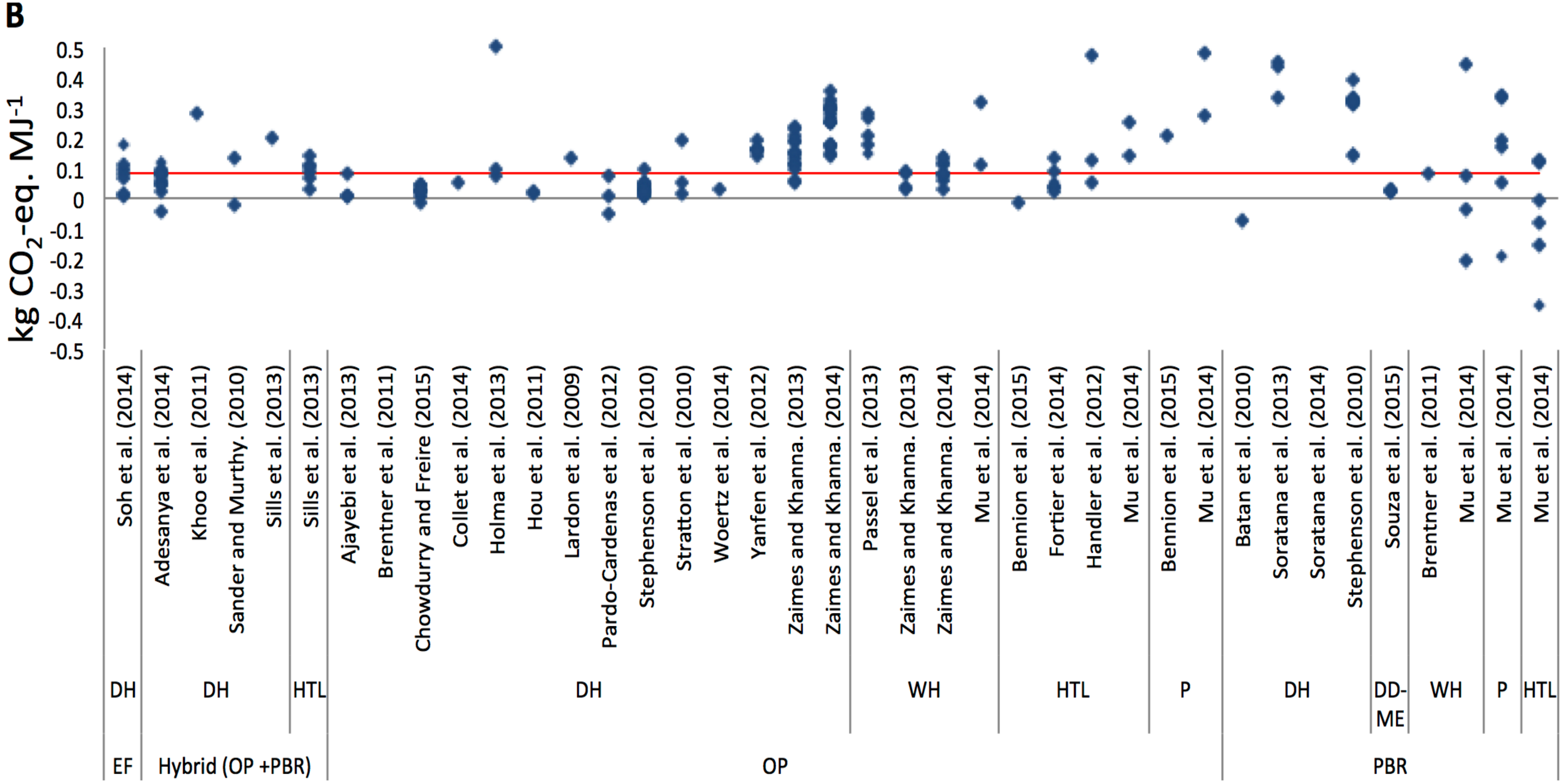


Figure 8-2B: Detailed range of GHG intensity in reviewed studies [-0.5–0.5 kg CO_2eq MJ^{-1}], **relevant for more than 85% of the reviewed studies**. Red line is GHG intensity of fossil diesel. Abbreviations: DH - Dry extraction with hexane; EF - Erlenmeyer flasks; HTL - Hydrothermal liquefaction; WH - Wet extraction with hexane; P - Pyrolysis; DD-ME - Dry extraction with dimethylether; OP - Open pond; PBR – Photobioreactor.

Resource Assessment and Availability

- Land use and resource availability needs to be integrated with a food-energy-water network
- Globally, algae have potential to influence the energy portfolio, assuming water, nutrients and CO_2 are not limiting
- Land use change (LUC, direct and indirect) emissions have received very little attention in the literature and need to be integrated into the overall LCA and sustainability modeling

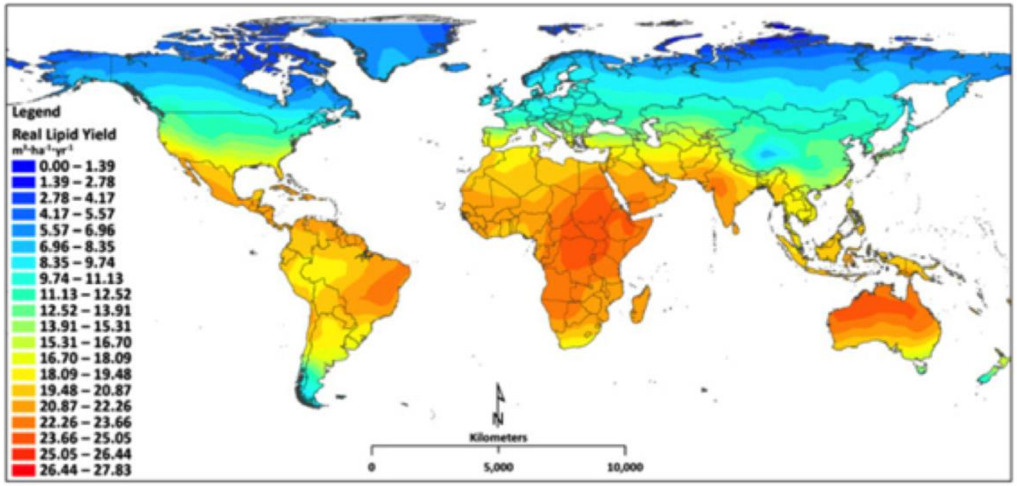
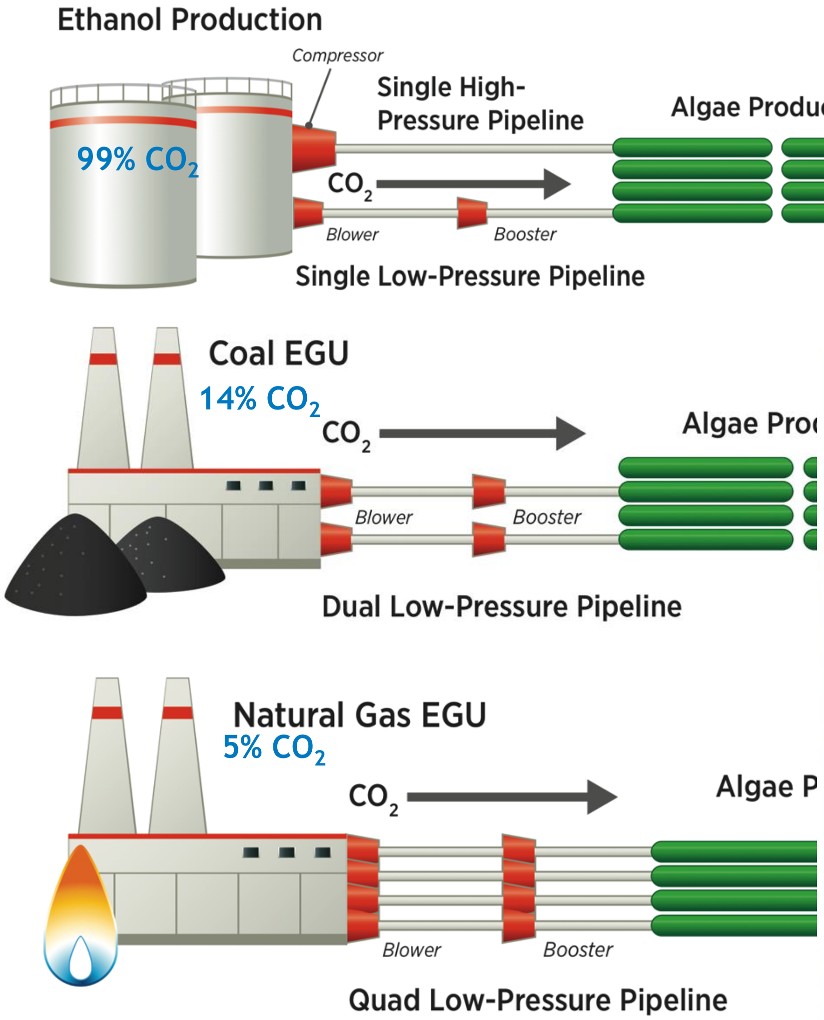
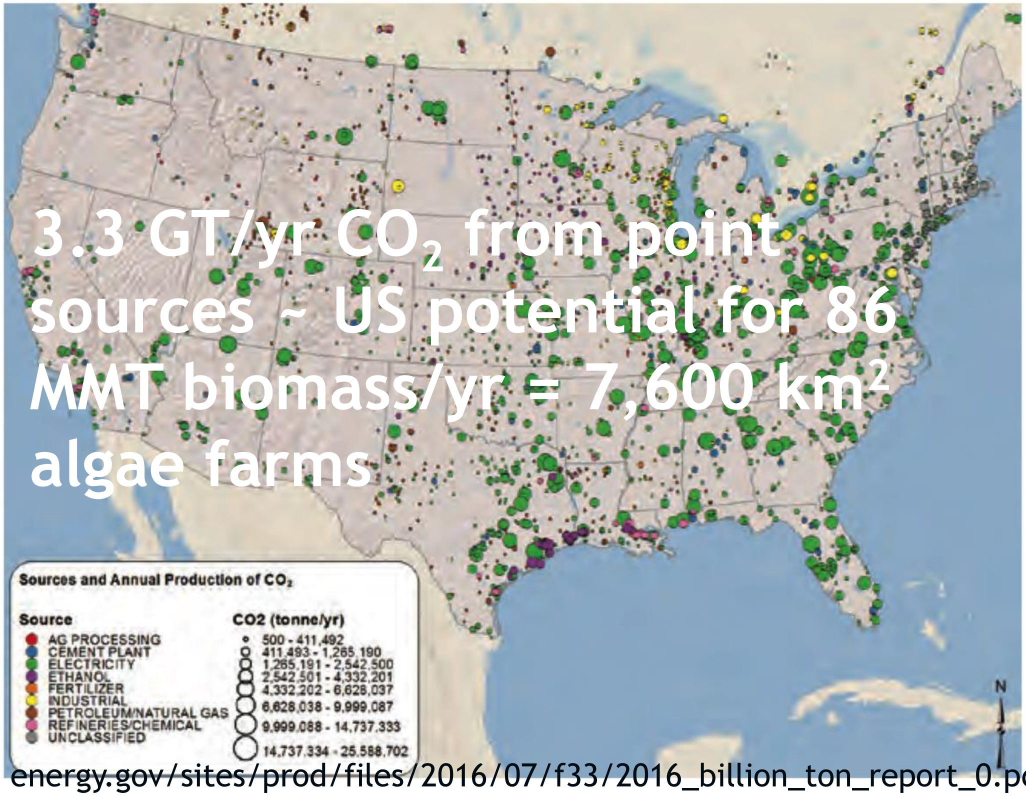


Figure 8-3 : Overview of global current near term lipid productivity of microalgae based on a validated biological growth model of Nannochloropsis cultivated in a photobioreactor, based on meteorological data from 4,388 geographical locations (reference 380)

CO_2 Valorization Potential



EGU = Electric Generating Unit



3.3 GT/yr CO_2 from point sources ~ US potential for 86 MMT biomass/yr = 7,600 km^2 algae farms

energy.gov/sites/prod/files/2016/07/f33/2016_billion_ton_report_0.pdf

Macroalgae as Bioenergy Feedstocks

- Macroalgae have potential to contribute biogas, chemicals and biofuels from cultivated and cast seaweed, with yields of **5 - 30 tonnes ha^{-1} yr^{-1}**
  - *This is a relatively new area of investigation and much remains to be learned about its potential*

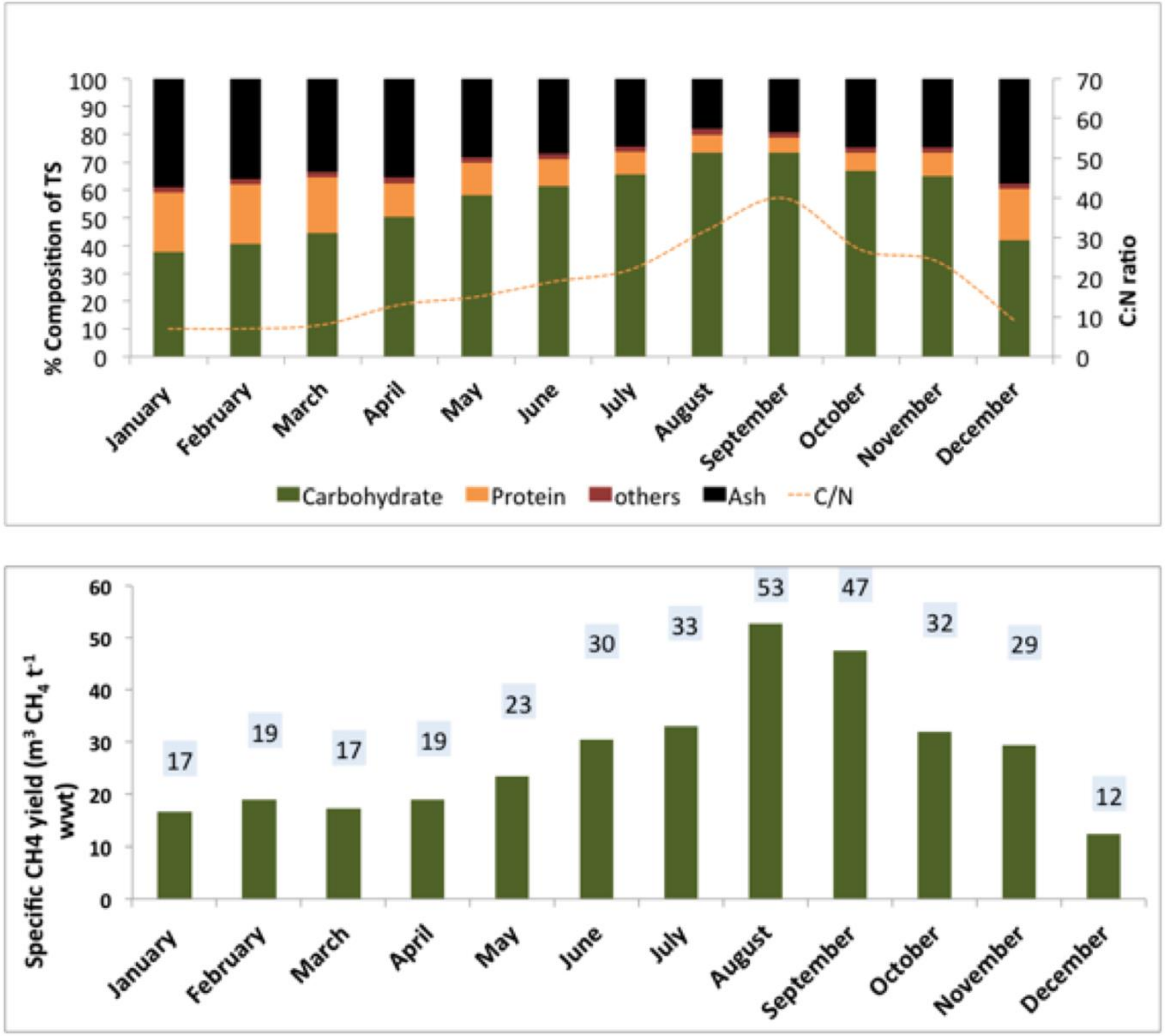


Figure 9-2: Annual variation in *L. digitata* composition in Ireland (top) and associated biomethane potential (bottom)

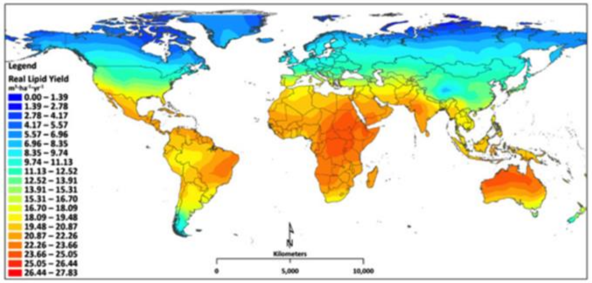
- Macroalgae yields range widely, 5 – 30 tonnes ha^{-1} yr^{-1}, with up to 20,000 m^3 biomethane potential ha^{-1} yr^{-1}
- Unlikely that cast seaweed resource sufficient to provide large quantities of liquid transportation fuels, however biogas can be upgraded and injected into the existing gas grid to supplement methane fuel demands
- Cast and cultivated seaweeds may have to be combined, perhaps also with terrestrial biomass, to achieve a consistent year-round supply of either gaseous or liquid biofuels

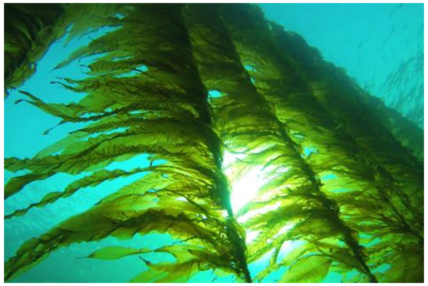
Conclusions

- IEA Bioenergy has authored a comprehensive updated report on the status and prospects for algae-based bioenergy production, **“State of Technology Review — Algae Bioenergy”**
- The report will e-publish in the next week and be available on both IEA Bioenergy’s and Task 39’s web sites:
    - http://www.IEABioenergy.com
    - http://www.Task39.org

Key Findings:

- Algae remain a promising source of bioenergy feedstock thanks to high photosynthetic efficiency but prospects for primary algae-based energy/fuels production are poor in the near- to mid-term due to the relatively high cost of growing and harvesting algal biomass
- Algae processing in a biorefinery context may permit economically feasible coproduction of bioenergy products in nearer term, as may integration with wastewater treatment
- **There is a clear, urgent need for more open data sharing and harmonization of analytical approaches, from cultivation to product isolation, to TEA and LCA modeling, to identify and prioritize the barriers that need to be overcome for commercialization**





Thank you!
Are there any questions?

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