ITALIAN NATIONAL AGENCY
FOR NEW TECHNOLOGIES, ENERGY AND
SUSTAINABLE ECONOMIC DEVELOPMENT

# Biofuels from algae: technology options, energy balance and GHG emissions

## *Insights from a literature review*


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**Pre-BASIC Biogas Seminar**

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# Context

**EXPECTATIONS: Algae are expected to offer several advantages compared to land-based agricultural crops:**

- better photosynthetic efficiency;
- higher oil yield;
- growth on non-fertile land;
- tolerance to a variety of water sources
- $CO_2$ re-using potential.
- integration in wastewater treatment (WWT) plants to combine the contaminant removal with biofuels production
- biorefinery concept: a wide range of marketable co-products can be extracted from algae, e.g. chemicals and nutrients,


European Commission

JRC SCIENCE FOR POLICY REPORT

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Joint Research Centre

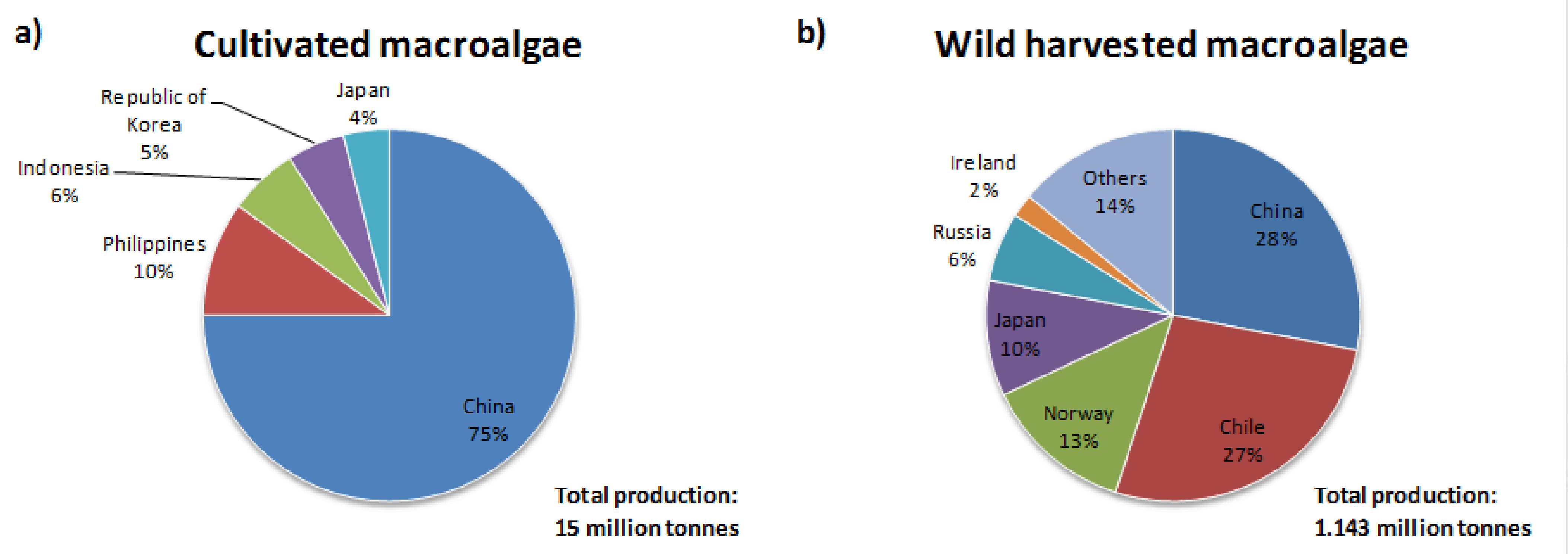
- POLICY:
- 2020-2030 targets:
- ILUC: limits the share of biofuels from crops grown on agricultural land to 7%
- sets an indicative 0.5% target for advanced biofuels

# Overview of the main process stages for production of biofuels from macroalgae and microalgae.

| Process step | Macroalgae (or seaweeds) | Microalgae |
| --- | --- | --- |
| Cultivation | natural stocks, drift material, cultivation (near-shore systems, off-shore systems, open ponds) | Photobioreactors<br>open ponds |
| Harvesting | manual<br>mechanised | flocculation<br>flotation<br>sedimentation<br>centrifugation<br>filtration |
| De-watering/Pre-treatment | cleaning/washing<br>crushing<br>maceration | dewatering<br>drying |
| Conversion to biofuels | biochemical processes:<br>• anaerobic digestion (AD)<br>• fermentation | Biochemical processes:<br>• AD<br>• fermentation<br>Thermochemical processes:<br>• gasification<br>• hydrothermal liquefaction<br>• pyrolysis<br>• direct combustion<br>• trans-esterification and biodiesel production |

# Macroalgae: cultivation

- Commercial production (15 Mt) in Asia, for food and hydrocolloids for the food, pharmaceutical and chemical industries.
- In EU early stage of development (23 kt from wild stocks in 2011).
- Environemntal issues with wild stock.
- Near-shore cultivation commercial (off-shore and on-land in infancy)
- For biofuels production, large amounts, off-shore farming needed, long lines



# Harvesting

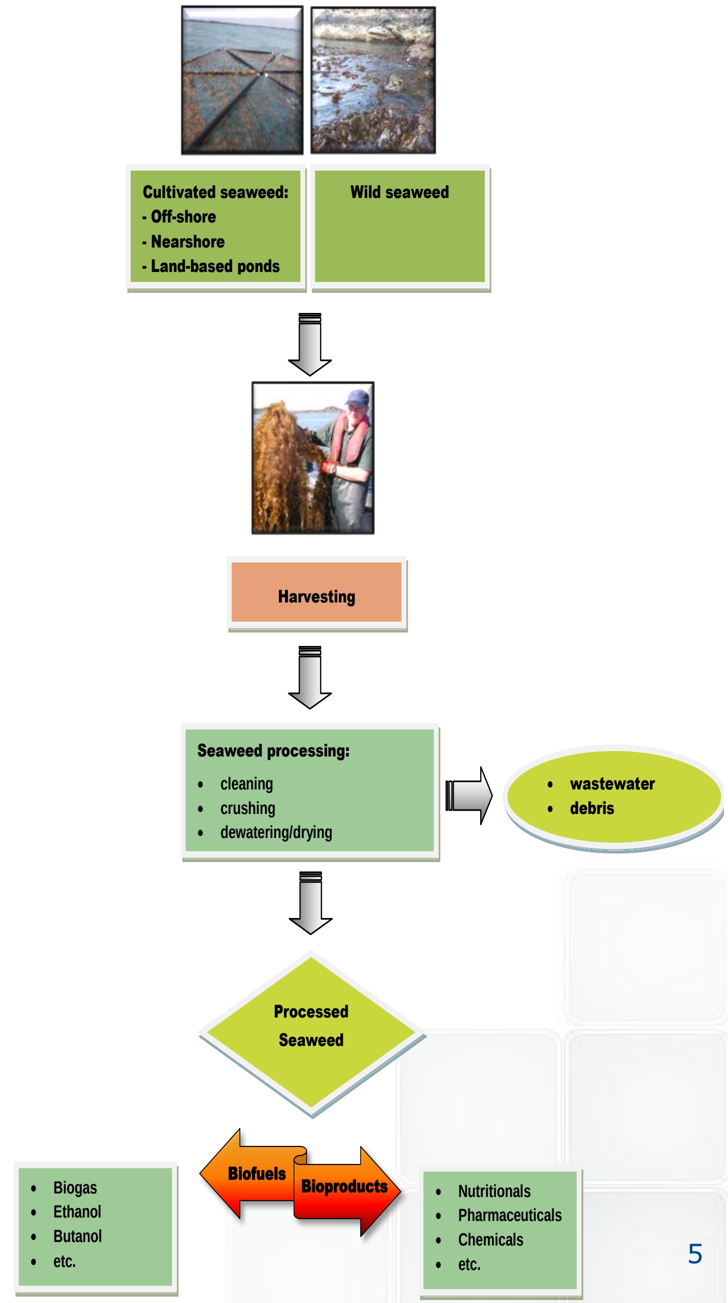
- Manual
- Mechanized

# Pretreatment:

- Cleaning
- Chopping/milling

# Drying:

## water content reduced from 80-85% to 20-30% to avoid degradation and facilitate transportation



# Macroalgae: biofuel options: biomethane

Macroalgae: high moisture (85-90% wt.) and fermentable carbohydrates content (23-79.4% by dry wt.); little cellulose and normally no lignin (i.e. recalcitrant fractions)

AD is an efficient conversion technology:

+ yield 0.08-0.40 m3 of CH4/kg VS
+ Methane concentration 49-78%
+ HRT 20 days sufficient
+ Inoculum: cow manure
+ Grinding improves yield
- Fluctuating supply
- Seasonal variable chemical composition

| Macroalgae | Reactor type | Volume | HRT | Temperature | OLR | Methane yield | References |
|---|---|---|---|---|---|---|---|
| | | (l) | (days) | (° C) | (gVS/l/day) | ($m^3 CH_4$/kg VS) | |
| Ulva sp. | CSTR | 50 | 26 | 37 | 1.9 | 0.15 | [90] |
| Ulva sp. | CSTR | 1 | 25 | 37 | 1.6-1.85 | 0.08-0.11 | [101] |
| Ulva sp. | CSTR | 6 | 30 | 37 | 1.04-1.25 | 0.19-0.29 | [101] |
| Ulva sp. | CSTR | 1 | 20 | 30 | 1.47 | 0.12-0.20 | [88] |
| Ulva sp. | CSTR | 5000 | 12-20 | 35 | 1.85-2.66 | 0.15-0.38 | [89] |
| Ascophyllum n. | semi continous | 10 | 24 | 35 | 1.75 | 0.11 | [91] |
| Laminaria h. | semi- continous | 10 | 24 | 35 | 1.65 | 0.23-0.28 | [91] |
| Laminaria sacch. | semi-continous | n.a. | 40 | na | n.a. | 0.22-0.27 | [92] |
| Graciliaria sp. | batch | n.a. | n.a. | 35 | n.a. | 0.28-0.40 | [103] |
| Sargassum fl. | batch | n.a. | n.a. | 35 | n.a. | 0.18 | [103] |
| Sargassum pt. | batch | n.a. | n.a. | 35 | n.a. | 0.15 | [103] |

# Macroalgae: biofuel options: bioethanol & biobutanol

Macroalgae: high moisture (85-90% wt.) and fermentable carbohydrates content (23-79.4% by dry wt.); little cellulose and normally no lignin (i.e. recalcitrant fractions)

Macroalgae can be suitable substrates for bioethanol production via hydrolysis followed by fermentation:

Hydrolysis

i) sulphuric acid ($H_2SO4$) at high temperature

ii) specific enzymes, such as cellulase, xylanase, and glucosidase, that facilitate the release of sugars during the process

Acid pre-treatment after grinding:

- Ethanol yield = 7.0-9.8 g/l from 50 g/l of sugars
- Butanol yield = 4 g/l from 15.2 g/l of sugars

The cost of macroalgae ethanol is about $ 0.50/kg, corn ethanol: $ 0.16/kg.

Considerable technological advancement is required to mechanise the planting and harvesting of potential large-scale macroalgal cultures

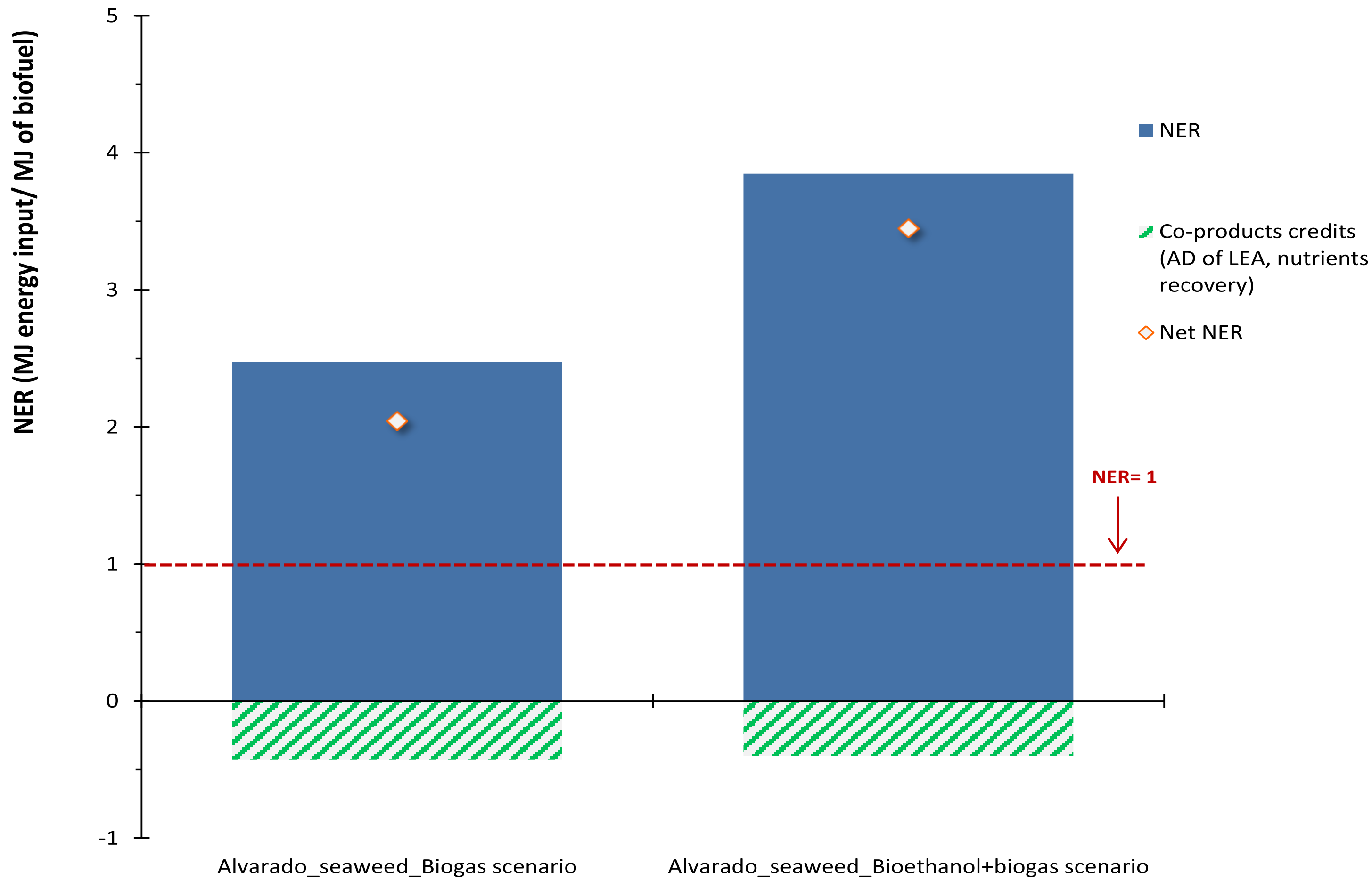
Biorefinery approach: glycerol and organic acids (e.g. acetate and succinate),

# Macroalgal biofuels Life Cycle Energy Balance Biogas

$$NER = \frac{\textbf{Non-renewable primary energy spent to produce the biofuel [MJ]}}{\textbf{Energy contained in the biofuel [MJ]}}$$

## Issues:

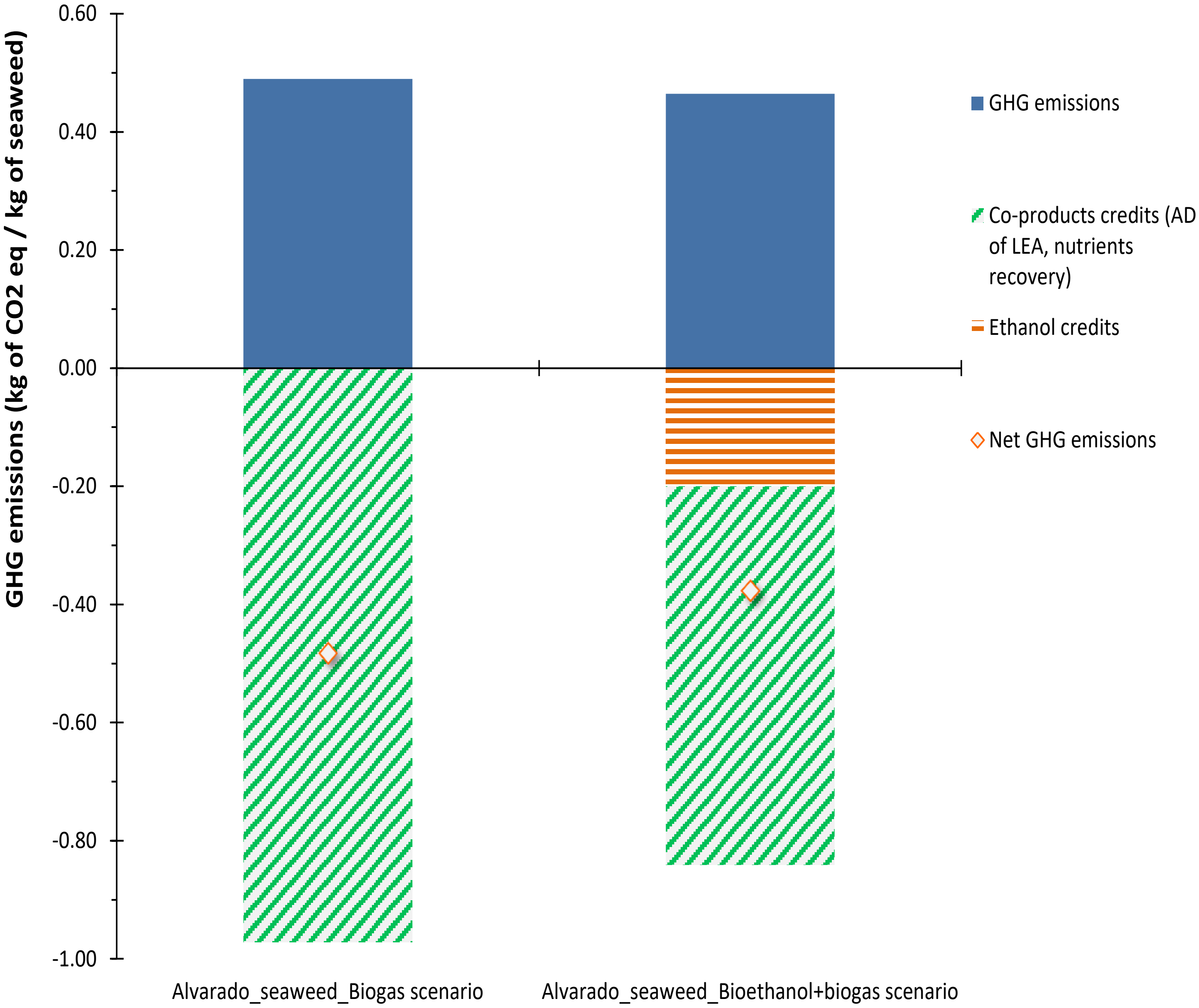
- **High diesel consumption for cultivation and harvesting**
- **Heat and electricity demand for AD, (thermophilic)**



# Macroalgal biofuels GHG emissions

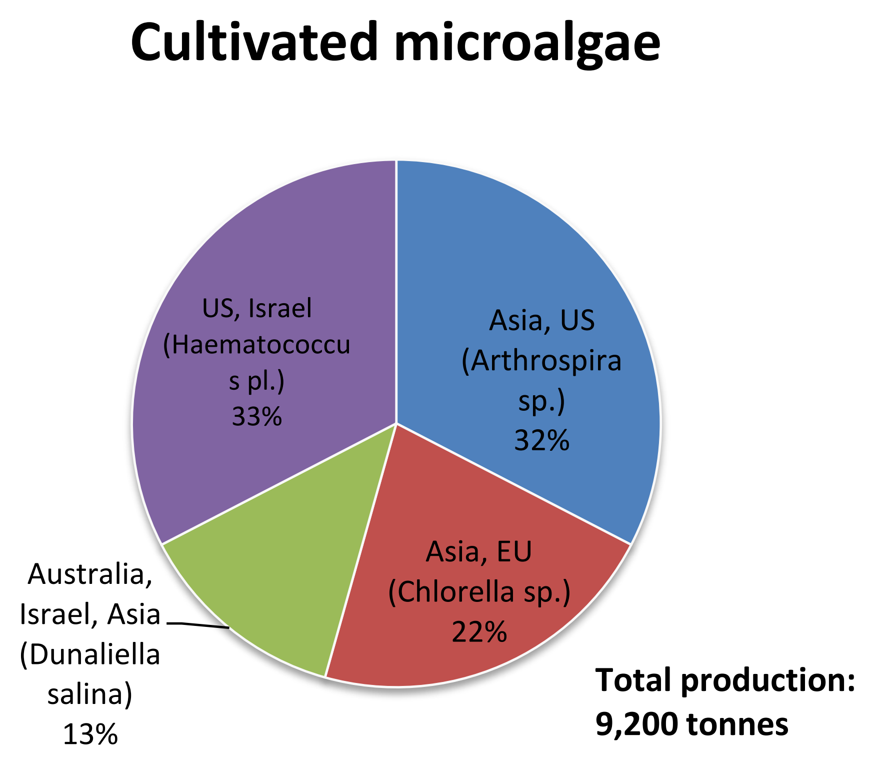
## Issues:

- Multifunctioality credits (electricity from coal)
- Carbon uptake credits
- Infrastructures
- Ancillary processes (WWT)



# Microalgae: cultivation

- Commercial scale cultures of microalgae are well-established in Asia, United States (US), Israel and Australia since the 1980s.
- Currently, about 9,200 dry wt. tonnes of microalgae are annually produced worldwide mainly for dietary or health food for human consumption and feed additives in aquaculture
- The most abundant strains correspond to Arthrospira platensis and Haematococcus pluvialis with production of about 3,000 dry wt. tonnes each, being cultivated in Asia, US and Israel.
- In Germany, cultivation of Chlorella

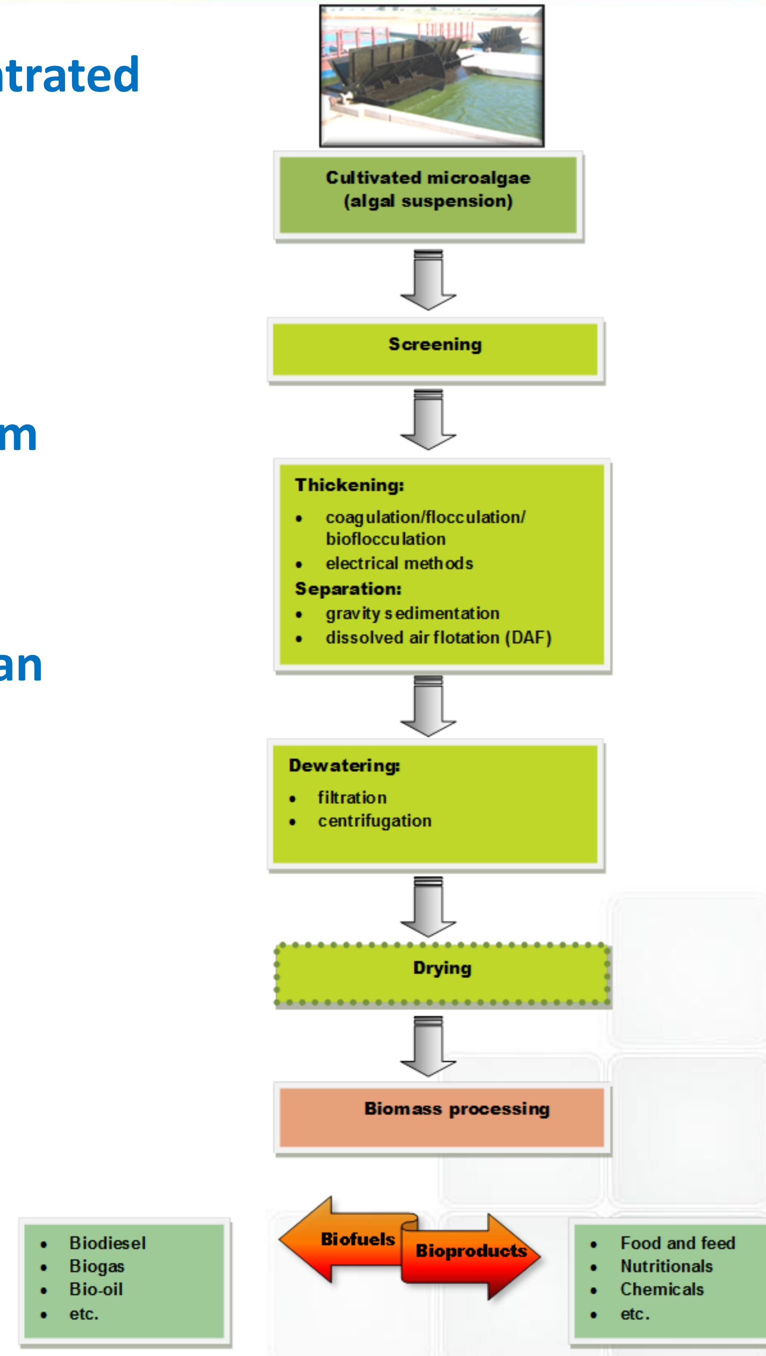


# Microalgae: cultivation

| Production system | Advantages | Limitations |
|---|---|---|
| **Open Race Pond** | Easy to clean | Poor biomass productivity |
| | Easy maintenance | Large area of land required |
| | Low energy inputs | Limited to a few strains of algae |
| | | Poor mixing, poor light and $CO_2$ utilisation |
| | Good for mass cultivation | Contamination risks for algal cultures |
| | Relatively cheap | Difficulty in growing algal cultures for long periods |
| **Tubular Photo Bio Reactor** | Large illumination surface area | Some degree of wall growth |
| | Suitable for outdoor cultures | Fouling |
| | Good biomass productivities | Requires large land area |
| | | Gradients of pH, dissolved oxygen and CO2 along the tubes |
| | | |
| **Flat plate Photo Bio Reactor** | High biomass productivities | Scale-up require many compartments and support materials |
| | Easy to sterilise | Difficult temperature control |
| | Low oxygen build-up | Small degree of hydrodynamic stress |
| | Readily tempered | Some degree of wall growth |
| | Good light path | |
| | Easy to clean up | |
| | Good for immobilization of algae | |
| | Large illumination surface area | |

# Microalgae: Harvesting and concentration

- **Thickening:** the microalgae suspension is concentrated into a slurry of about 6-10% TSS (starting from 0.1%);
  - Chemical coagulation/flocculation
  - Electricity based processes:
  - Autoflocculation/bioflocculation
- **Separation:** of the algae from the growth medium
  - Gravity sedimentation
  - Dissolved Air Flotation
- **Dewatering:** to convert the processed slurry to an algal paste containing 10-25% TSS
  - Filtration
  - Centrifugation
- **Drying:** Depending on the selected downstream processing



# Microalgae: biofuel options: biodiesel

Most explored option.

Extraction of oil from microalgae difficult (thick cell walls obstruct its release)

Two lipids extraction methods:

i) chemical solvent extraction for dry biomass (50-98% dry wt.); n-hexane, chloroform and methanol

ii) supercritical fluid extraction for wet biomass (12-30% dry wt.); ethylene, CO2, ethane, methanol, ethanol, benzene, toluene and water; less efficient

Transesterification as for 1st gen. biodiesel

| Microalgal strains | Lipids content | Lipids productivity |
|---|---|---|
| | % dry wt. biomass | mg/l/day |
| Green | | |
| Chlorella emersonii | 25-63 | 10.3-50 |
| Chlorella protothecoides | 14.6-57.8 | 1,214 |
| Chlorella sorokiniana | 19-22 | 44.7 |
| Chlorella vulgaris CCAP 211/11b | 19.2 | 170 |
| Chlorella vulgaris | 5-58 | 11.2-40 |
| Chlorella sp. | 10-48 | 42.1 |
| Chlorococcum sp. UMACC 112 | 19.3 | 53.7 |
| Dunaliella salina | 16-44 | 46.0 |
| Nannochloropsis oculata NCTU-3 | 30.8-50.4 | 142 |
| Nannochloropsis oculata | 22.7-29.7 | 84-142 |
| Neochloris oleoabundans | 29-65 | 90-134 |
| Scenedesmus quadricauda | 1.9-18.4 | 35.1 |

| Crop | Oil yield |
|---|---|
| | (l/ha) |
| Corn | 172 |
| Soybean | 446 |
| Canola | 1190 |
| Jatropha | 1892 |
| Coconut | 2689 |
| Oil palm | 5950 |
| Microalgae (a) | 58,700 |
| Microalgae (b) | 136,900 |

# Microalgae: biofuel options
# Biomethane & Bioethanol

**BIOMETHANE:**

- **Microalgae excellent substrates for biogas production: high content of lipids, carbohydrates and proteins and low amount of recalcitrant material**
- **Lipids-Extracted Algal, LEA, biomass) can be valorised by AD. LEA biomass contains mainly carbohydrates and proteins**
- **Digestate from AD, of either the whole microalgae or LEA biomass, may be separated into the liquid and solid fractions. The liquid fraction, which mainly contains soluble nutrients components, may be recycled to the microalgae cultivation. The solid fraction of the digestate may be used as fertilizer.**

**BIOETHANOL:**

- **Microalgal biomass can contain significant amount of carbohydrates (about 40-50% dry wt.) with no structural biopolymers, such as lignin and hemicelluloses, suitable feedstock for bioethanol production.**
- **Bioethanol production from microalgae has received less attention compared to biodiesel production.**
- **The production of bioethanol from LEA biomass in combination with biodiesel generation can also be a viable option.**

# Microalgae: biofuel options: biohydrogen and bio-oil

## BIOHYDROGEN:

- Production of hydrogen from different microalgal strains can occur via dark-fermentaton process or photofermentation, under anoxic conditions. Not very efficient. A combination of dark-fermentation, photo-fermentation and Anaerobic Digestion is recommended to enhance energy conversion.

## BIO-OIL

- Biocrude via thermochemical conversion pathways, such as pyrolysis and hydrothermal liquefaction (HTL). The HTL technology is considered promising as it does not require the drying. The bio-oil produced can be stabilized and upgraded to various hydrocarbon biofuels, such as renewable gasoline, and jet fuel

# Microalgal biodiesel Life Cycle Energy Balance

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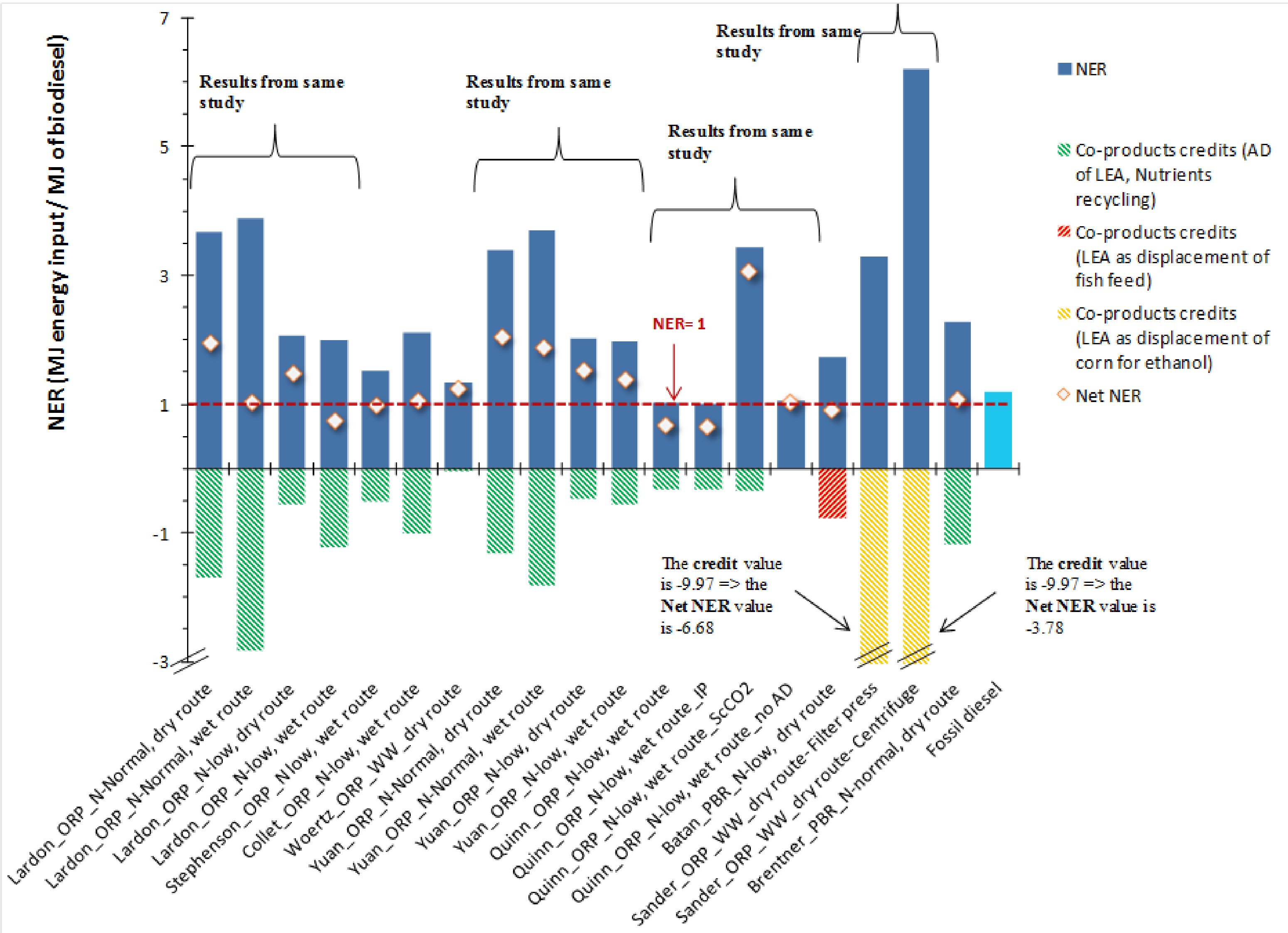
## Issues:

- Co-products management credits
- Infrastructures
- Ancillary processes

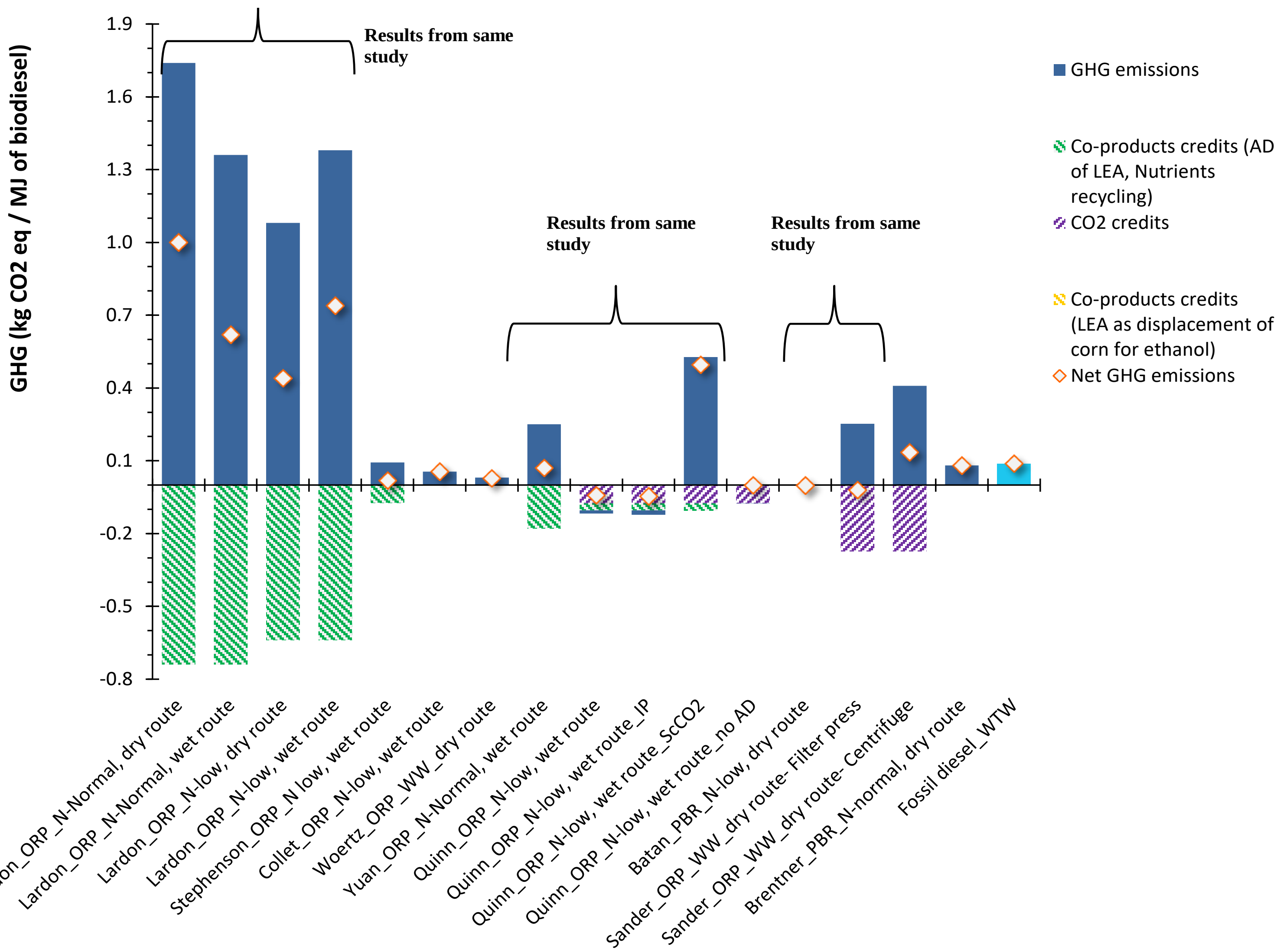
$$\mathrm{NER} = \frac{\text{Non} - \text{renewable primary energy spent to produce the biofuel [MJ]}}{\text{Energy contained in the biofuel [MJ]}}$$



# Microalgal biodiesel GHG emissions

## Issues:

- Co-products management credits
- Infrastructures
- Ancillary processes (flue gas, WWT)
- Carbon uptake credits
- Direct emissions
    - N2O
    - Indirect N2O
    - Biogas plant

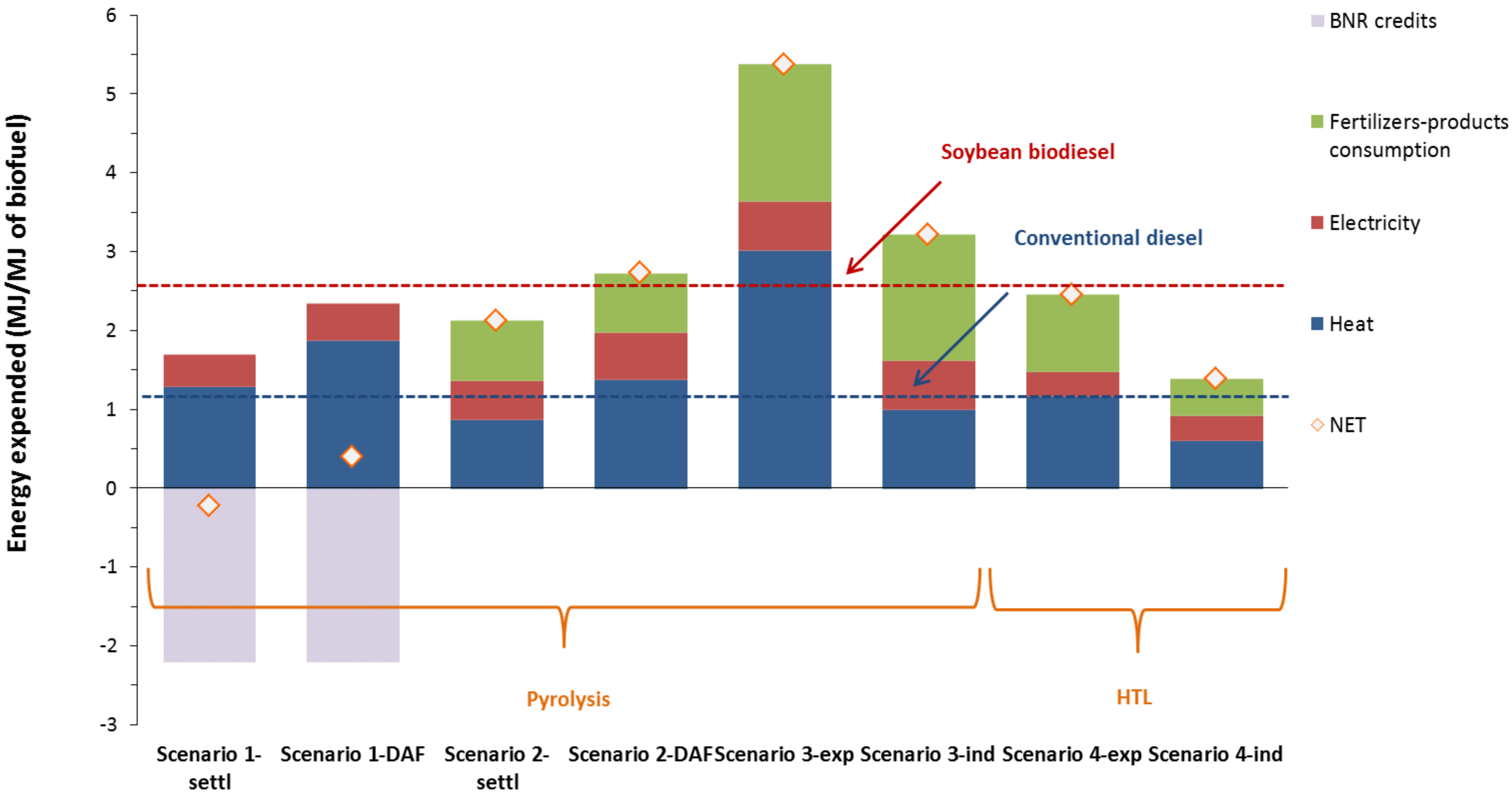


# Microalgal biocrude Life Cycle Energy Balance

$$\text{NER} = \frac{\textbf{Non-renewable primary energy spent to produce the biofuel [MJ]}}{\textbf{Energy contained in the biofuel [MJ]}}$$

## Issues:

- Without co-products credits NER>1 (WW BNR)
- Infrastructures
- Ancillary processes



# Microalgal biocrude GHG emissions

## Issues:

- Multifunctioality credits
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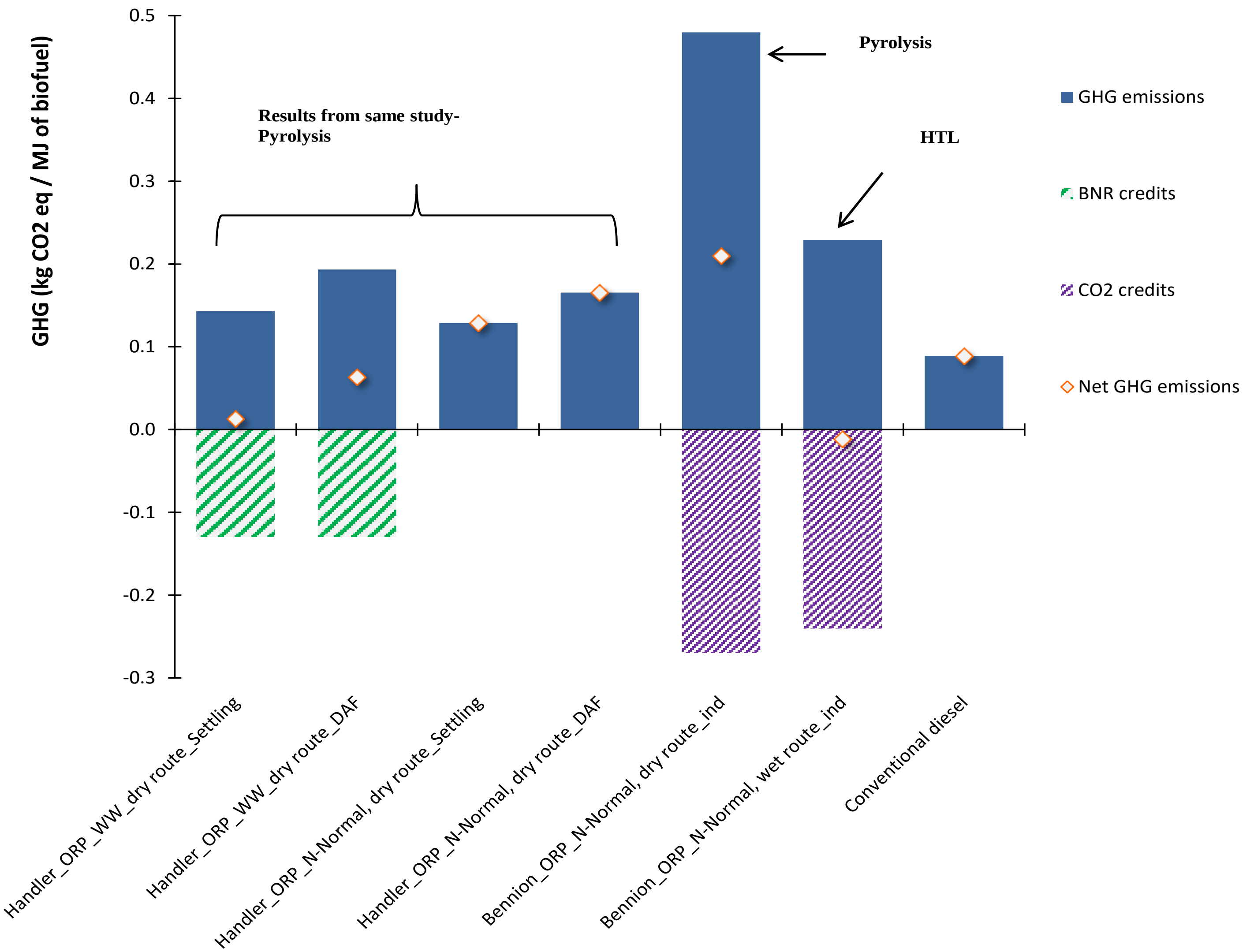

# Remarks on LCA studies

## Remarks on data

- The LCA studies are not representing nor representative for actual plants.
- They are all hypothetical scenarios based on a mix of assumed, modelled and/or experimental data that have been extrapolated from laboratory results and/or pilot scale experiments.
- Unpublished experimental data and personal communications.
- Lack of transparency and calculations could not be reproduced

## Remarks on methods

- The large variations in the energy and GHG emissions balances depend, beside the specific technologies adopted, on the system boundaries, modelling parameters and how multifunctionality was solved.
- Especially the credits considered for co-products management play an essential role.
- Sensitivity analysis are missing.

# Conclusions

**To date, biofuel from microalgae are still far from commercialization.**

- High demands of key resources for **algal growth**, such as **energy**, nutrients, water and $CO_2$ and high **energy consumption** associated with the conversion to biofuels; -> NER > 1 and GHG > fossil alternative
- **Technical challenges** of scaling up lab/pilot scale projects
- Profitability: high capital and operational **costs** of production; high added value products fundamental, but mismatch with amounts;
- Biogas from residues to recycle nutrients
- BNR from WWT promising

**Macroalgae for biofuel (biomethane) promising technology, but:**

- Off-shore cultivation energy intensive.
- Combination of **macroalgal** biofuels in with existing platforms, such as aquaculture or wind systems to generate synergies.
- On shore cultivation, social acceptance
- Wild seaweed harvest environmental impacts, drift seaweed opportunity

Thanks for your attention

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## Summary of the main objectives, systems boundaries and functional unit (FU) of previous LCA studies on microalgae-to-biodiesel processing and modelling scenarios (ordered from the oldest to the most recent).

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| Reference | Objectives of the LCA study | System boundaries | FU |
|---|---|---|---|
| Lardon et al. [24] | Comparison of two fertilization conditions for microalgae growth, i.e. N sufficient supply and N starvation supply (i.e. based on the approximate molecular formula of microalgae biomass and its protein content); comparison of dry and wet methods for extraction of lipids from microalgae. | "Cradle to grave" analysis of the biodiesel production system; "Cradle-to-combustion" analysis of the fuel in a diesel engine. | 1 kg of biodiesel |
| Batan et al. [73] | Analysis of PBR system for microalgae growth, on average yearly basis. The microalgae growth model was based on the results from pilot scale reactor, including the recycling of growth media but not that of Nitrogen from lipids-extracted biomass. | "Well to pump" analysis through GREET 1.8c model, including growth stage; dewater (via centrifugation); oil extraction and conversion to biodiesel; transport and distribution of biodiesel to consumer pumping station. Energy required for construction of ORP and PBR excluded. | 1 MJ of biodiesel |
| Sander et al. [71] | Comparison of microalgae dewatering methods, i.e. filter press and centrifuge; use of wastewater for algal growth. | "Well to pump" analysis through RMEE method. | 1 GJ of biodiesel |
| Stephenson et al. [26] | Comparison of cultivation design (ORP and tubular PBR) for microalgae growth; two-stage culturing approach: stage 1 with N sufficient supply and stage 2 with no N supply. Comparison of cell disruption methods (homogenization and cell hydrolysis). Anaerobic digestion of residual (lipids-extracted) biomass to generate electricity to be used on-site. | "Well to Wheels" analysis, including the emissions from microalgae biodiesel blended with conventional fossil-derived diesel. Foreground system: microalgae cultivation; harvesting; oil extraction and transesterification, background system: materials and energy used by the foreground system. | 1 ton of biodiesel |
| Brentner et al. [72] | Comparison of microalgae cultivation design (i.e. ORP, annular PBR, tubular PBR and flat panel PBR); comparison of technologies for microalgae harvesting, lipids extraction and conversion to biodiesel (under economic allocation). | "Cradle to gate" analysis of five process steps, including: microalgae cultivation; harvesting; oil extraction and transesterification and by-products management. The analysis excludes transport infrastructure, labour, inputs and non-reactor capital equipment. | 10 GJ of biodiesel |
| Collet et al. [125] | Assessment of the effects of an increased microalgae biomass productivity, biomass concentration and use of renewable source of electricity on climate change from microalgae derived biodiesel. | Attributional LCA of microalgae system including: biomass production; conversion to biodiesel (wet extraction); biodiesel combustion; construction/dismantling and disposal of culture infrastructure. | 1 MJ of biodiesel |
| Quinn, et 2014 [74] | Assessment of the effects of an increased microalgae biomass productivity, extraction technologies (hexane vs. supercritical CO2) and integration of AD unit (allowing to nutrients recycling and CHP unit for on-site energy supply) on net energy ratio and life cycle GHG emissions. | "Well to pump" analysis of the energy and GHG emissions through GREET model. System includes: microalgae production; dewatering; lipids extraction and end-use of lipids-extracted biomass. | 1 MJ of biodiesel |
| Woertz et al. [14] | Calculation of life cycle GHG emissions of microalgae biodiesel. Culturing of microalgae in ORP system by means of wastewater. | "Well to Wheels" analysis, including: microalgae cultivation; primary products transport; oil refining; fuel transportation to distribution terminal station and fuel combustion. | 1 MJ LHV of biodiesel |
| Yuan et al. [67] | Development of mass balance model focusing on nutrients, carbon and energy flows through a microalgae biodiesel system with alternative technology options (four combinations of harvesting and dewatering options). Comparison of two fertilization conditions for microalgae growth, i.e. N sufficient supply and N starvation supply (i.e. based on the approximate molecular composition of microalgal biomass) | "Cradle to gate" analysis, including: algae cultivation; harvesting and dewatering; drying; oil extraction and utilization of residual biomass within the same facility. Next, the extracted oil is transported to a nearby biorefinery for biodiesel production. The analysis excludes: equipment; infrastructure construction, repair and maintenance; waste management. | 1 MJ of biodiesel |

**Main features of the projected microalgae growing systems and site location considered by the different LCA studies under review.**

| Reference | Cultivation system design | Facility area (ha) | Site location |
|---|---|---|---|
| Lardon et al. [24] | ORP: system of 100 m length, 10 m width, 0.30 m depth. Operating regime: N-normal growth conditions. | 100 | Mediterranean location |
| Lardon et al. [24] | ORP: system of 100 m length, 10 m width, 0.30 m depth. Operating regime: N-low growth conditions. | 100 | Mediterranean location |
| Batan et al. [73] | PBR: system of 36 m length and 0.12 mm tick polyethylene bags supported in a thermal bath. The reactor bags are subdivide into three reactor sets, namely: incubation reactors to provide microalgae inoculums under N rich medium; reactor set for microalgae linear growth under nutrients rich conditions and reactor set for microalgae stationary growth under N-low conditions. | 315 | Colorado, US |
| Sander et al. [71] | ORP: system of 1.15 m length, 0.18 m depth. Operating regime: N-normal growth conditions (nutrients are supplied by wastewater). | unspecified | unspecified |
| Stephenson et al. [26] | ORP: system designed using two different ORP units, i.e: 1) ORP stage 1 of 150 m length, 10 m width, 0.30 m depth. Operating regime: N-normal growth conditions; 2) ORP stage 2 of 190 m length, 20 m width, 0.30 m depth. Operating regime: N-low growth conditions | 1.21 | United Kingdom |
| Brentner et al. [72] | ORP system of 77 m length, 14m width, 0.20 m depth. of 100 m length, 10m width, 30 cm depth. Operating regime: N-normal growth conditions | 1.3 | Phoenix, US |
| Brentner et al. [72] | Annular PBR cylinder of 2 m height, 0.5 m width, radius of 0.2 m. Operating regime: N-normal growth conditions | 1 | Phoenix, US |
| Brentner et al. [72] | Tubular PBR of 2.5 m height, 0.75 m width, 2 m depth. Operating regime: N-normal growth conditions | 0.1 | Phoenix, US |
| Brentner et al. [72] | Flat panel PBR of 2.5 m length, 1.5 m height, 1.5 m width. Operating regime: N-normal growth conditions | 1.4 | Phoenix, US |
| Collet et al. [125] | Pond for inoculums conservation and culturing ORP of 310 m length and 30 m width, 45 cm depth, 30 cm water depth. ORP are excavated and made by polypropylene liner; covered with a liner of polyethylene; ponds are covered by a removable greenhouse (made by flexible polyethylene film fixed to a wooden frame) to maintain a favourable temperature for microalgae growth while reducing water loss due to evaporation. Operating regime: N-low growth conditions | 80 | Mediterranean site (shrub land) |
| Quinn, et 2014 [74] | Three stages bioreactor system, including: 1) low volume closed bioreactor (under N-normal growth conditions) for supplying inoculum for large-scale facility; 2) high volume ORP facility; 3) section of the ORP dedicated to microalgae lipids accumulation (N-low growth conditions). Down-flow U-Tube configuration to minimize the energy to move the culture from bioreactor to processing facilities. Unspecified dimension | unspecified | unspecified |
| Woertz et al. [14] | High rate ORP system of 0.30 m depth. | 4 | Southern California, US |
| Yuan et al. [67] | ORP system of 0.30 m depth. Operating regime: N-normal growth conditions | unspecified | Southern New Mexico |

Inputs of nutrients (N and P), $CO_2$ and water that are required for the cultivation of different microalgae strains, as documented from reviewed LCA studies. Results are reported to the functional unit of 1 kg of dry wt. algae.

| Reference | Microalgae strain | Cultivation unit | N growth conditions | Nitrogen | | Phosphorus | | $CO_2$ | | Water | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | g N/kg | source | g P/kg | source | kg/kg | Flue gas source | l/kg | source |
| Lardon et al. [24] | Chlorella v. | ORP | N-normal | 46.03 | calcium nitrate | 7.4 | superphosphate | 1.76 | power plant | 4 | freshwater |
| Lardon et al. [24] | Chlorella v. | ORP | N-low | 10.94 | calcium nitrate | 1.8 | superphosphate | 2.10 | power plant | 4 | freshwater |
| Batan et al. [73] | Nannochloropsis salina | PBR | N-normal+N-low | 147 | unspecified | 20 | unspecified | unspecified | $CO_2$ enriched air | unspecified | unspecified |
| Sander et al. [71] | Mixed strains | ORP | unspecified | / | / | / | / | 2.02 | boiler, furnace or power plant | unspecified | WW (supplying N,P) |
| Stephenson et al. [26] | Chlorella v. | ORP | N-normal+N-low | 65.89 | ammonium nitrate | 13.24 | triple superphosphate | 1.88 | power plant | 1.3 | freshwater |
| Brentner et al. [72] | Scenedesmus d. | ORP/PBR | N-normal | 60.26 | ammonium nitrate | 13.32 | calcium phosphate | 1.79 | flue gas from power or ammonia plant | unspecified | freshwater |
| Collet et al. [125] | Nannochloropsis occulata | ORP | N-low | 41.3 | ammonium nitrate | 8.9 | diammonium phosphate | 2.02 | fume gas | unspecified | seawater |
| Quinn et al. [74] | Nannochloropsis salina | PBR+ORP | N-normal/N-low stages | 18 [(a)] | Urea | 27 [(a)] | diammonium phosphate | unspecified | flue gas power plant | unspecified | unspecified |
| Quinn et al. [74] | Nannochloropsis salina | PBR+ORP | N-normal/N-low stages | 53 [(b)] | Urea | 13.14 [(b)] | diammonium phosphate | unspecified | flue gas power plant | unspecified | unspecified |
| Woertz et al. [14] | Mixed strains | ORP | N-low | / | / | / | / | unspecified | flue gas power plant | unspecified | WW (supplying N,P) |
| Yuan et al [67] | Scenedesmus d. | ORP | N-normal | 52.5 | Urea | 13.24 | monopotassium phosphate | 1.83 | flue gas power plant | 239 | groundwater (light to medium salinity) |
| Yuan et al. [67] | Scenedesmus d. | ORP | N-low | 17.5 | Urea | 13.85 | monopotassium phosphate | 1.83 | flue gas power plant | 373 | groundwater (light to medium salinity) |

Biomass productivity, chemical composition (in terms of lipids, carbohydrates, proteins and ash) and lower heating value (LHV) of selected microalgae strains under different culturing systems (ORP/PBR designs and N supplies), as assumed by the different LCA studies under review.

| Reference | Microalgae strain | Cultivation unit | N growth conditions | Biomass productivity | Lipids | Carbohydrates | Proteins | Ash/others | LHV |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ($g/m^2/day$) | (% dry wt.) | (% dry wt.) | (% dry wt.) | (% dry wt.) | (MJ/kg) |
| Lardon et al. [24] | Chlorella v. | ORP | N-normal | 24.75 | 17.5 | 49.5 | 28.2 | 4.8 | 17.5 |
| Lardon et al. [24] | Chlorella v. | ORP | N-low | 19.25 | 38.5 | 52.9 | 6.7 | 1.9 | 22.7 |
| Batan et al., [73] | Nannochloropsis salina | PBR | N-normal+N-low | 25 | 50 | unspecified | unspecified | unspecified | unspecified |
| Sander et al. [71] | Mixed strains | ORP | unspecified | 5 | 30 | 31 | 37.5 | 1.5 | unspecified |
| Stephenson et al. [26] | Chlorella v. | ORP | N-normal+N-low | 11 | 40 | unspecified | unspecified | unspecified | unspecified |
| Brentner et al. [72] | Scenedesmus d. | ORP | N-normal | 48 | unspecified | unspecified | unspecified | unspecified | unspecified |
| Brentner et al. [72] | Scenedesmus d. | annular PBR | N-normal | 96 | unspecified | unspecified | unspecified | unspecified | unspecified |
| Brentner et al. [72] | Scenedesmus d. | tubular PBR | N-normal | 646 | unspecified | unspecified | unspecified | unspecified | unspecified |
| Brentner et al. [72] | Scenedesmus d. | flat panel PBR | N-normal | 68 | unspecified | unspecified | unspecified | unspecified | unspecified |
| Collet et al. [125] | Nannochloropsis occulata | ORP | N-low | 20 | 45.7 | 16 | 22.3 | 15.9(b) | 23 |
| Quinn et al. [74] | Nannochloropsis salina | PBR+ORP | N-normal/N-low stages | 25 | 50 | unspecified | unspecified | unspecified | unspecified |
| Woertz et al. [14] | Mixed strains | ORP | N-low | 22 | 30 | 37.5 | 37.5 | / | unspecified |
| Yuan et al [67] | Scenedesmus d. | ORP | N-normal | 25 | 25 | 35 | 32 | 8 | 19.1 |
| Yuan et al. [67] | Scenedesmus d. | ORP | N-low | 16 | 40 | 41 | 11 | 8 | 22.4 |

# Summary of the main objectives, systems boundaries and functional unit (FU) of previous LCA studies on microalgae pyrolysis and HTL scenarios.

AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

| Reference | Objectives of the LCA study | System boundaries | FU |
|---|---|---|---|
| **Handler et al. [25]** | Calculation of the life cycle (fossil) energy demand and GHG emissions of two microalgae biofuels scenarios, namely:<br>Scenarios ORP_WW_dry route (with settling or DAF): culturing of mixed species in ORP system by means of (primarily treated) WW effluent. Fast pyrolysis of (dried) microalgae to produce "rapid thermal processing" (RTP) green fuel. Upgrading of RTP fuel to hydrocarbon biofuel (similar to petroleum gasoline) by catalytic hydroprocessing;<br>Scenarios ORP_N-Normal_dry route (with settling or DAF): culturing of selected strain (Nannochloropsis sp.) in ORP system by means of brackish/saline water, with inputs of fertilizers and CO2. Fast pyrolysis of (dried) microalgae to produce Rapid Thermal Processing (RTP) green fuel. Upgrading of RTP fuel to hydrocarbon biofuel (similar to petroleum gasoline) by catalytic hydroprocessing; | "Well-to-wheels" analysis from microalgae cultivation to biofuel production. The model includes input parameters for cultivation, harvesting-dewatering, drying, bio-oil recovery through pyrolysis, bio-oil stabilization, bio-oil hydroprocessing and co-products use. | 1 MJ of biofuel |
| **Bennion et al. [28]** | Calculation of the life cycle (fossil) energy demand and GHG emissions of two microalgae scenarios, each considering results of an existing laboratory-scaled system and industrial-scaled projected system, as following:<br>Scenario ORP_N-Normal_dry route_exp: pyrolysis pathway, including a small scale modelled system based on the results of laboratory experiments, under optimal conditions;<br>Scenario ORP_N-Normal_dry route_ind: pyrolysis pathway, including an industrial scale modelled system based on information extrapolated from literature/field data, while assuming a given rate of improvement in terms of biomass yields and energy efficiencies;<br>Scenario ORP_N-Normal_wet route_exp: HTL pathway, including a small scale modelled system based on the results from laboratory experiments, under optimal conditions;<br>Scenario ORP_N-Normal_wet route_exp: HTL pathway, including an industrial scale modelled system based on information extrapolated from literature/field data, while assuming a given rate of improvement in terms of biomass yields and energy efficiencies. | "Well-to-pump" model including: growth, dewatering, bio-oil recovery through pyrolysis or HTL, bio-oil stabilization, bio-oil conversion to renewable diesel, transport and distribution to consumers pump. | 1 MJ of biofuel |

Inputs of nutrients (N and P), $CO_2$ and water that are required for the cultivation of different microalgae strains, from previous LCA studies on pyrolysis or HTL scenarios. Results are referred to the production of 1 kg of dry wt. algae.

| Reference | Microalgae strain | Cultivation unit | N growth conditions | Nitrogen | | Phosphorus | | $CO_2$ | | Water | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | g N/kg | source | g P/kg | source | kg/kg | Flue gas source | l/kg | source |
| **Handler et al. [25] - ORP_WW_dry route (with settling or DAF)** | Mixed strains | ORP | unspecified | unspecified | WW | unspecified | WW | unspecified | WW[(a)] | unspecified | WW |
| **Handler et al. [25] - ORP_N-Normal_dry route (with settling or DAF)** | Nannochloropsis sp. | ORP | unspecified | unspecified | unspecified fertilizer | unspecified | unspecified | unspecified | flue gas | unspecified | brackish or saline water |
| **Bennion et al. [28] scenarios ORP_N-Normal_dry route/wet route_exp** | Scenedesmus d. | ORP | unspecified | 920 | BG-11[(b)] | 920 | BG-11[(b)] | / | atmospheric $CO_2$ | unspecified | unspecified |
| **Bennion et al. [28] ORP_N-Normal_dry route/wet route_ind** | Scenedesmus d. | ORP | unspecified | 88.6[(c)] | Urea | 3.4[(c)] | Diammonium phosphate | / | atmospheric $CO_2$ | unspecified | unspecified |

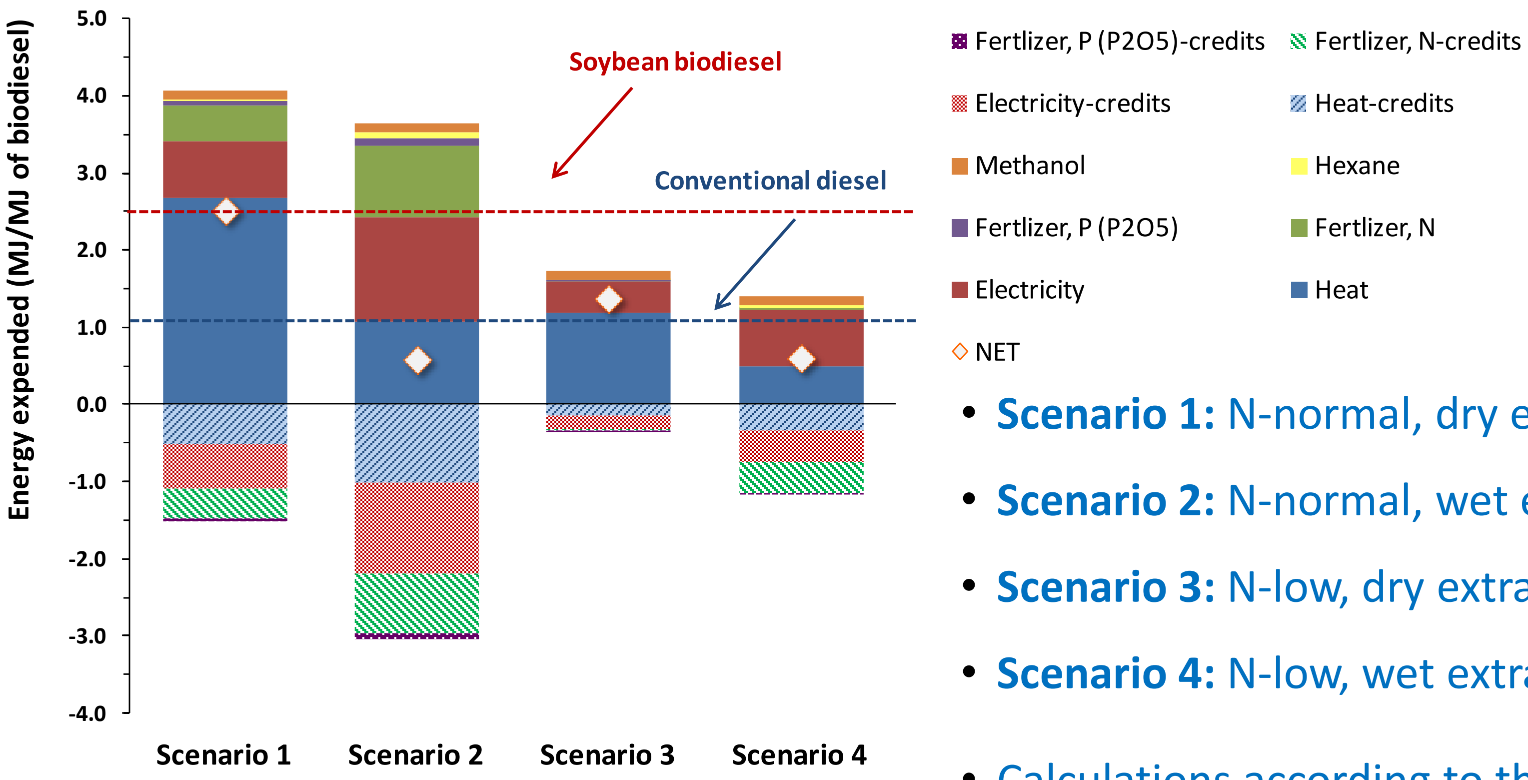
[(a)] Carbon sources from wastewater effluent, including: carbon compounds (remaining after primary treatment) and dissolved CO2;
[(b)] Growth medium that was supplied to the lab-scale cultivation system;
[(c)] Calculated from given data of urea and di-ammonium phosphate supplied to the system [28]

Overview of the biomass productivity, chemical composition and lower heating value (LHV) of selected microalgae strains under different growth systems, from LCA scenarios investigated in previous works.

| Reference | Microalgae strain | Cultivation unit | N growth conditions | Biomass productivity | Lipids | Carbohydrates | Proteins | Ash/others | LHV |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ($g/m^2/day$) | (% dry wt.) | (% dry wt.) | (% dry wt.) | (% dry wt.) | (MJ/kg dry wt.) |
| Handler et al. [25] - ORP_WW_dry route (with settling or DAF) | Mixed strains | ORP | unspecified | 12 | 10 | unspecified | unspecified | unspecified | unspecified |
| Handler et al. [25] - scenarios ORP_N-Normal_dry route (with settling or DAF) | Nannochloropsis sp. | ORP | unspecified | 25 | 25 | unspecified | unspecified | unspecified | unspecified |
| Bennion et al. [28] - scenarios ORP_N-Normal_dry route/wet route_exp | Scenedesmus d. | ORP | unspecified | 6.5 | unspecified | unspecified | unspecified | unspecified | 24 |
| Bennion et al. [28]- scenarios ORP_N-Normal_dry route/wet route_ind | Scenedesmus d. | ORP | unspecified | 13 | unspecified | unspecified | unspecified | unspecified | unspecified |

# Primary energy balance

❑ **Production of 1 MJ of biodiesel without/with the AD process**

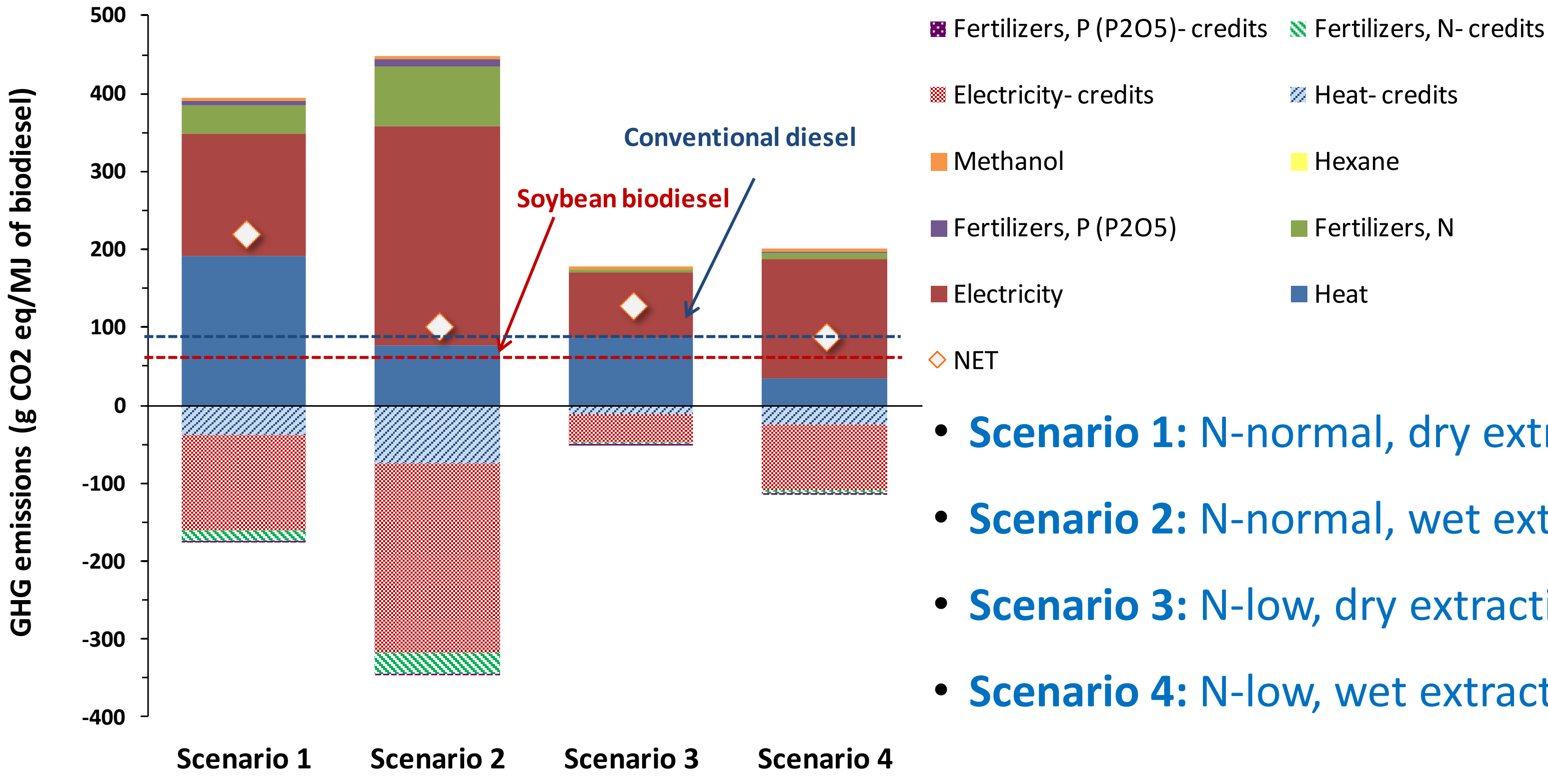



- **Scenario 1:** N-normal, dry extraction
- **Scenario 2:** N-normal, wet extraction
- **Scenario 3:** N-low, dry extraction
- **Scenario 4:** N-low, wet extraction

- Calculations according to the methodology set in JRC WTT studies (Report EUR 26236EN; EUR 27215EN)

# GHG emissions

- Production of 1 MJ of biodiesel without/with AD process




- **Scenario 1:** N-normal, dry extraction
- **Scenario 2:** N-normal, wet extraction
- **Scenario 3:** N-low, dry extraction
- **Scenario 4:** N-low, wet extraction

- Calculations according to the methodology set in JRC WTT studies (Report EUR 26236EN; EUR 27215EN)

# Emissions sensitivities

1. BMP of LEA biomass (± 25% of the base case)
2. N in liquid fraction of digestate (± 15% of the base case)

- LEA biomass= Lipids-extracted algal biomass
- BMP= Bio-Methane Potential

- **Scenario 2:** N-normal, wet extraction
- **Scenario 4:** N-low, wet extraction

- The BMP of LEA biomass is a key factor influencing the net g $CO_2$ per MJ of biodiesel, under N-normal/low supply conditions

# Macroalgae: Current applications and future perspectives

Worldwide boost on research, technological development and patents registration on macroalgal cultivation systems.

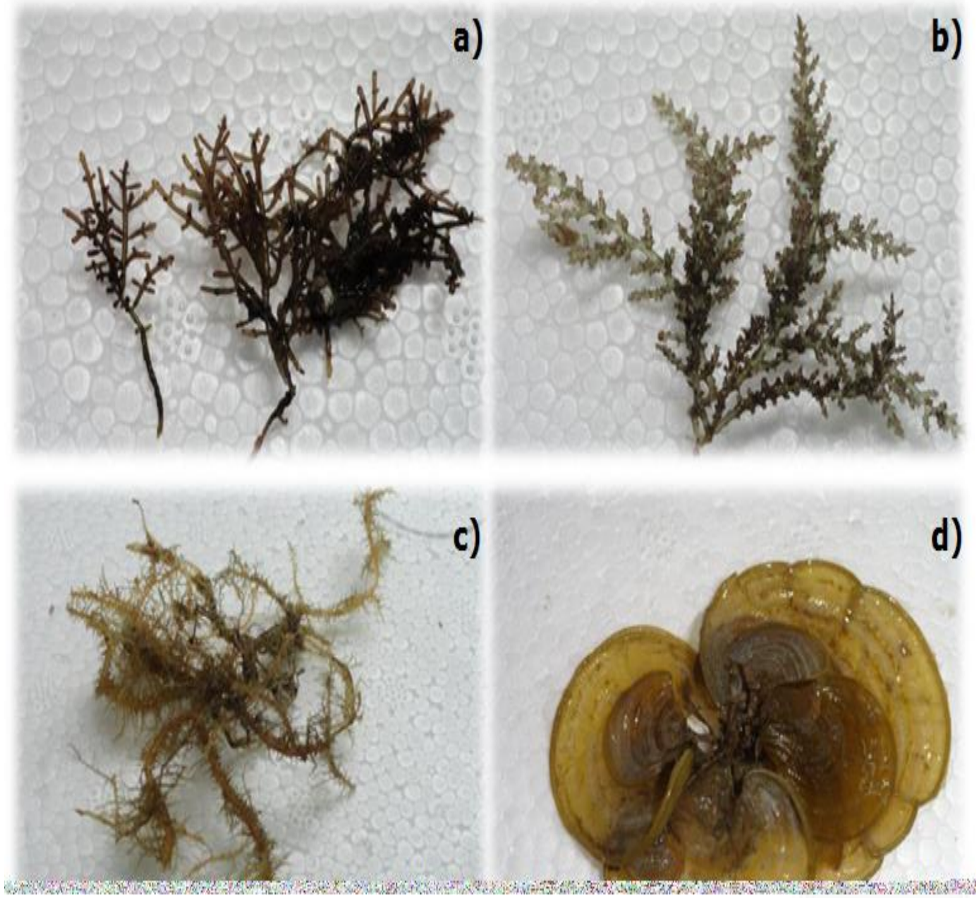
- South Korea and China +28% and +20% per year in the last decade, respectively,
- Europe + 3.9% per year during the last decade.

European commercial farming operations, notably in France, Germany and Ireland, are still at an early stage of development.

Seaweeds are receiving increasing attention as potential renewable feedstock for production of gaseous and liquid transportation biofuels, such as biomethane and bioethanol.

Macroalgal biofuels non-competitive: cultivation and processing too expensive.

Biorefinery approach necessary: producing multiple high-value products, such as hydrocolloids for the food industry, feed and chemicals, is fundamental to develop marketable products.

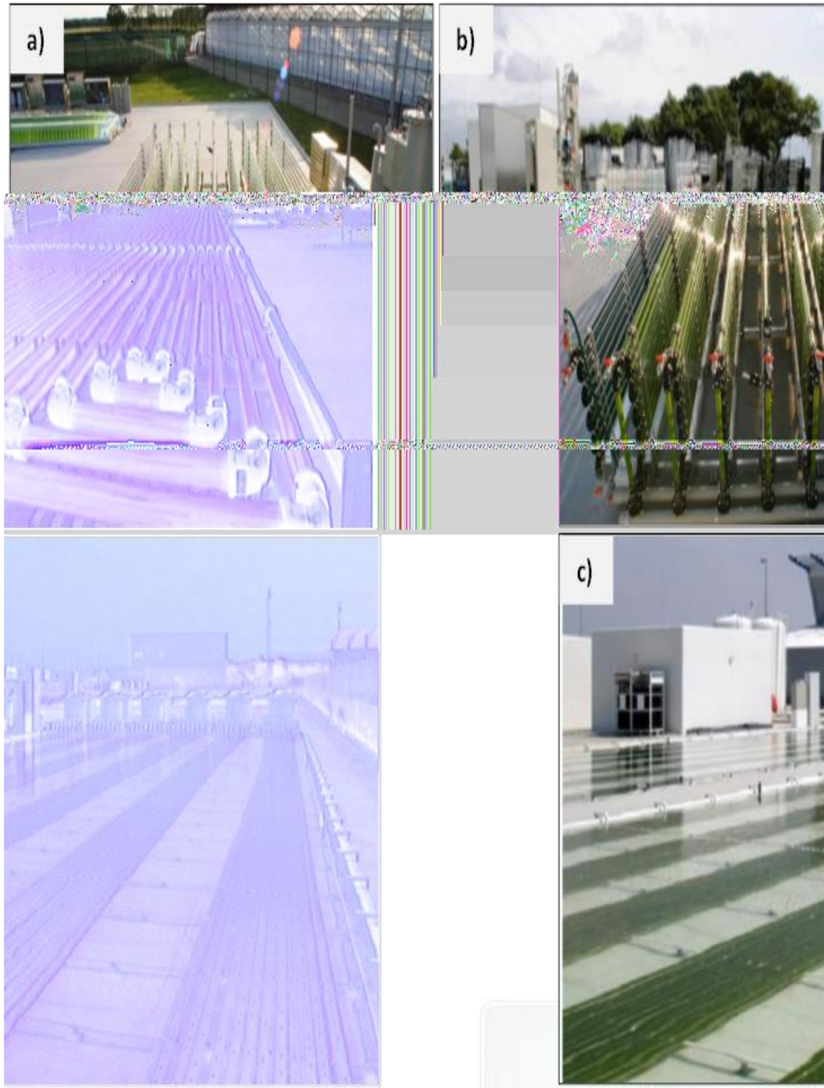


# Microalgae: Harvesting and concentration

| Microalgal species | Harvesting | Efficiency | Energy consumption | Costs |
|---|---|---|---|---|
| | | % | MJ/$m^3$ | USD/ton |
| Chlorella vulgaris | Coagulation/flocculation+sedimentation | 92-99 | n.a. | n.a. |
| | Autoflocculation+Sedimentation | 98 | n.a. | 18 |
| | Bioflocculation+Sedimentation | 34-99 | n.a. | n.a. |
| | Filtration | 98 | 0.972 | n.a. |
| Chlorella minutissima | Coagulation/flocculation+sedimentation | 80 | n.a. | n.a. |
| Chlorella sp. | Flotation | 90 | n.a. | n.a. |
| Chlorella sorokiniana | Coagulation/flocculation+sedimentation | 99 | n.a. | 200 |
| Dunaliella salina | Flocculation+flotation | 98.2 | n.a. | n.a. |
| | Electrolytic Flocculation | 98.9 | 0.828 | n.a. |
| Tetraselmins sp. | Electro-Flocculation | 87 | 0.559 | n.a. |
| | Electro-Flocculation+sedimentation | 91 | 0.328 | n.a. |
| Nannochloropsis oc. | Bioflocculation+Sedimentation | 88 | n.a. | n.a. |
| Nannochloropsis sp. | Centrifugation | 96 | 72 | n.a. |
| | | 17 | 2.88 | |
| Scenedesmus sp. and Coelastrum rob. | Centrifugation | 2-15 | 2.6-3.6 | |
| Phaeodactylum tr. | Coagulation/flocculation+sedimentation | 67-91.8 | 1.19 | 0.429-1.429[a]<br>0.976-2.073[b]<br>2-100[c] |

# Microalgae: Current applications and future perspectives

- The production of algal biomass with $CO_2$ from flue gases from energy/industry may increase the cost-effectiveness.
- Only a limited number of microalgal strains are tolerant to high levels of SOx and NOx.
- High temperature tolerance to minimise the costs of cooling exhaust flue gases.
- However, the amount of $CO_2$ absorbed is released with the combustion of the algal biofuels.
- Microalgae can be efficiently grown in ORPs using wastewater (WW) effluent as a source of low-costs water and nutrients
- Microalgae can contribute to the metals and toxic compounds removal.



# Context

**European Union (EU) energy strategy**: substantial transformation of Europe's energy system based on a more secure, sustainable and low-carbon economy, with the commitment to achieve, by 2030, at least 27% (20 % by 2020) share of renewables relative to emissions in 1990. 10 % is the target for the transport sector in 2020.

## ILUC Directive

- limits the share of biofuels from crops grown on agricultural land to 7%
- sets an indicative 0.5% target for advanced biofuels

**increasing interest in algae as potential feedstock for advanced biofuels production**

# Mandate

As the European Commission's science and knowledge service, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

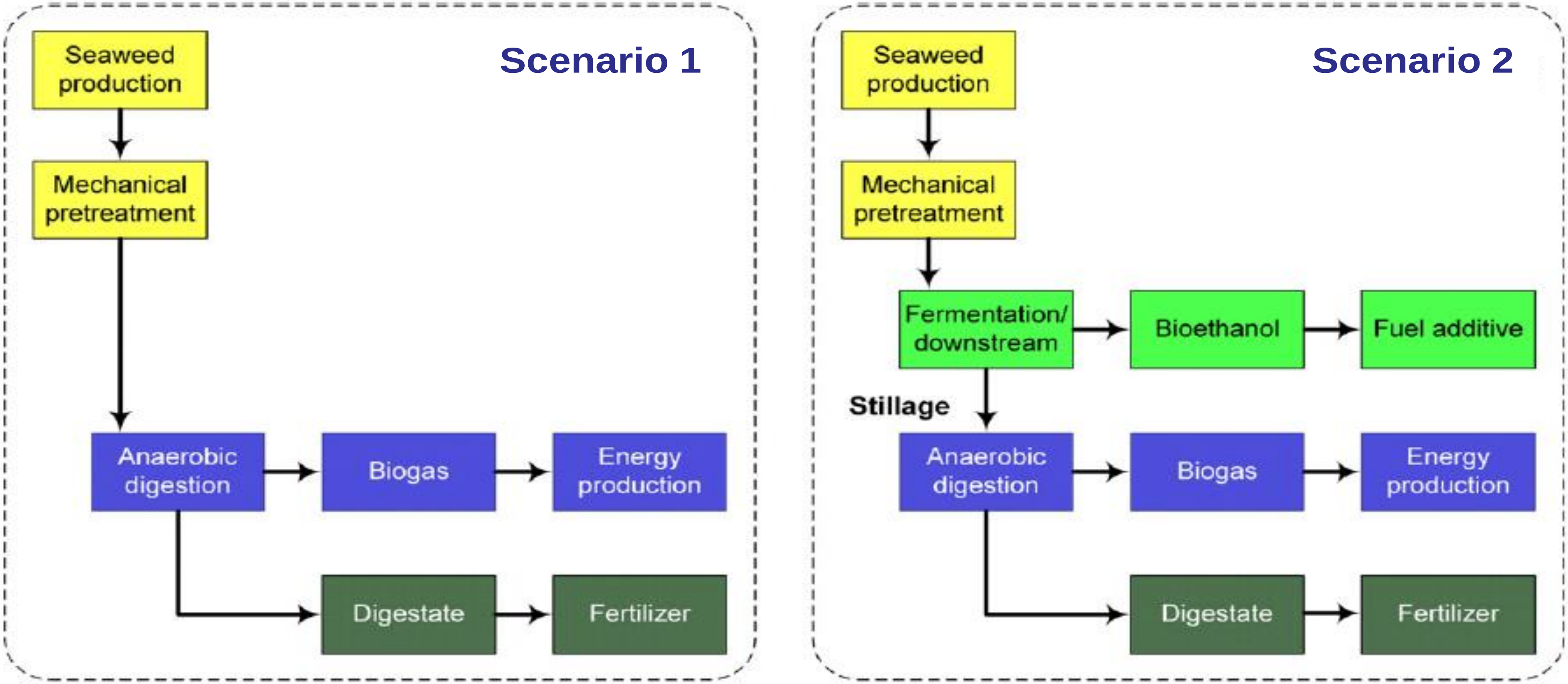
# Scope

The scope of this work is to report on the current status and development in the potential exploitation of algae (both macro- and microalgae species) as a feedstock for biofuels production.

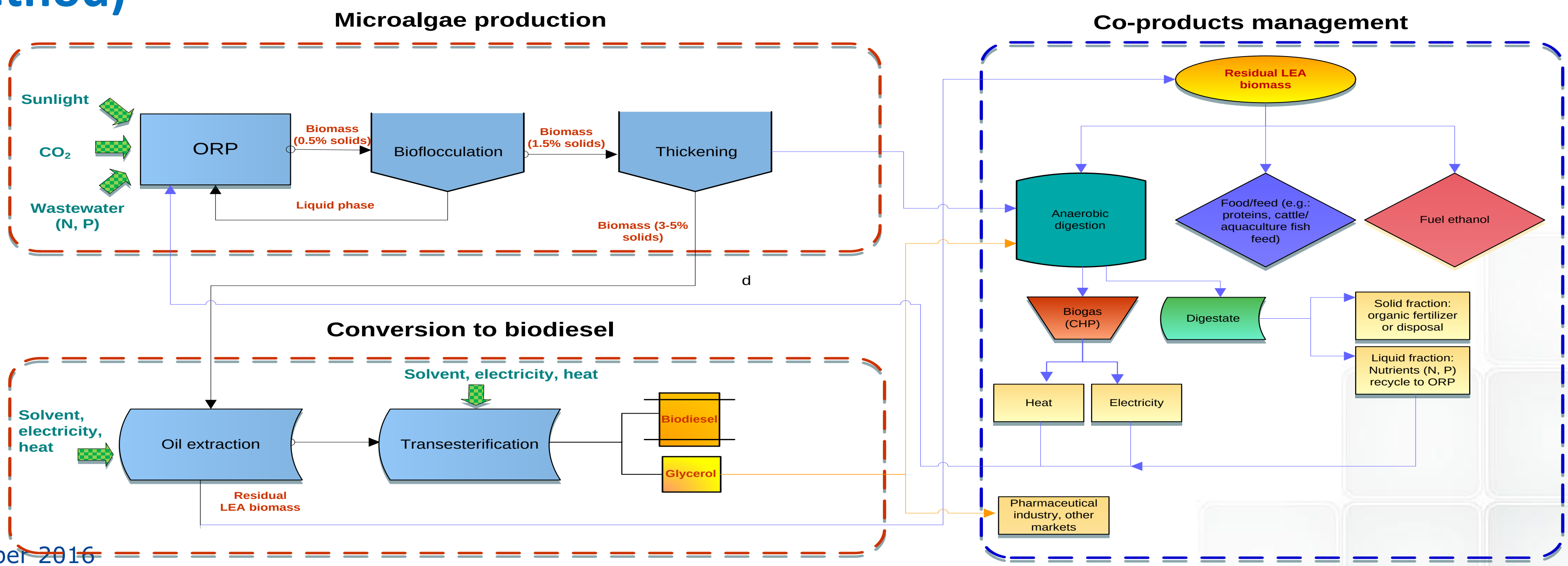
# Approach

We carried out a comprehensive review of the most promising algal biofuel pathways, based on recent findings and developments, in terms of technological options, opportunities and limitations to their overall effectiveness.

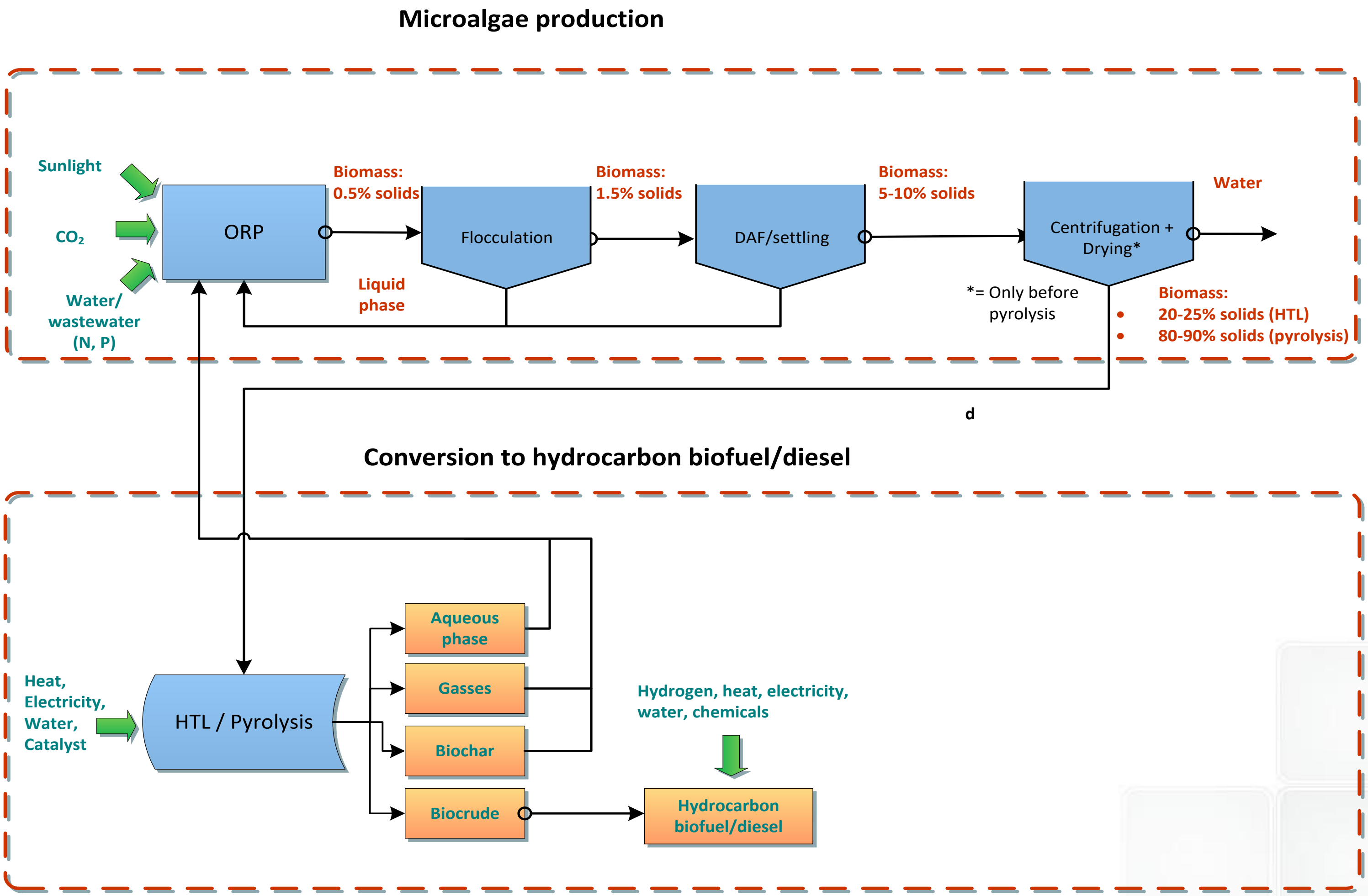
- **Macroalgal biofuel pathways**
- **Only 1 study in literature from secondary and tertiary data (unpublished primary)**
- **Biomethane from AD and bioethanol from SSF**



- **Microalgal biodiesel pathways**
- Several studies in literature
- Analysis of hypothetical scenarios based on a mix of assumed, modelled and/or experimental data extrapolated from laboratory results and/or pilot scale experiments, due to the lack of large-scale operational data
- Harmonisation and normalisation not feasible (different functional units, system boundaries, multifunctionality approach, impact assessment method)



- **Microalgal biocrude pathways**
- **Bio-oil from thermochemical processing**
- **Limited number of studies in literature (2), ORP (assumptions), HTL or pyrolysis**



# Conclusions: perspectives

Our analysis of the state of the art has shown that, for most pathways, the **energy consumed** to produce biofuels from algae is higher than the energy contained in the biofuels itself. And the **GHG emissions** are higher than the fossil alternative.

The demand of key resources for algal growth, such as energy, nutrients, water and CO2, as well as the capital and operational costs of algal biofuels production need to be dramatically reduced to achieve **profitability**.

Techno-economic challenges and environmental impacts of algae-to-fuels strategies need to be **properly assessed** before implementing strategies leading to the deployment of the algal biofuels industry.

Future efforts shall be focused on the effective assessment and possible implementation of viable technologies aiming at:

**i)** **coupling** algal biofuel production with low-cost inputs: $CO_2$ from flue gas, waste heat and wastewater sources;

ii) implementing viable bio-refining schemes for the production of **high – added-value products** in combination with biofuels products.

# Conclusions: Research needs

- The development of selected **high productivity and lipids-rich strains** is of critical importance,
- Energy efficient and low-cost microalgae **harvesting-dewatering methods** need to be developed.
- Processes not requiring **drying** should be developed and validated.
- Appropriate management strategies the valorisation microalgal biodiesel **co-products**, such as LEA biomass, digestate and glycerol, are crucial for achieving favourable energy and emissions balances;
- Develop technologies to use **WWT effluent** as a source of water and nutrients (substitution of BNR occurring at the WWT plant).