Algae for biofuel production

Process description, life cycle assessment and some information on cost

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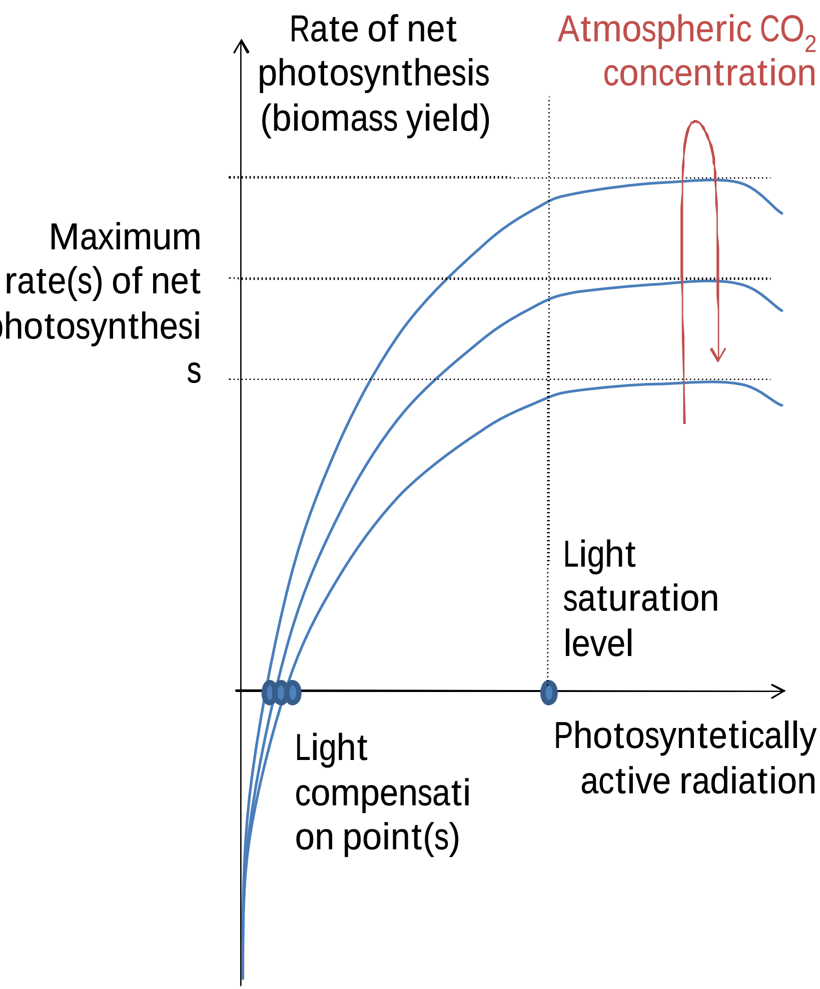
Photosynthesis

Fundamentals

- Photosynthesis: metabolic synthesis of complex organic material using carbon dioxide, water, inorganic salts, and energy from the solar radiation
- Net primary productivity: the rate at which an ecosystem accumulates energy or biomass, excluding the energy it uses for the process of respiration
- The main limiting factors for the net primary productivity of photosynthesis include CO_2 availability (depending on the partial pressure of CO_2 in the air), water availability, soil/water characteristics (need for enough N and P), ambient temperature (affecting the efficiency of enzymes)
- The theoretical efficiency of photosynthesis in natural plants (energy content of biomass synthesized/total incident solar radiation) is close to 6% (15% when the photosynthetically available solar irradiation is considered)

Photosynthesis

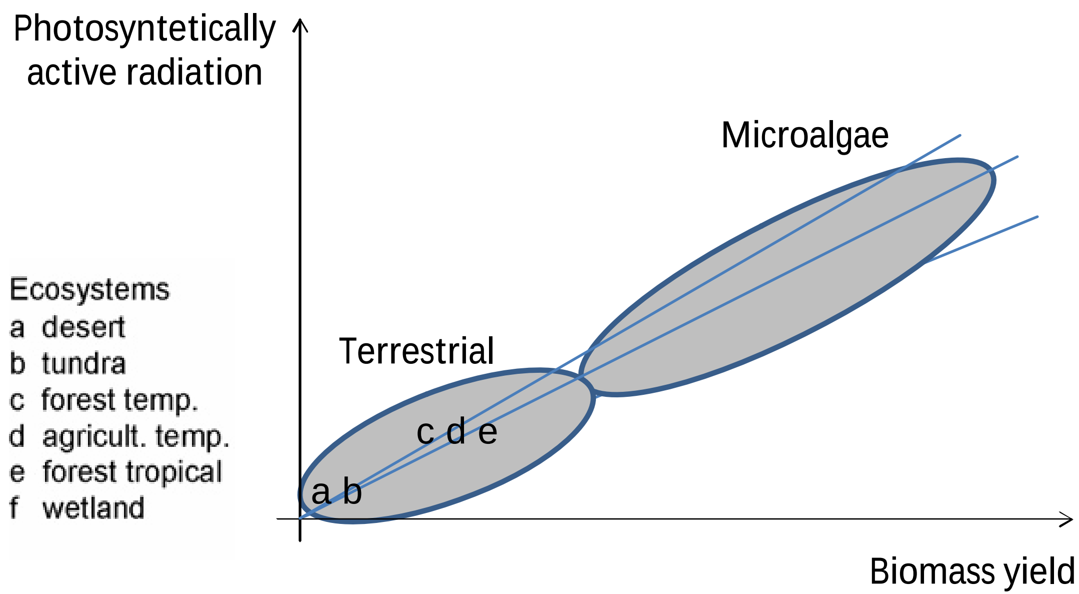
Characteristics



- Given the atmospheric CO_2 concentration, there is no increase in biomass yield beyond a certain amount of solar radiation (light saturation level)
- Increasing the atmospheric CO_2 concentration can increase (up to an optimal value) the efficiency of the photosynthesis (higher net primary productivity efficiency, and higher biomass yields per unit of land surface)
- Enriching the CO_2 concentration is difficult for terrestrial plants, but it is feasible in the case of microalgae (flue gases, opportunities for sequestration)

Algae

Characteristics



- Typical efficiencies of the photosynthesis for terrestrial plants, are around 1% (3-4% in the best cases, like sugar cane)
- Typical biomass yield is below 10 g/m^2/day for terrestrial plants

- Certain algal species have photosynthetic efficiency and lipids/oil production potential at least an order of magnitude higher than many terrestrial crop plants
- Algae may achieve an efficiency of the photosynthesis of 5%, and biomass yields above 20 g/m^2/day

Algae

Biofuel production chain

Nutrients, **CO_2**, **water**, **sunlight,** electricity → Cultivation

Cultivation ↓

Electricity → Harvesting and concentration ↓

Heat, electricity → Combined water separation and oil extraction

Harvesting and concentration ← Electricity ↓

Drying ← **Heat**, electricity ↓

Oil extraction ← **Solvents**

Separation of water and biomass and oil extraction

Harvesting and concentration ← Electricity ↓

Extraction of fats from a concentrated solution without drying ← **Organic solvents** ~~**Heat**~~

↓

Conversion to biodiesel

Algae

Cultivation systems (1)

- Currently, two main solutions for algae cultivation have been adopted
  - Open ponds (raceways)
  - Photobioreactors (PBR)

Algae

Cultivation systems (2)

- Open ponds (raceways)
  - Large, beyond lab scale, but not commercial
  - Subject to contamination from predator strains
  - Subject to evaporative water loss
  - Subject to a difficult control of temperature (day/night, seasonal)
  - Lead to solutions with little biomass concentration
  - Require larger amount of nutrients (N, P, K)

Algae

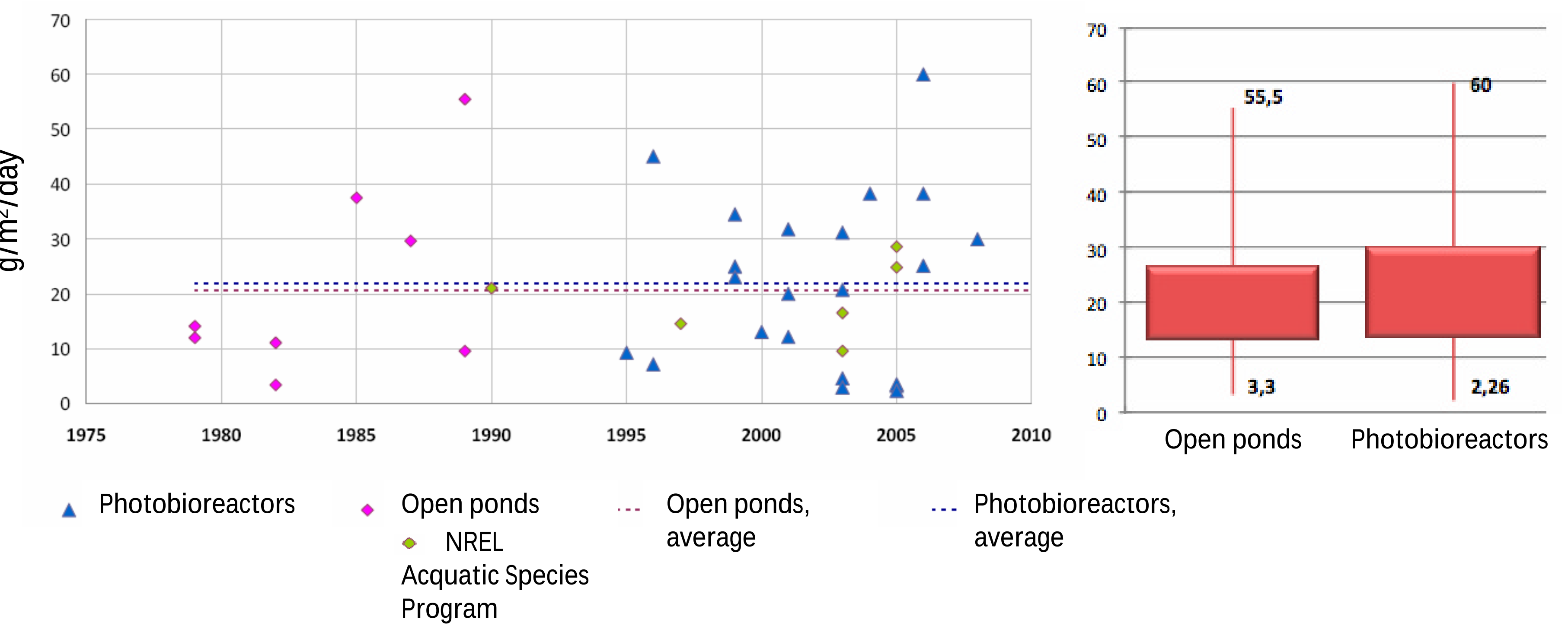
Cultivation systems (3)

- Photobioreactors (PBR)
  - Allow single species culture
  - Allow easier and accurate provision of nutrients (N, P)
  - Lead to more concentrated solutions
  - Need larger amounts of energy for mixing and to maintain temperature
  - With flue gases (having an higher CO_2 concentration than the atmosphere) PBR can lead to higher biomass yield compared to open ponds and lower energy requirements
  - Reduced footprint if there is sufficient light (e.g. when solar radiation is high) because the optimal illumination intensity for algae is below those typical of a sunny day in between the tropics (light saturation, opportunity to pile up PBRs)
  - Laboratory scale, never scaled up, not commercial

Algae

Yields

Evolution of biomass yields reached from 1975 to 2008 in labs (excluding company claims)



- PBR developed mainly after 1995
- No clear indication of higher yields from PBR with respect to open ponds, notwithstanding other advantages

Algae

Yields used for the analysis

- Biomass yield on average around 20 $g/m^2/day$, with peaks at 60 $g/m^2/day$ (claims beyond that exist, but they are likely to refer to very special and limited conditions)
- 20 $g/m^2/day$ considered as indicative for average production across long periods of time (maybe conservative)
- Average yield of oil suitable for the production of biodiesel is typically included between 20 and 50 %
  - It can even reach 90% for some species (under particular conditions), but high lipid fractions are generally associated to low overall biomass productivity (plants tend to produce fats when they are under stress, and therefore when their growth rates are limited)
- Assuming 20%(maybe conservative), yields of algal oil are close to 20000 L/ha/year, about 5 times higher than the best yields achieved for the "first generation" crops (palm oil in South East Asia)
  - Less conservative estimates (especially for oil yields) lead to even higher values

Algae

Water separation → oil extraction

- Algae are produced in a water-rich solution
- The oily component needs to be extracted and then converted to fuel
- The extraction of the oily component can be done through chemical processes that
  a) require mechanical disruption of the biomass cells to free the lipid materials (generally contained in the cell walls) from the cellular structure (harvesting). Such processes need high temperatures and pressures, and:
    - may require the use of solvents (e.g. organic two-solvent system, leveraging on the “like dissolves like” principle), applied in combination with a de-watering step and a drying phase before the oil extraction, to reduce the need for solvents and to enhance their effectiveness
    - may not require solvents, and could combine oil extraction and water separation (subcritical water extraction, taking advantage of the higher miscibility of oils in quasi-supercritical water and their easy separation once the temperature and the pressure of the solution are reduced)

  b) extract the fats using organic solvents that are compatible with a re-cycling of the algae in the bio-reactor, without requiring high temperatures and pressures
    - such processes are the object of an increased attention from companies that are patenting their developments while undertaking small-scale pilot tests

Algae

Harvesting, concentration

- The harvesting process occurs through a number of steps
- Flocculation
  - Use of chemical binding agents and air flotation (established solution for sewage systems) in order to collect biomass
- Filtration
  - Process used after flocculation, to reduce the amount of water
  - It needs to be Risk of blinding of pores vs. efficacy for de-watering
- Centrifugation
  - Mechanical process well established in industry, it enhances the concentration and may destroy the cell wall, leading to a difficult extraction of oils. As a result, appropriate strains would need to be developed

- Flocculation, filtration → about 3% concentration in water
- Centrifugation → about 20%

- Further concentration of the biomass is required for the oil extraction through conventional solvents

Algae

Drying, other high-temperature & pressure processes

- Drying is one option for the achievement of a higher biomass concentration in water
  - Very energy intensive (need for heat and high pressure), it can require around 60% of the energy content of algae
- Strains with higher energy content may help reduce energy needs for drying, especially if the non-oil biomass residues are re-cycles for the generation of heat
- Drying leads to concentrated biomass and oils, which can be separated using solvents

- Combined water separation and oil extraction in quasi-supercritical water (relying on the larger solubility of oil in quasi-supercritical water) is a possible alternative
  - This approach is also very energy intensive (need for heat to reach very high temperatures, and high pressure)
  - Its energy demand can be reduced by limiting the amount of quasi-supercritical water. In this case centrifugation is not enough

Algae

Water separation and oil extraction

- Organic solvents may provide an alternative oil extraction process
  - They do not require high temperatures and pressures, making their use much less energy intensive than other processes
  - They are compatible with a re-cycling of the algae in the bio-reactor, but this feature implies a reduced effectiveness of the organic solvents

- Skipping the drying step is a challenge (and an opportunity) to reduce the energy consumption needed for the production of algae biofuels (and to cut production costs!)
  - this approach is being increasingly investigated because of the significant potential advantages that would derive from its successful application

- Some startups (Algae Link, Origin oil) are examples of those aiming to skip the drying phase through the direct extraction of oils, combined with the use of biomass residues for biogas production

Algae

Conversion to fuels (1)

- Algal-oils are suitable for processes conventionally used for the conversion of vegetable oil to biodiesel, like hydrogenation and trans-esterification
  - Some lipids and pigments (e.g. chlorophyll) are not suitable for trans-esterification
  - The oil extraction through organic solvents can exclude such components

- If grown in the dark, algae can also convert sugars into ethanol and other alcohols (heterotrophic fermentation), as well as hydrocarbons
  - Photosynthetic processes are suppressed once algae are grown in the dark, and the synthesis of hydrocarbons or alcohols occurs if the organisms are fed with sugars
  - Alcohol production can also be accomplished through the production and storage of starch through photosynthesis within the algae

- Algae may also be more suitable than other organisms for the conversion of cellulosic materials if they are proven more resistant to pre-treatment agents

Algae

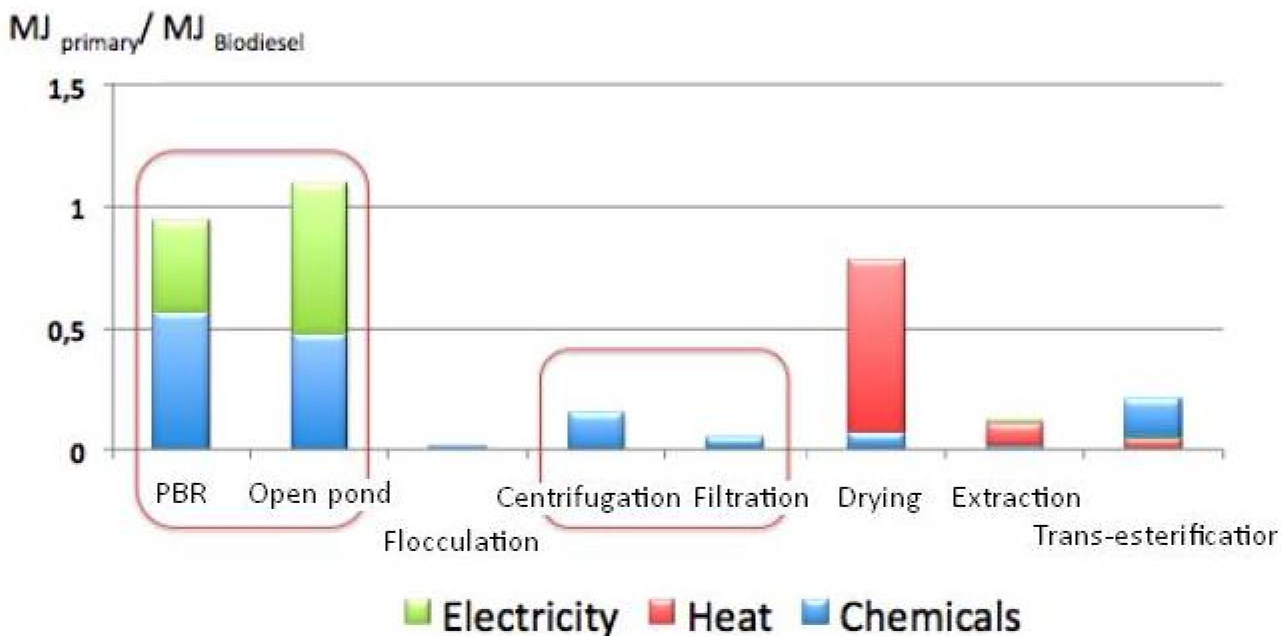
Conversion to fuels (2)

- Technologies like pyrolysis, gasification, anaerobic digestion, and supercritical processing allow the conversion of whole algae into fuels instead of first extracting oils and post-processing
  - Pyrolyisis typically yields to a material that can enter the refining process and be converted (hydrotreating and hydrocracking) to refining products
  - Being already fractioned, algae are particularly suitable for flash-pyrolysis, but the presence of water and the need to dry the biomass poses significant problems (high energy requirements and high costs)
  - Algae are a potential feedstock for biomass gasification and conversion to fuels via Fischer-Tropsch synthesis (biomass-to-liquids, BTL). Since FT synthesis is an exothermic process, it could provide some of the heat needed for the drying phase
  - Biogas can be produced from the anaerobic digestion of macroalgae, eliminating some of the energy intensive steps of other conversion processes
  - The extraction and simultaneous trans-esterification of oils using supercritical ethanol or methanol is emerging as a lower-cost innovative approach (up to half of the conventional approach) to convert vegetable oils. Its applicability to algae is not yet proven, but the pathway (exhibiting some water tolerance) could be promising

Algae

Life cycle analysis (1)

- The cultivation and the drying phase are extremely relevant when the production of algae is analyzed with respect to life-cycle emissions
  - The cultivation is affected by the need to provide nutrients (chemicals) to the microalgae, and by the energy requirements and emissions due to their manufacture
  - Drying is characterized by high energy requirements. Specific GHG and pollutant emissions depend on the type of fuel used for the provision of the heat needed in the drying process



Algae

Life cycle analysis (2)

Scenario 1 "Base case"	*Scenario 2* "Dry Path"	*Scenario 3* "Wet Path"
Production of algae biodiesel with drying before extraction of oil	Production of algae biodiesel with drying before extraction of oil	Production of algae biodiesel without drying before extraction of oil
<u>No use for residues</u> of extraction and trans-esterification	<u>Extraction residues are burnt</u> and the generated <u>heat completely recovered</u>.	<u>Extraction residues are used for biogas generation via anaerobic digestion</u> followed by <u>heat and power generation via biogas-fuelled CHP</u> <u>Some nitrogen is recovered</u> after anaerobic digestion and is used for the cultivation phase <u>Trans-esterification residue (glycerol) is burnt</u> and the resulting heat recovered.

<u>Key assumptions:</u>

Algae biomass Yield: 20 g/m2/ day

Lipid content: 20% oil (On weight basis)

Lower heating value of algal biomass after extraction: 11,25 MJ/kg dry biomass

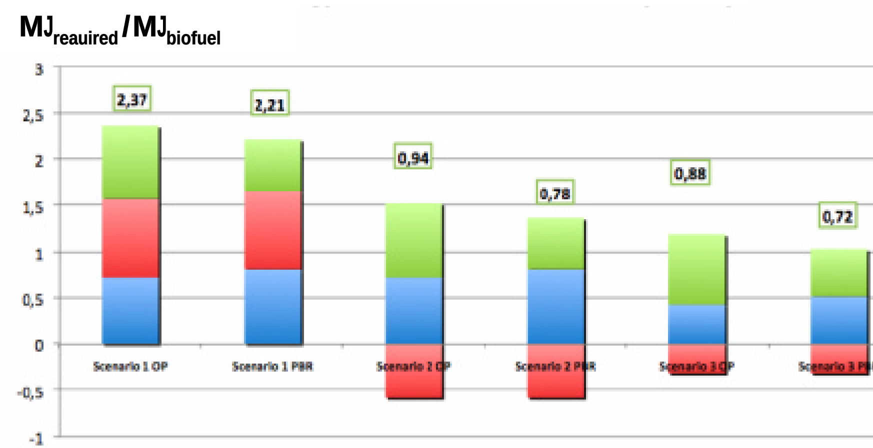
Comparative value

<u>Gasoline (WTW)</u>

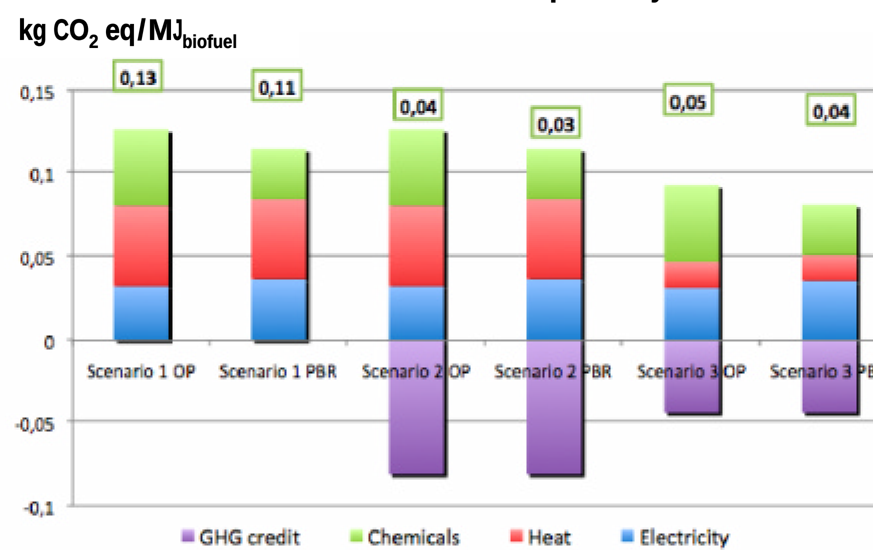
0.15-0.2 $MJ_{required}/Mj_{biofuel}$

0.08-0.084 kg CO_2 eq/$MJ_{biofuel}$

Energy balance of different pathways



GHG balance of different pathways



Algae

Costs

- Little information in literature
- Wide technical-economic estimates (yields and oil content ad those assumed), differences of orders of magnitude…
- Best ones indicate cost estimates close to:
  - USD 2-2.5/L of oil produced in open ponds and fermenters (algae grown in the dark)
  - USD 5-6/L of oil produced in PBR
- The production processes are still under development
- Some of the steps currently required (notably drying) lead to relatively high costs because of the important energy requirements. These are such that algal biofuels are not cost competitive at the moment
- Process improvements are possible and are currently the subject of research in this area
- Possible targets for improvement are:
  a) The development of new strains of plants, optimised for biomass production or oil synthesis, for instance
  b) The development of extraction and conversion processes allowing th recycling of water, little energy consumption and even the recycling of the living organisms, ideally

Next steps

- Continue analysis, focusing more on costs and the overall potential worldwide (with scale-up)
- IEA biofuels roadmap effort will begin late 2009 and go through 2010
  - This will include vehicle/fuel issues, conversion and feedstock supply issues
  - It will also include algae and other advanced biofuels
- Interim results to be fed into ETP 2010; we need them by February 2010
  - Inputs from Bioenergy IA are certainly welcome