Can we reduce impacts of algae biorefinery?

A Life Cycle Assessment perspective

Paula Pérez-López

Center Observation, Impacts, Energy (O.I.E.) of Mines Paris - PSL

MINES PARIS - PSL

Evry site

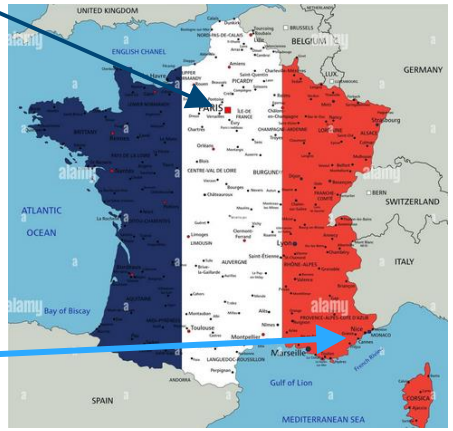
Paris site

Palaiseau site

Fontainebleau site

Sophia Antipolis site
(SE of France, close to Nice)

- **5 departments:**
  - Earth and environmental sciences
  - Energy and processes
  - Mechanical and materials engineering
  - Mathematics and systems
  - Economy, management and society



MINES PARIS - PSL

Evry site

Paris site

Palaiseau site

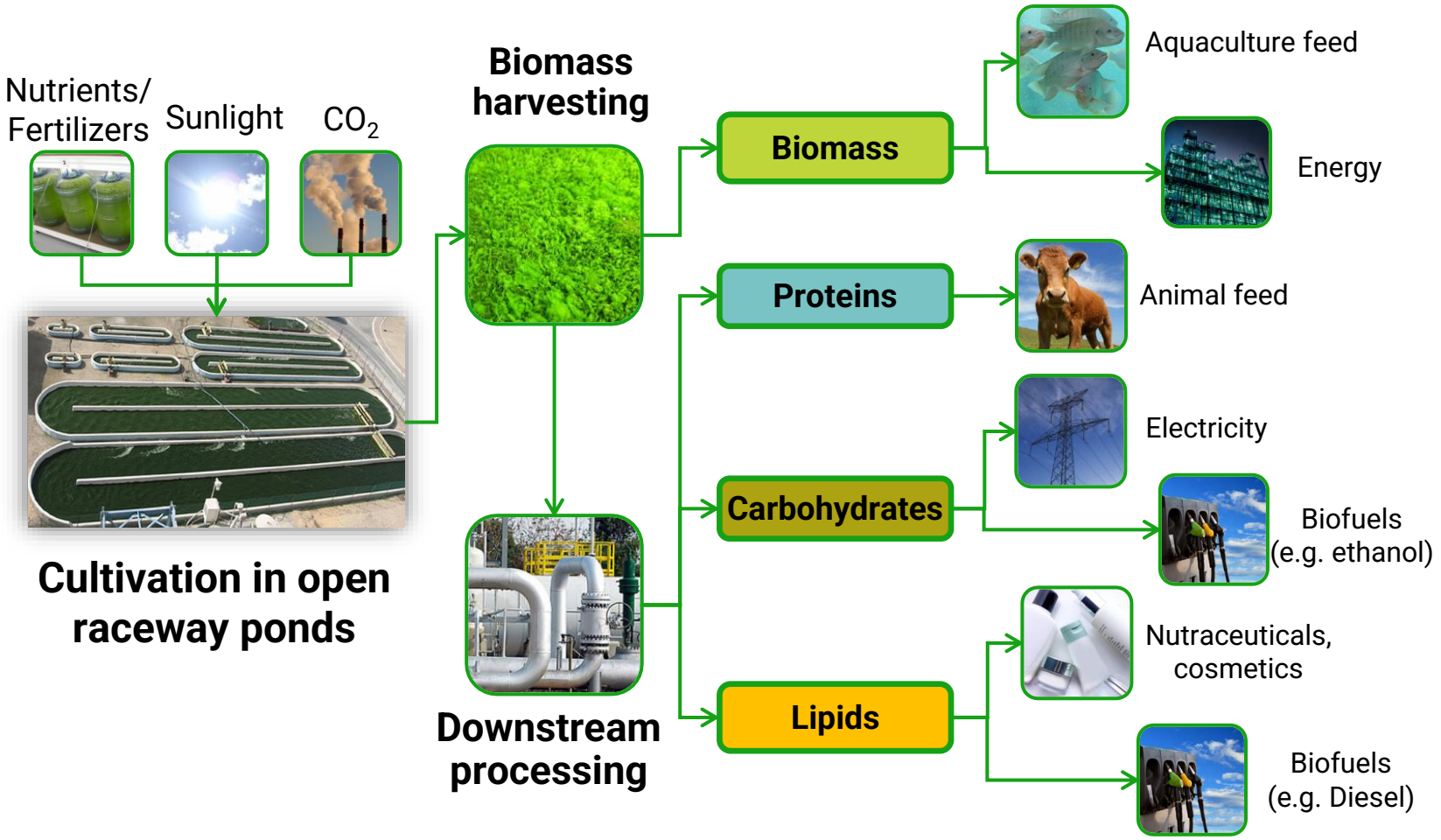
Fontainebleau site

Sophia Antipolis site
(SE of France, close to Nice)

- **5 departments:**
  - Earth and environmental sciences
  - Energy and processes
  - Mechanical and materials engineering
  - Mathematics and systems
  - Economy, management and society

- **Center Observation, Impacts, Energy**
  - Centre Efficacité énergétique des Systèmes (CES)
  - Centre Thermodynamique des Procédés (CTP)
  - Centre Procédés, Energies Renouvelables et Systèmes Energétiques (PERSEE)

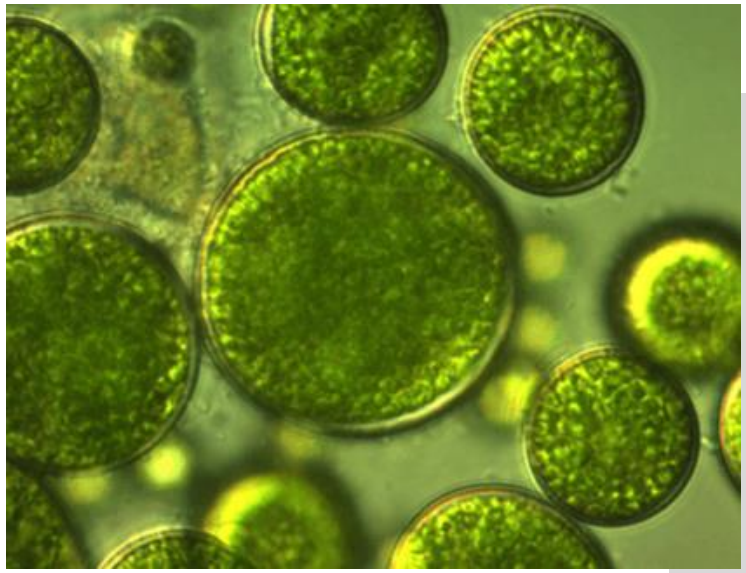
ALGAE: A PROMISING RESOURCE



BENEFITS

- Renewable source of multiple products
- Higher solar energy to biomass conversion efficiency than terrestrial crops
- No need for arable land
- Possibility to couple with waste streams treatment
- ....

BEING A BIORESOURCE, ALGAE SHOULD HAVE NO ENVIRONMENTAL IMPACTS, SHOULDN'T THEY?



https://www.nature-et-forme.com/page /dossier/la-chlorella-fabuleuse-micro-algue

MAYBE, BUT…

- Both culture and downstream processing require energy
- Culture needs water and nutrients
- Downstream may need solvents
- Raw materials and products have to be transported
- …

→

Energy demand

Greenhouse gas emissions

Water consumption

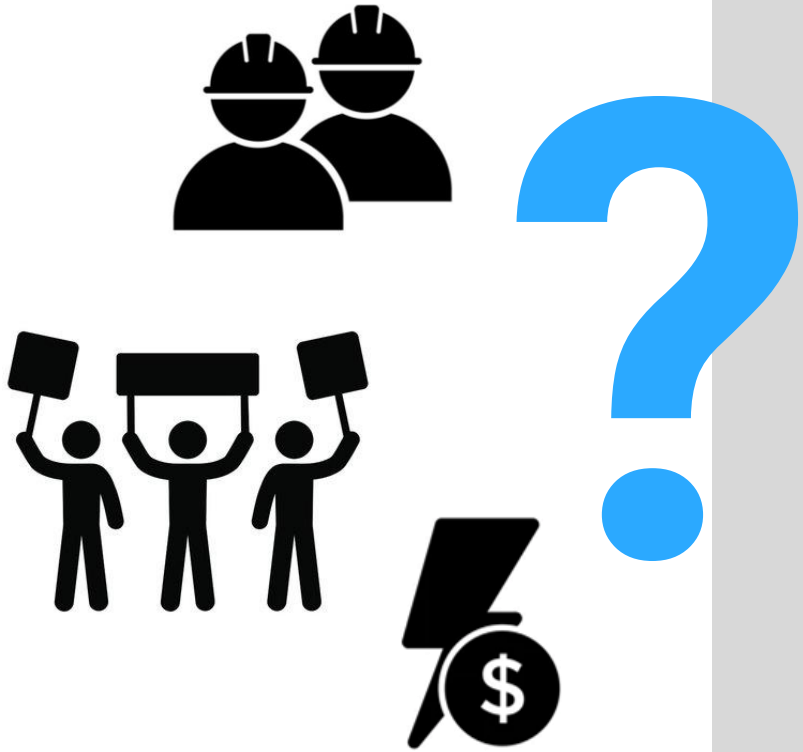
Water emissions of N and P leading to eutrophication

Water emissions of organic compounds

…

BEING A BIORESOURCE, ALGAE SHOULD HAVE NO ENVIRONMENTAL IMPACTS, SHOULDN'T THEY?

IN ADDITION



MAYBE, BUT…

- Both culture and downstream processing require energy
- Culture needs water and nutrients
- Downstream may need solvents
- Raw materials and products have to be transported
- …

→

Energy demand

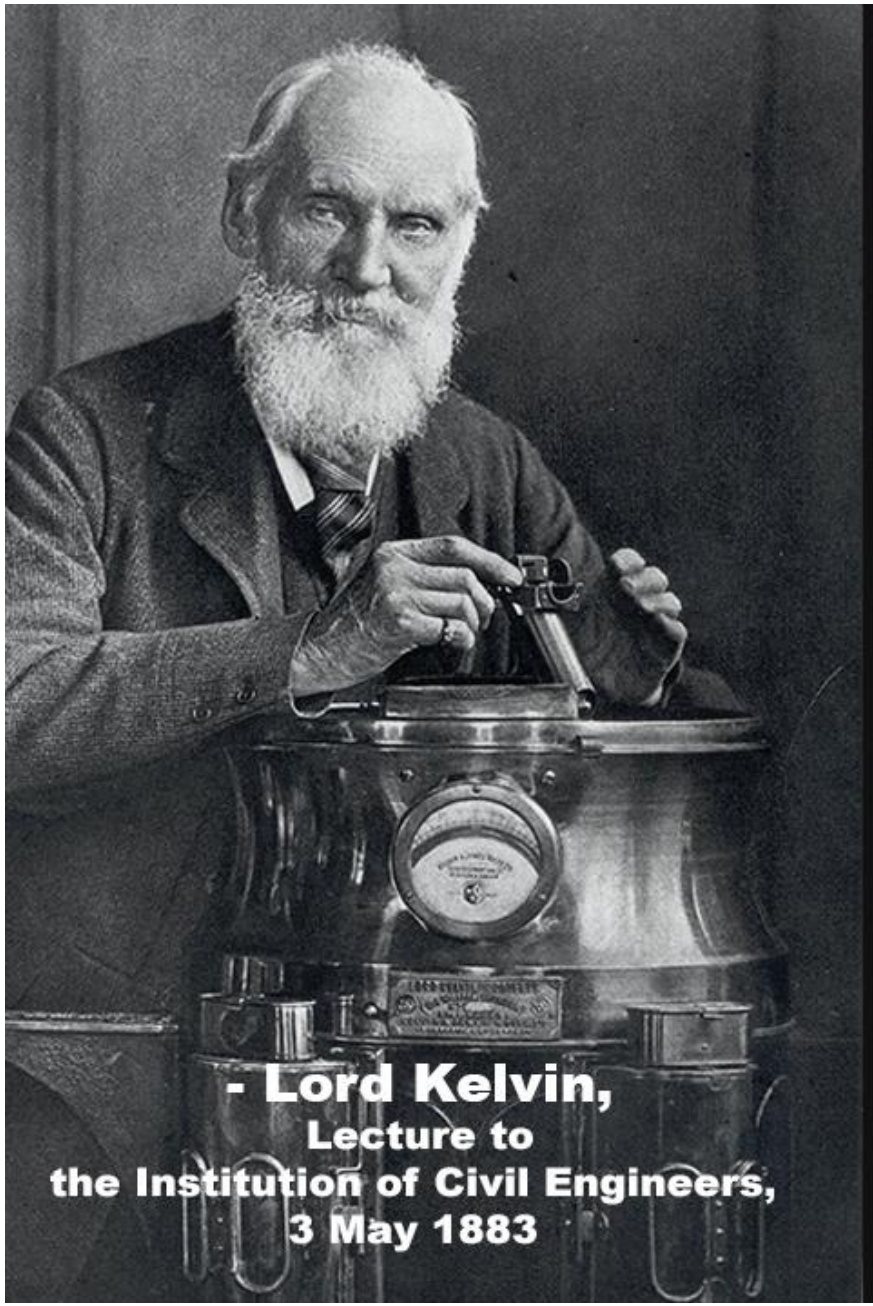
Greenhouse gas emissions

Water consumption

Water emissions of N and P leading to eutrophication

Water emissions of organic compounds

…



- Lord Kelvin,
Lecture to
the Institution of Civil Engineers,
3 May 1883

“ I often say that

when you can measure what you are speaking about, and express it in numbers, you know something about it;

but when you cannot measure it,

when you cannot express it in numbers,

your knowledge is of a meagre

and unsatisfactory kind;

it may be the beginning of knowledge,

but you have scarcely in your thoughts

advanced to the state of Science,

whatever the matter may be.”

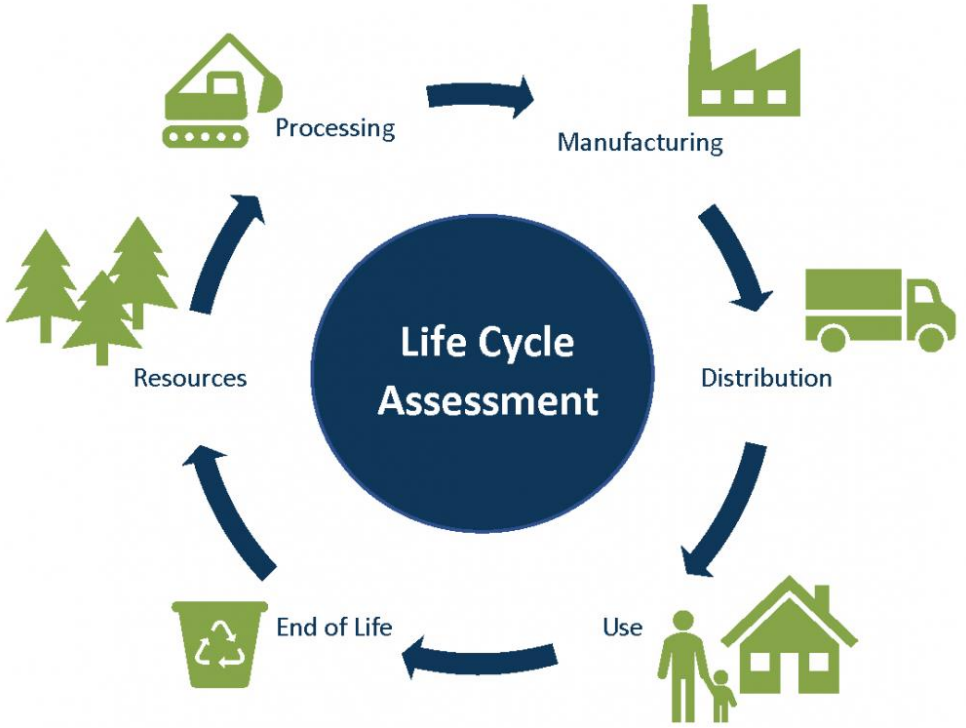
LIFE CYCLE SUSTAINABILITY ASSESSMENT

Venn diagram of sustainability

LIFE CYCLE ASSESSMENT: A HOLISTIC ENVIRONMENTAL TOOL

Life Cycle Assessment (LCA) is an environmental management tool that *"addresses the **environmental aspects** and **potential environmental impacts** throughout a product's life cycle, from the raw material acquisition through production, use, end-of-life treatment, recycling and final disposal"*.

ISO 14040 (2006)



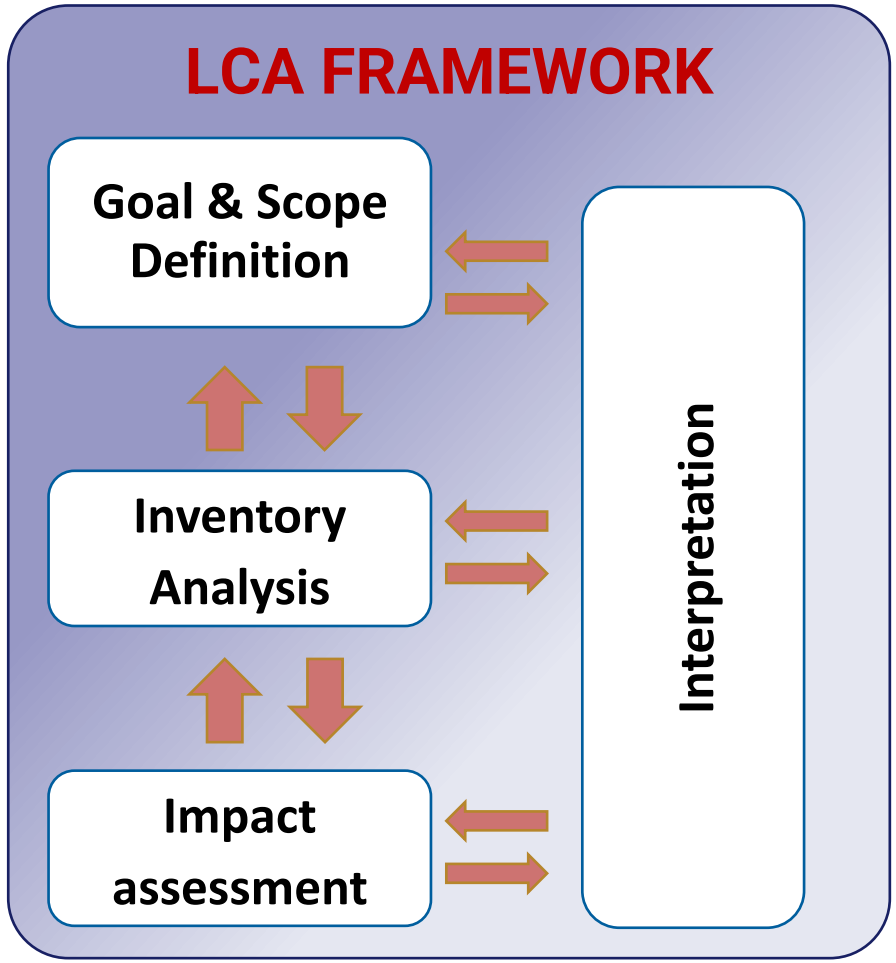
Source: *https://www.ncasi.org/technical-studies/sustainable-manufacturing/life-cycle-assessment/*

LIFE CYCLE ASSESSMENT: A HOLISTIC ENVIRONMENTAL TOOL

ADVANTAGES

- ✓ Product-oriented systematic approach
  - All stages considered
  - Avoids sub-optimization
  - Avoids potential burden shifting between impact categories or life cycle stages
- ✓ Quantitative
- ✓ Multi-criteria: many different impact categories evaluated
- ✓ Recommended by the EU and worldwide accepted

ISO 14040 (2006)



HOW CAN LCA RESULTS BE USED TO IDENTIFY OPPORTUNITIES FOR IMPACT REDUCTION?

ENVIRONMENTAL HOTSPOTS

- ✓ Relevant contribution of cultivation step
- ✓ Highest contribution related to energy consumption

Braud, 2023

HOW CAN LCA RESULTS BE USED TO IDENTIFY OPPORTUNITIES FOR IMPACT REDUCTION?

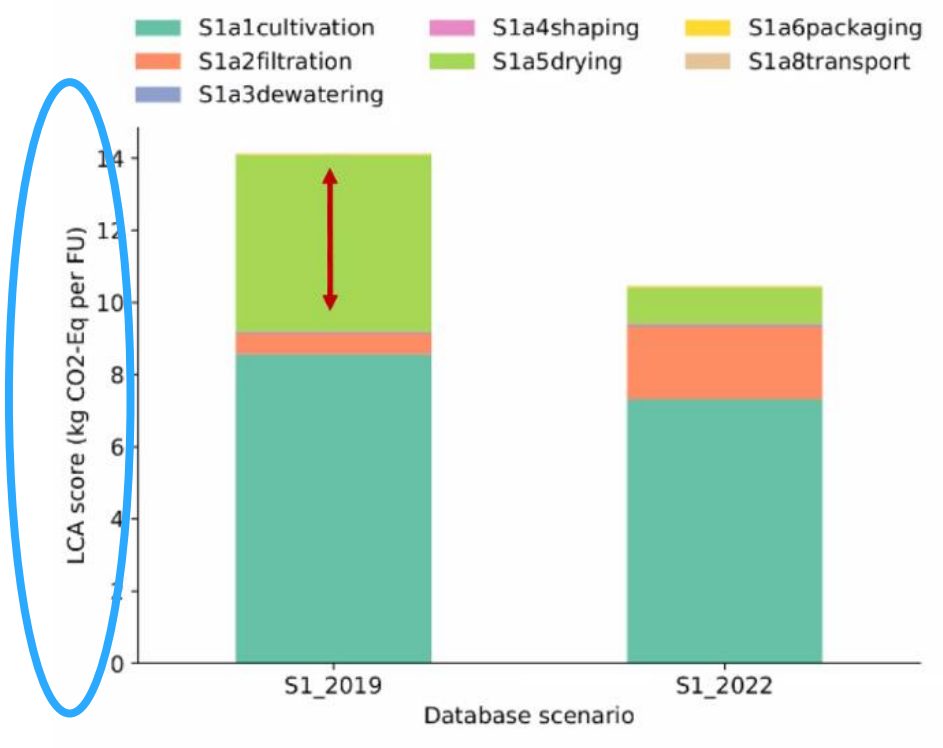
ABSOLUTE ENVIRONMENTAL RESULTS

$$\text{LCA score (impact/FU)} = \frac{\text{total impact}}{\text{total product (or service)}}$$

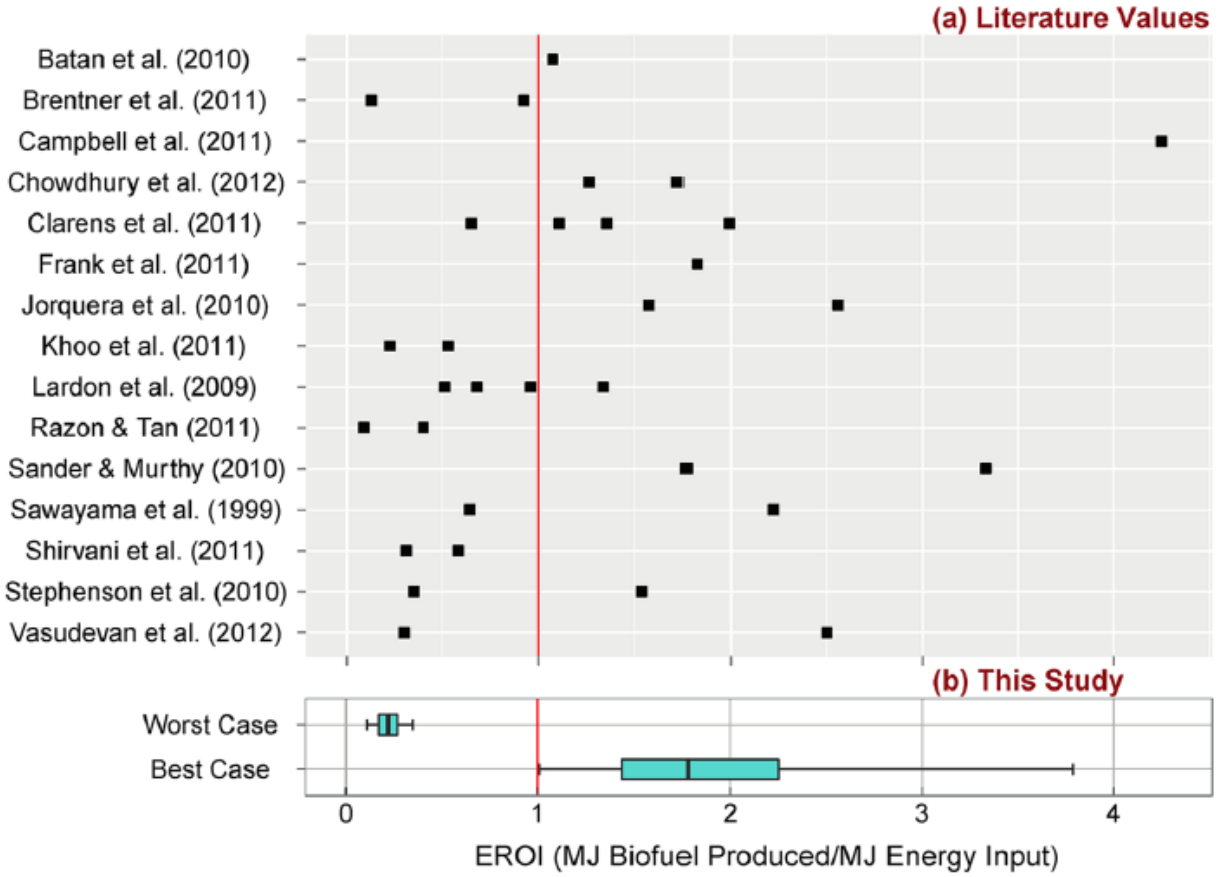
Amount of product ↑ ➡ LCA results ↓

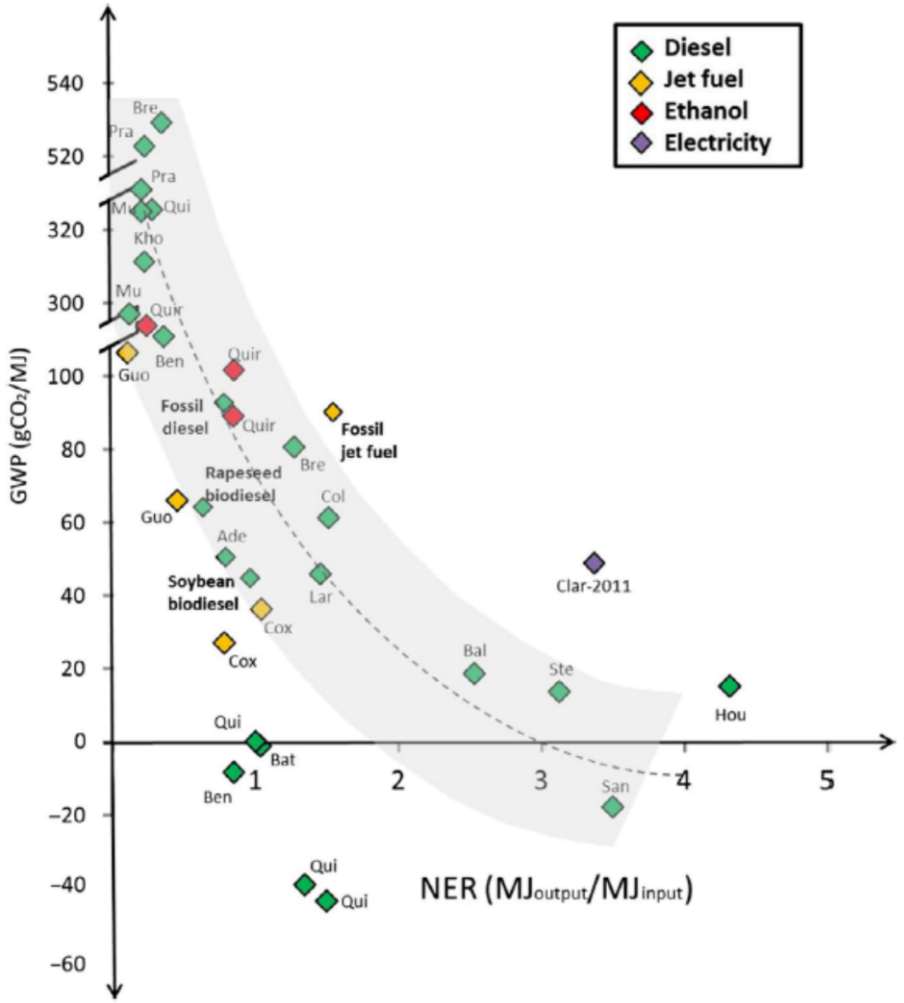
- ✓ Biomass productivity increase
- ✓ Process optimization to maximize production
- ✓ Co-product valorization
- ✓ …

Braud, 2023



MANY LCA STUDIES, MANY DIFFERENT OUTCOMES





Source : Sills (2013)

Source : Morales et al (2019)

CHALLENGES OF LCA MODELLING FOR ALGAE SYSTEMS

+ comparability & reproducibility

Goal and scope definition

- Functional unit: 1 kg biomass?, 1 kg active compound? , 1 m2 culture surface? 1 m2 treated water ? ….
- Allocation: what % impact for each co-product?
- System boundaries: what life cycle elements included/excluded ?
- …

Inventory Analysis

- Low TRL → Data scarcity & low quality
- Variability of weather (e.g. solar radiation, temperature) and other surrounding conditions affecting yield
- Methodological choices and uncertainties
- …

Impact assessment

- Multi-criteria assessment needed: not only greenhouse gases, but water use? Land use? Chemicals-related impacts?....
- CO2 capture potential 0.5 - 2.5 kg CO2/kg DM → BUT to be compared with indirect emissions
- …

AN EXAMPLE OF HOW WEATHER VARIABILITY CAN INFLUENCE LCA RESULTS: A CASE STUDY IN THE NETHERLANDS

Goal & scope

- FU = 1 kg algal biomass
- 3 real pilot cultivation systems
- Comparative assessment under average summer conditions (1,5 months total operation)
- Identification of hot spots

Vertical tubular PBR
0.56 m^3

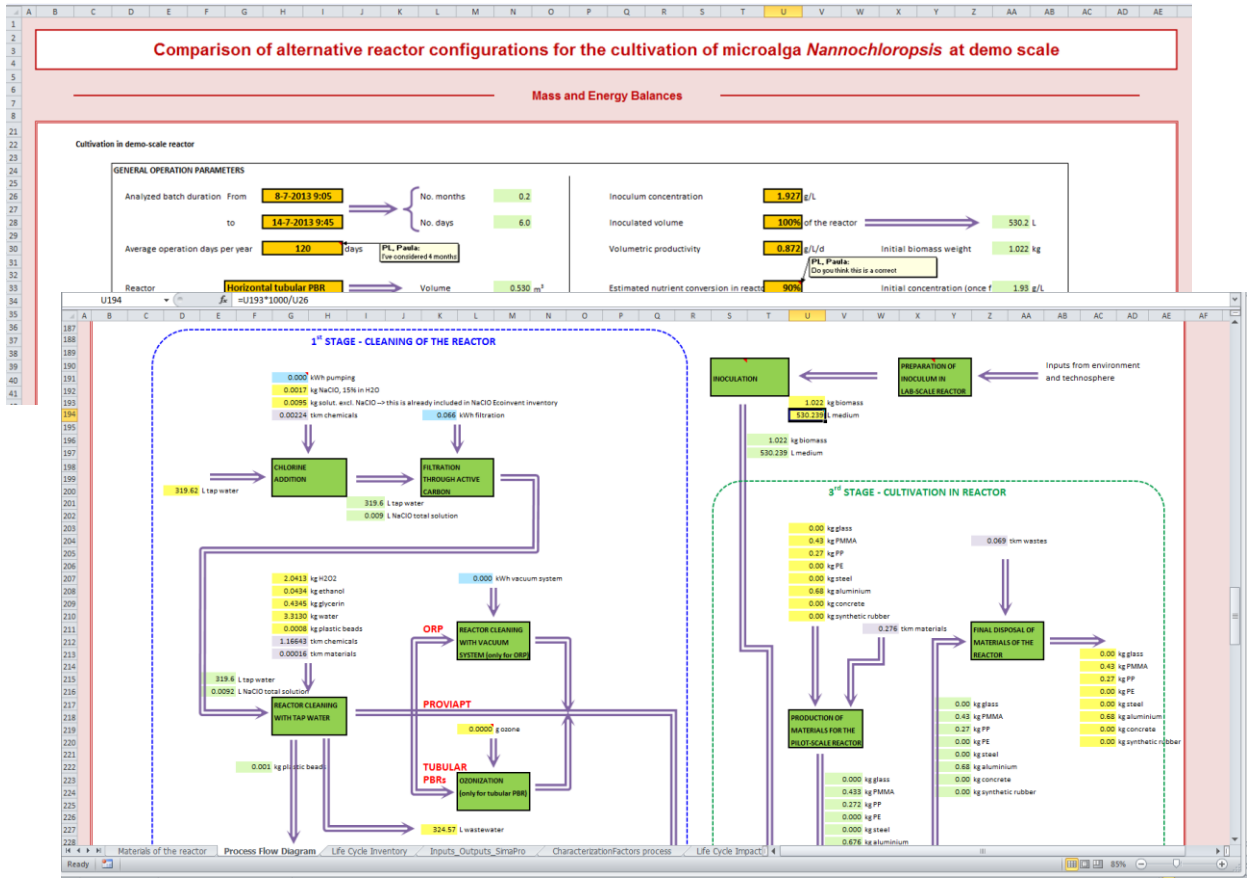
Horizontal tubular PBR
0.56 m^3

Open raceway pond
4.73 m^3

Source : Pérez-López et al (2017)

AN EXAMPLE OF HOW WEATHER VARIABILITY CAN INFLUENCE LCA RESULTS: A CASE STUDY IN THE NETHERLANDS

Inventory analysis



Vertical tubular PBR
0.56 m^3

Horizontal tubular PBR
0.56 m^3

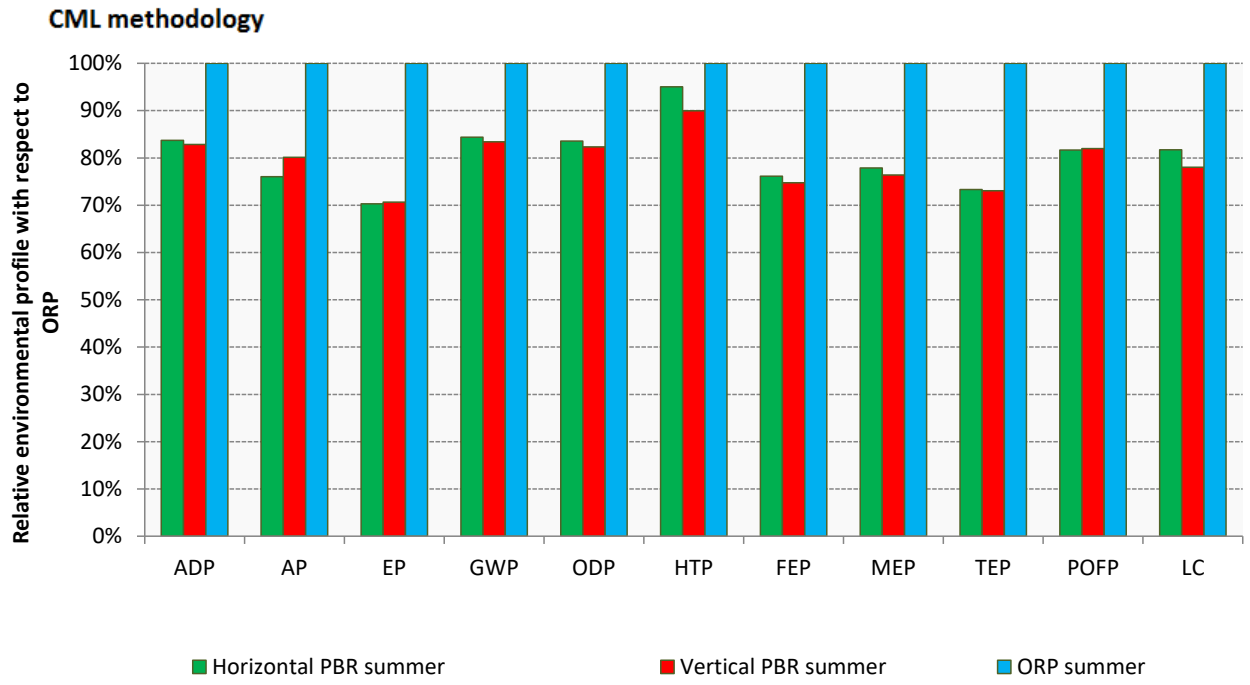
Open raceway pond
4.73 m^3

Source : Pérez-López et al (2017)

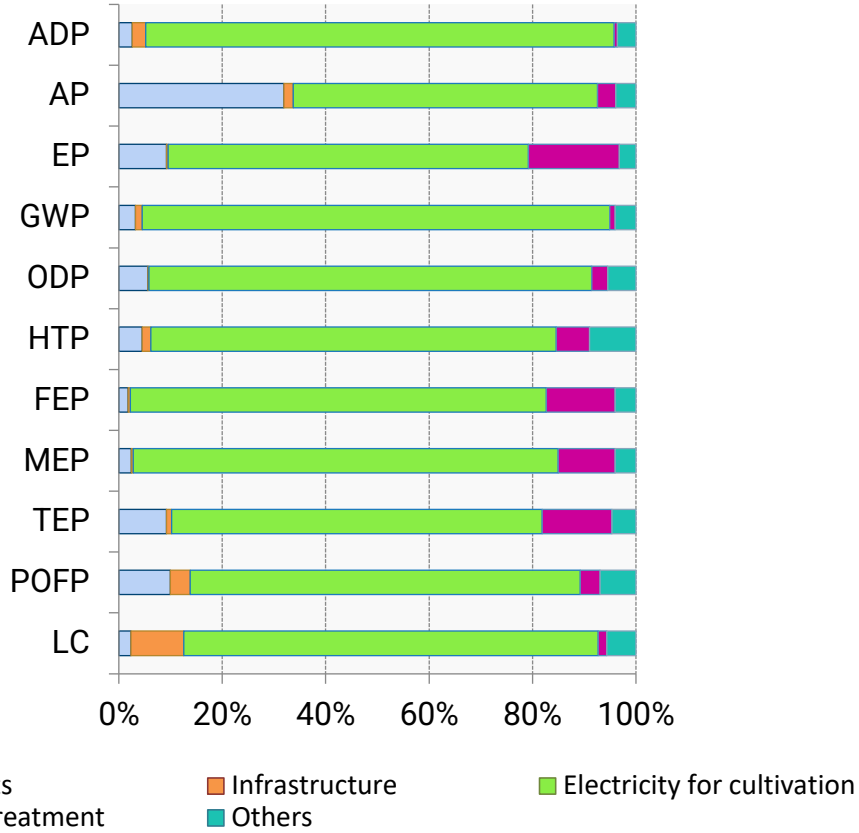
AN EXAMPLE OF HOW WEATHER VARIABILITY CAN INFLUENCE LCA RESULTS: A CASE STUDY IN THE NETHERLANDS

Impact assessment

Relative results of pilot systems with respect to ORP (100%)



Hotspots for ORP



Source : *Pérez-López et al (2017)*

AN EXAMPLE OF HOW WEATHER VARIABILITY CAN INFLUENCE LCA RESULTS: A CASE STUDY IN THE NETHERLANDS

3 scenarios

SUMMER CONDITIONS

- ↑ irradiance
- ↑ temperature
- ↓ precipitations
- ↑ growth rate

WINTER CONDITIONS

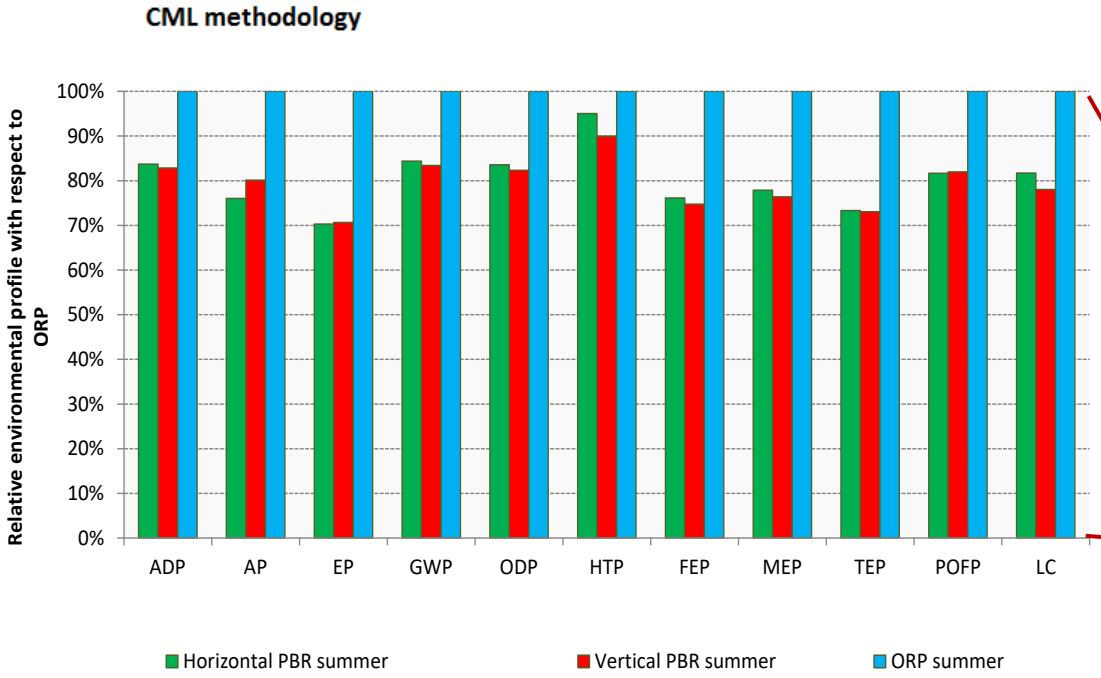
- ↓↓ irradiance
- ↓↓ temperature
- ↑ precipitations
- ↓↓ growth rate

FALL CONDITIONS

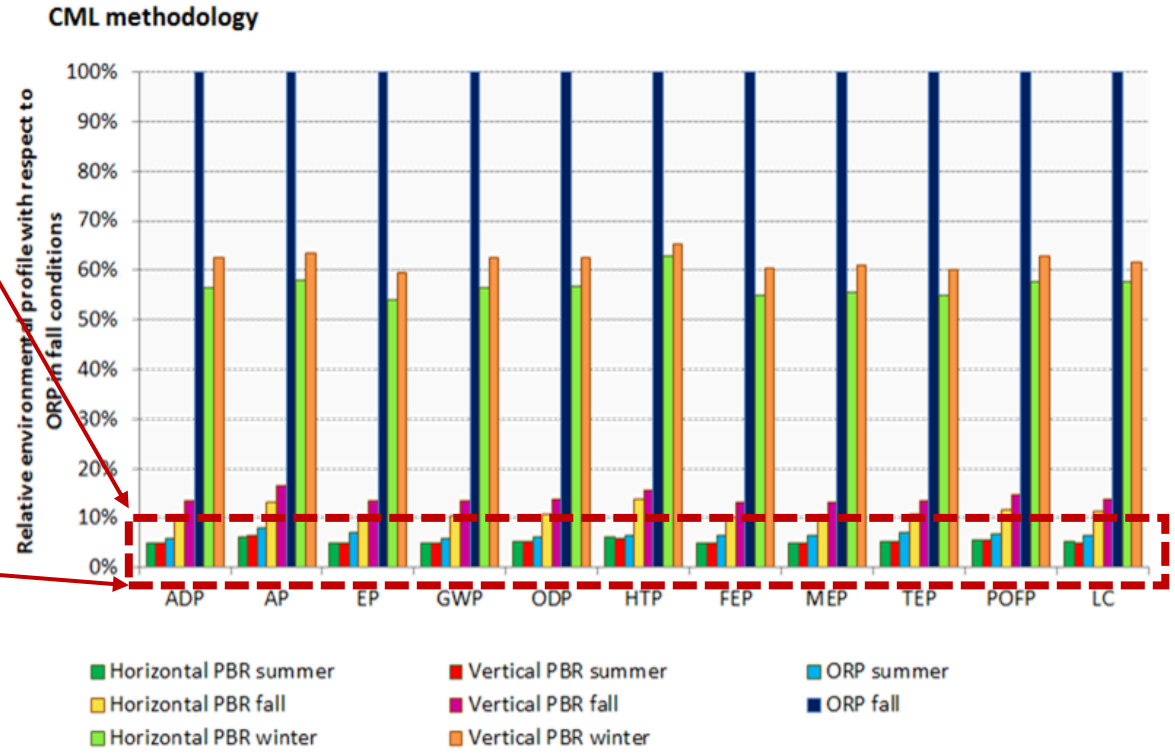
- ↓ irradiance
- ↓ temperature
- ↑ precipitations
- ↓ growth rate

AN EXAMPLE OF HOW WEATHER VARIABILITY CAN INFLUENCE LCA RESULTS: A CASE STUDY IN THE NETHERLANDS

Relative results of pilot systems with respect to ORP (100%)



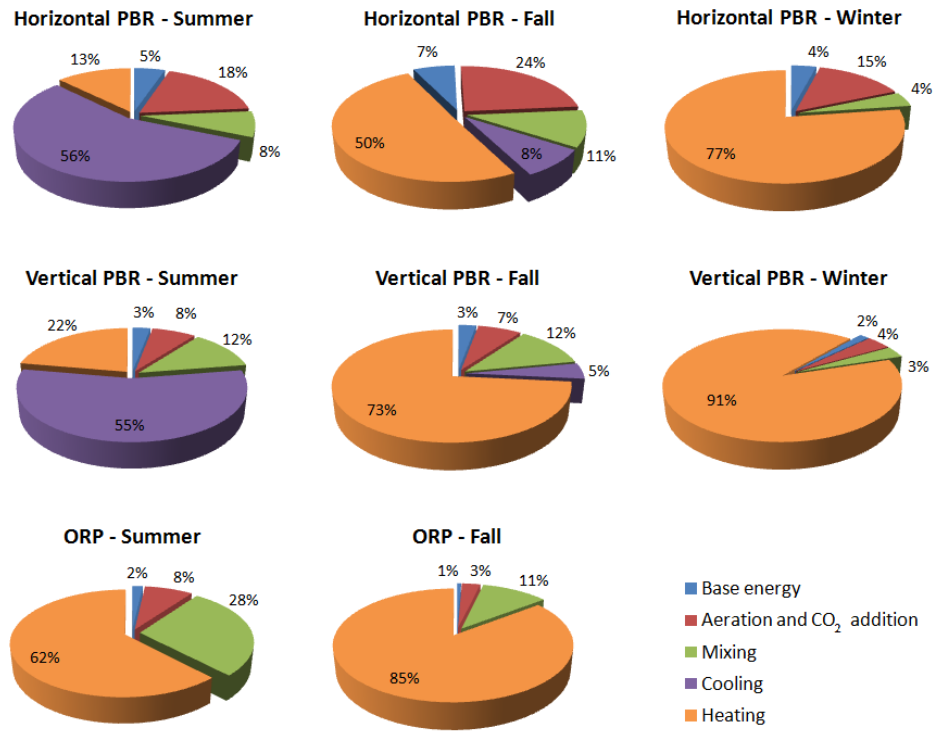
Relative results of pilot systems with respect to ORP in fall (100%)



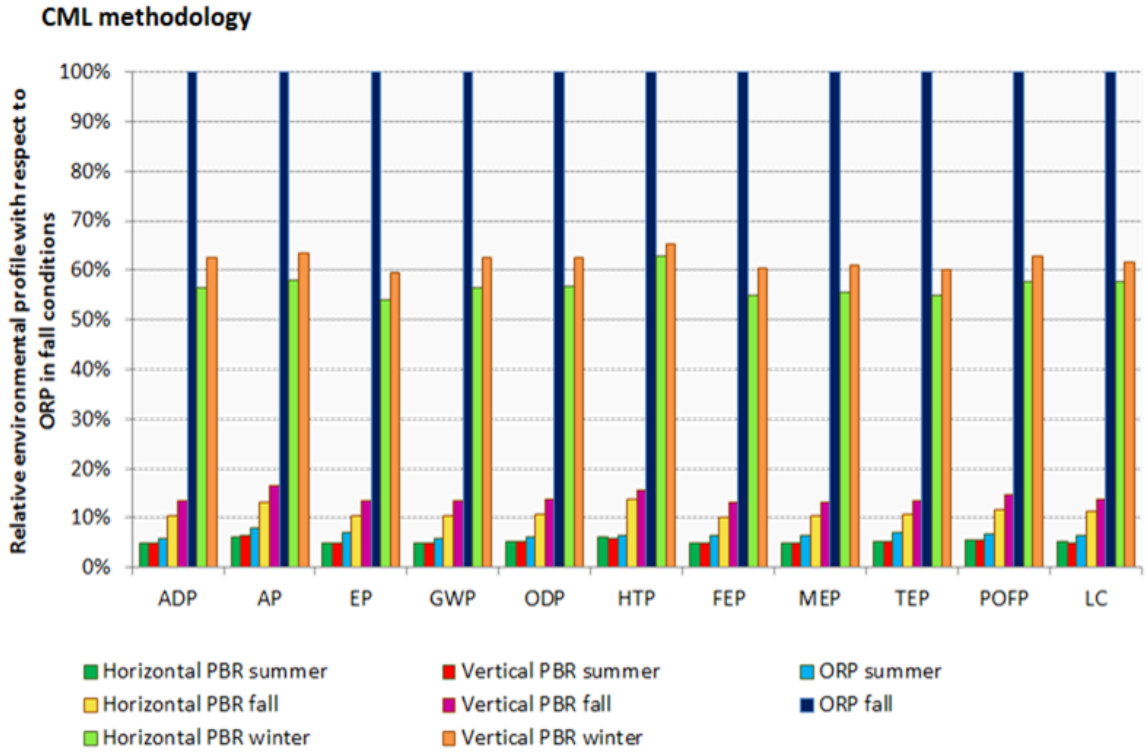
Source : Pérez-López et al (2017)

AN EXAMPLE OF HOW WEATHER VARIABILITY CAN INFLUENCE LCA RESULTS: A CASE STUDY IN THE NETHERLANDS

Hotspot: Electricity (~ 70-95%)



Relative results of pilot systems with respect to ORP in fall (100%)

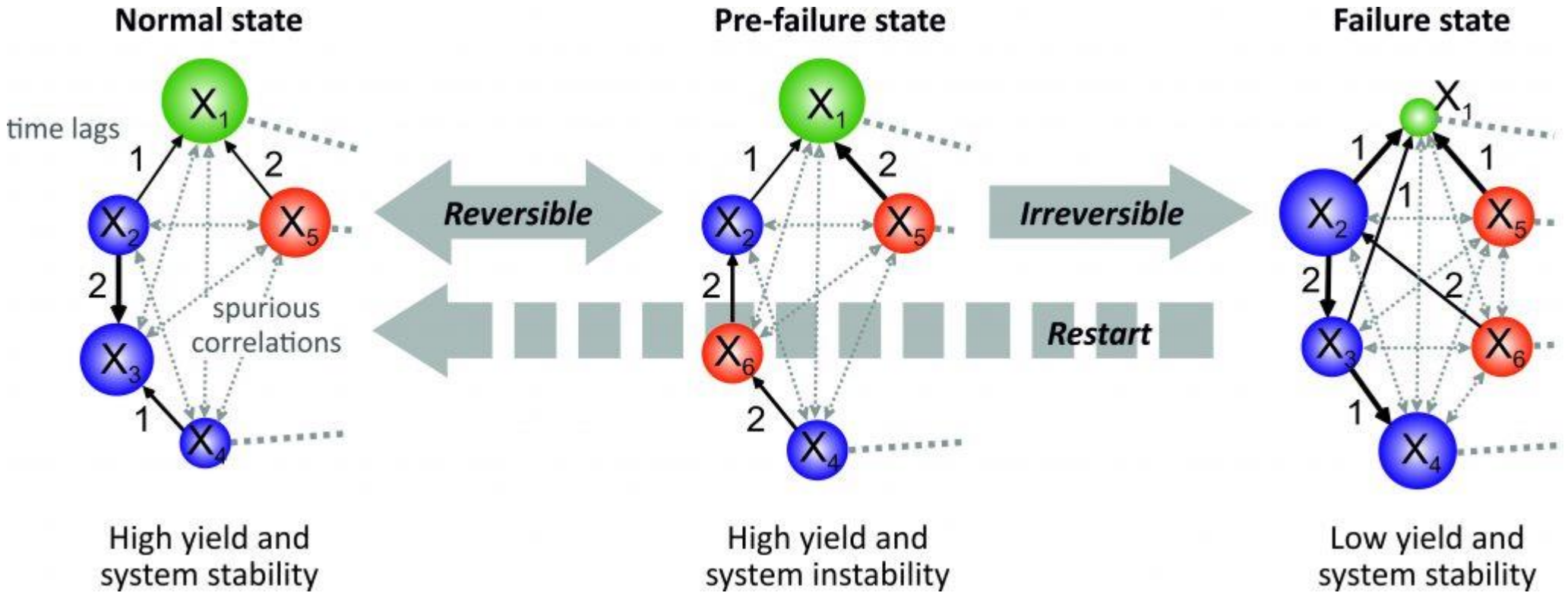


Source : *Pérez-López et al (2017)*

ADVANCED SYSTEMS TO ENHANCE THE EFFICIENCY OF ALGAE PROCESSES

Prodigio

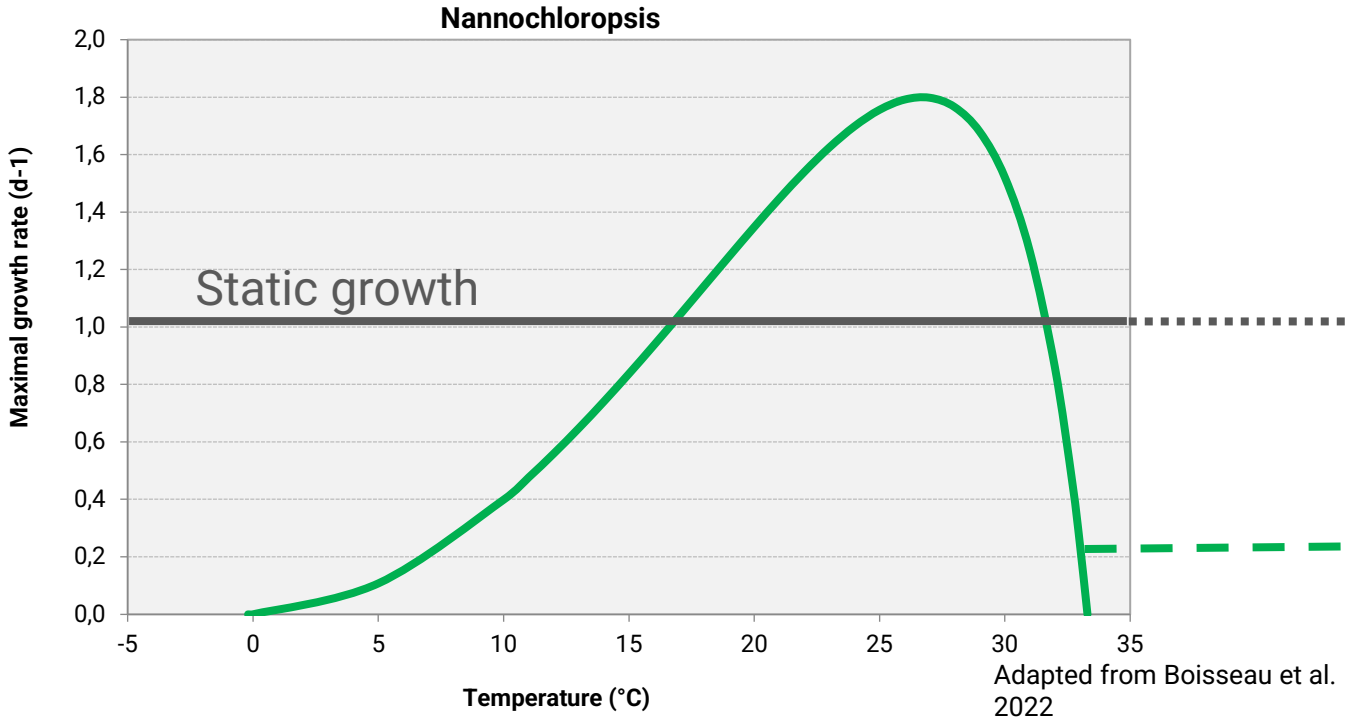
H2020, 2021-2023



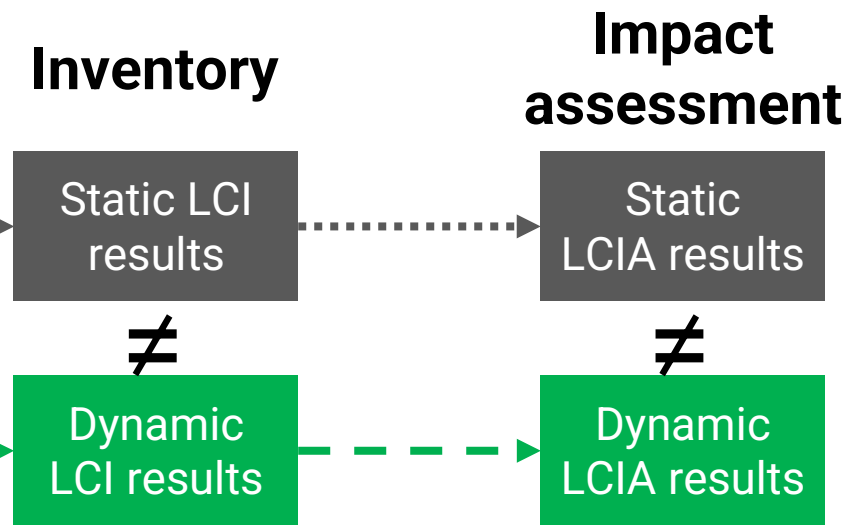
ADVANCED SYSTEMS TO ENHANCE THE EFFICIENCY OF ALGAE PROCESSES – PRODIGIO STATIC & DYNAMIC LCA MODELS

Prodigio
H2020, 2021-2023

Static vs Dynamic LCA



Adapted from Boisseau et al. 2022



LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment

ADVANCED SYSTEMS TO ENHANCE THE EFFICIENCY OF ALGAE PROCESSES – PRODIGIO STATIC & DYNAMIC LCA MODELS

Prodigio
H2020, 2021-2023

On-site
Data collection

Visit at University of Almeria, Spain (June 2022)

Parameterized LCA models

Initialization

All initialization commands are gathered in one file "init_tlc.py"

Entrée [39]:
```
from init_tlc import *
```

Impact assessment selection

There's a bunch of cathegories, but let's try with these 3 most used

Entrée [40]:
```
# Common prefix
ILCD = 'ILCD 2.0 2018 midpoint'
```

Entrée [41]:
```
# Command to see the impact cathegories including 'climate change','ecosystem quality','human health', and 'resources'
#impacts = [m for m in bw.methods if 'ILCD' in str(m) and 'climate change' and 'ecosystem quality' and 'human health' a
```

Selected impact cathegories

Entrée [42]:
```
#Climate change cathegory
climate_change = (ILCD, 'climate change', 'climate change total')

#Human health cathegory
ion_rad=(ILCD, 'human health', 'ionising radiation')
ozone_lay_depl=(ILCD, 'human health', 'ozone layer depletion')
photo_ozone_creat=(ILCD, 'human health', 'photochemical ozone creation')
respiratory_effects=(ILCD, 'human health', 'respiratory effects, inorganics')

human_health=[ion_rad, ozone_lay_depl, photo_ozone_creat, respiratory_effects]

#Resources cathegory

fossils=(ILCD, 'resources', 'fossils')
land_use=(ILCD, 'resources', 'land use')
minerals_metals=(ILCD, 'resources', 'minerals and metals')

resources=[fossils, land_use, minerals_metals]
```

LCA Database

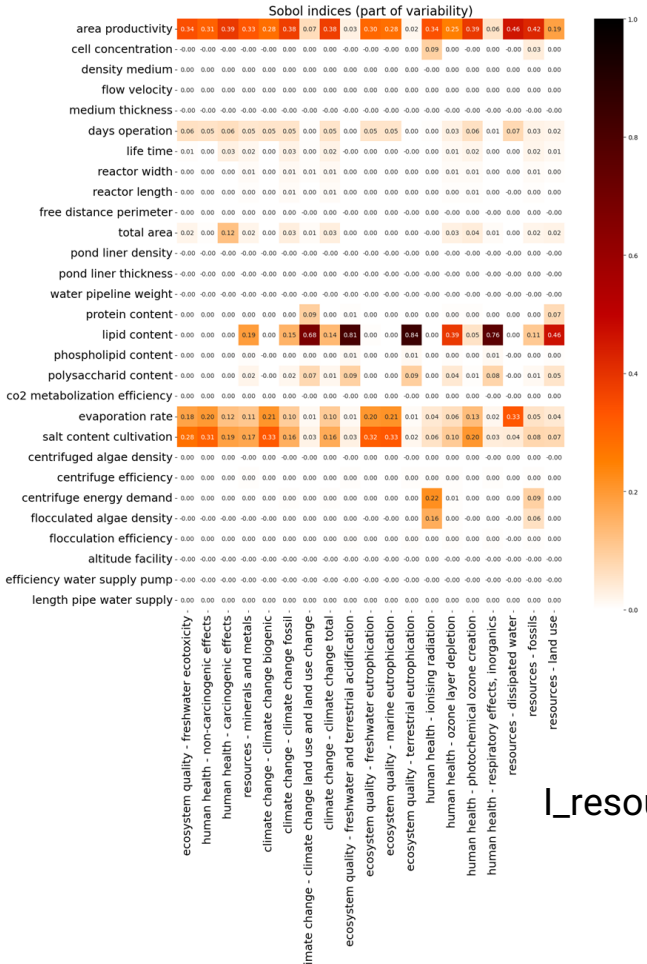
ecoinvent 3.7

Advanced programming tools

python
jupyter
Brightway

lca_algebraic

ADVANCED SYSTEMS TO ENHANCE THE EFFICIENCY OF ALGAE PROCESSES – PRODIGIO STATIC & DYNAMIC LCA MODELS



Simplified models for fast estimates

$$\log\left(\frac{6.71.10^{-6}\pi^{0.9}}{\left(\frac{f_{evap}\cdot f_{salt}}{f_{days}^{(0.286 f_{salt}-1)}}\right)^{0.9}}+4.05.10^{-4}\right)^2 \left(\begin{array}{l} -6.11.10^{-8}\pi^4 f_{prod}\cdot f_{days}\cdot f_{lipid}\cdot f_{salt} \\ +2.14.10^{-7}\pi^4 f_{prod}\cdot f_{days}\cdot f_{lipid} \\ +4.96.10^{-6}\pi^4 f_{prod}\cdot f_{days}\cdot f_{salt} \\ -1.74.10^{-5}\pi^4 f_{prod}\cdot f_{days} \\ +2.18.10^{-8}\pi^4 f_{evap}\cdot f_{salt}\left(\frac{f_{evap}\cdot f_{salt}}{f_{days}^{(0.286 f_{salt}-1)}}\right)^2 \\ +4.66.10^{-9}\pi^4 f_{evap}\cdot f_{salt} \\ +4.89.10^{-6}\pi^4 f_{evap} \\ +2.16.10^{-6}\pi^4 f_{salt} \\ -7.56.10^{-6}\pi^4 \end{array}\right)$$

$$I\_resource = \frac{+1.15.10^{-4}\pi^4 f_{evap}\cdot f_{salt}\left(\frac{f_{evap}\cdot f_{salt}}{f_{days}^{(0.286 f_{salt}-1)}}\right)^2}{\pi^4 f_{prod}\cdot f_{days}(0.286 f_{salt}-1)\log\left(\frac{6.71.10^{-6}\pi^{0.9}}{\left(\frac{f_{evap}\cdot f_{salt}}{f_{days}^{(0.286 f_{salt}-1)}}\right)^{0.9}}+4.05.10^{-4}\right)^2}$$

Prodigio
H2020, 2021-2023

LCA Database

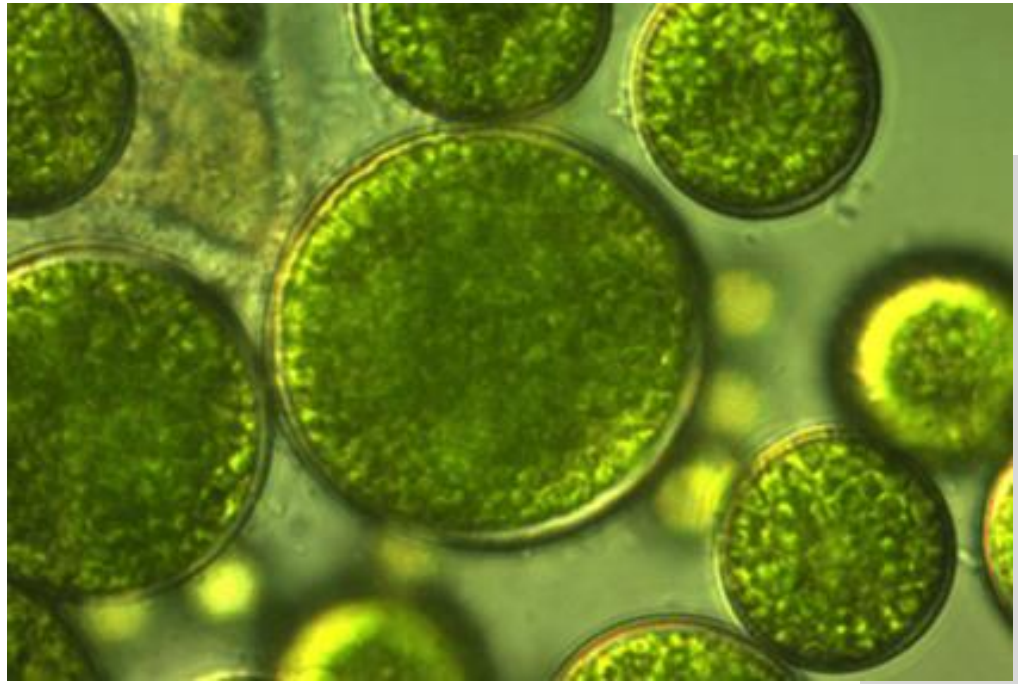
ecoinvent 3.7

Advanced programming tools

python
jupyter
Brightway

lca_algebraic

IN CONCLUSION, ARE ALGAE “GREEN” OR NOT?



https://www.nature-et-forme.com/page /dossier/la-chlorella-fabuleuse-micro-algue

IT DEPENDS

- On the weather
- On the geographical location of the site
- On the operation conditions
- On the species
- On the target product and co-products
- On the scale of production
- On LCA-related methodological choices
- …

BUT CAN WE REDUCE THE IMPACTS OF ALGAE PROCESSES?

LCA still serves …

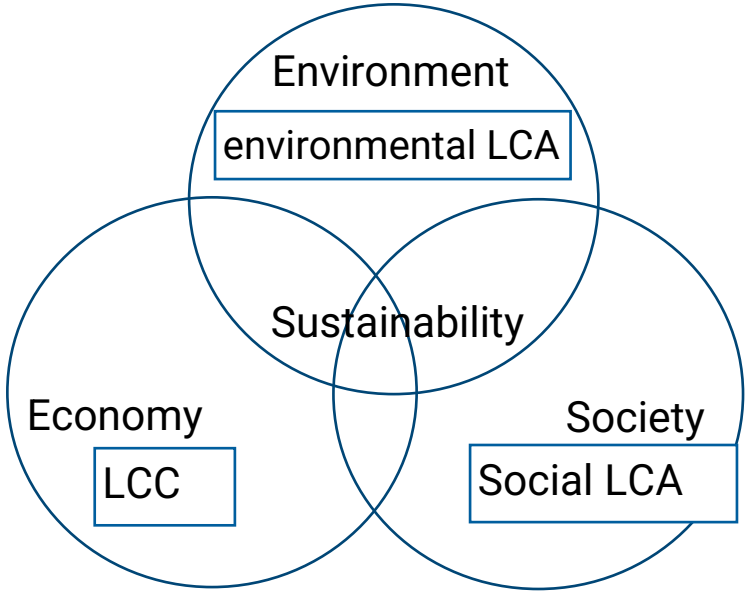
- to identify environmental hotspots
- to compare scenarios/alternatives
- to focus on key parameters
- overall, to identify opportunities for improvement and provide information for decision-making

IT DEPENDS

- On the weather
- On the geographical location of the site
- On the operation conditions
- On the species
- On the target product and co-products
- On the scale of production
- On LCA-related methodological choices
- …

SOME KEY QUESTIONS FOR FUTURE SUSTAINABILITY ASSESSMENTS

- How to ensure **comparability** between different studies?
- How to define representative **functional unit**(s)?
- How to **allocate** impacts to co-products in multi-functional systems?
- How to deal with **uncertainties** (← data scarcity, upscaling) & **variability** (e.g. weather-dependency)?
- How to account for **social & economic** dimensions of sustainability over the life cycle?



Can we reduce impacts of algae biorefinery?

A Life Cycle Assessment perspective

Paula Pérez-López

Center Observation, Impacts, Energy (O.I.E.) of Mines Paris - PSL