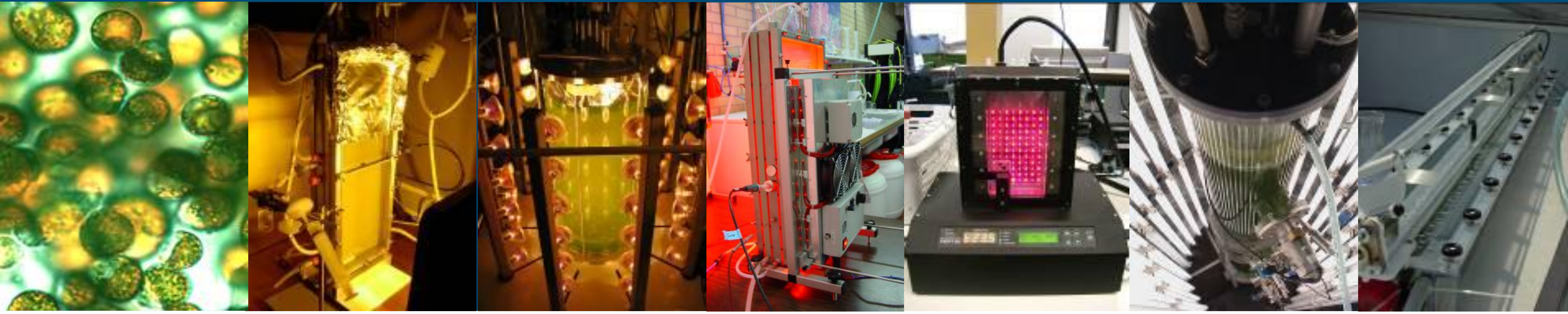
Microalgae biotechnology for a biobased economy

Packo Lamers
Wageningen UR

VU, 20 April 2012



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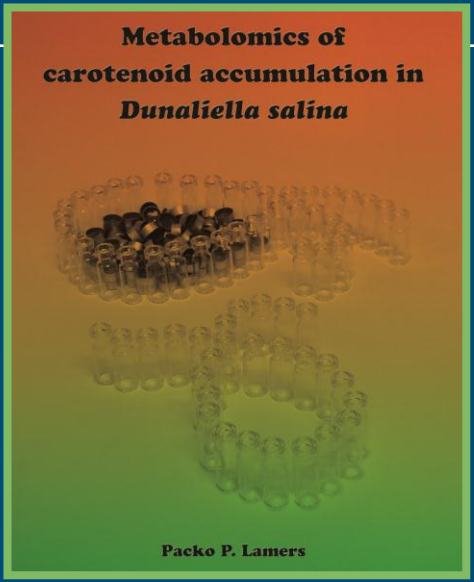
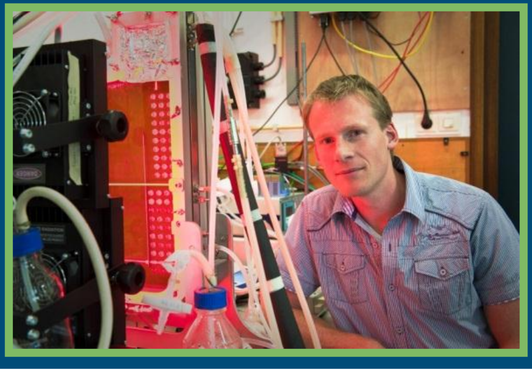
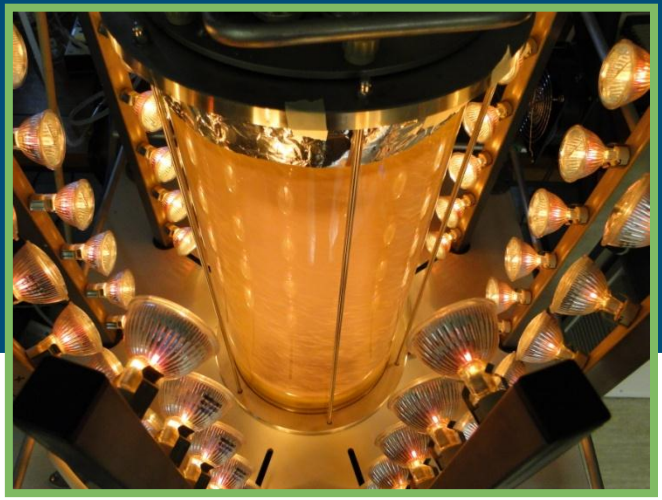
Who's talking?

- Assistant professor Biotechnology

- Before:
  - *BSc-MSc: Bioprocess technology*
  - *PhD: Pigment production with algae*
  - *PostDoc: Metabolic processes in algae*







A biobased economy

- What is it?

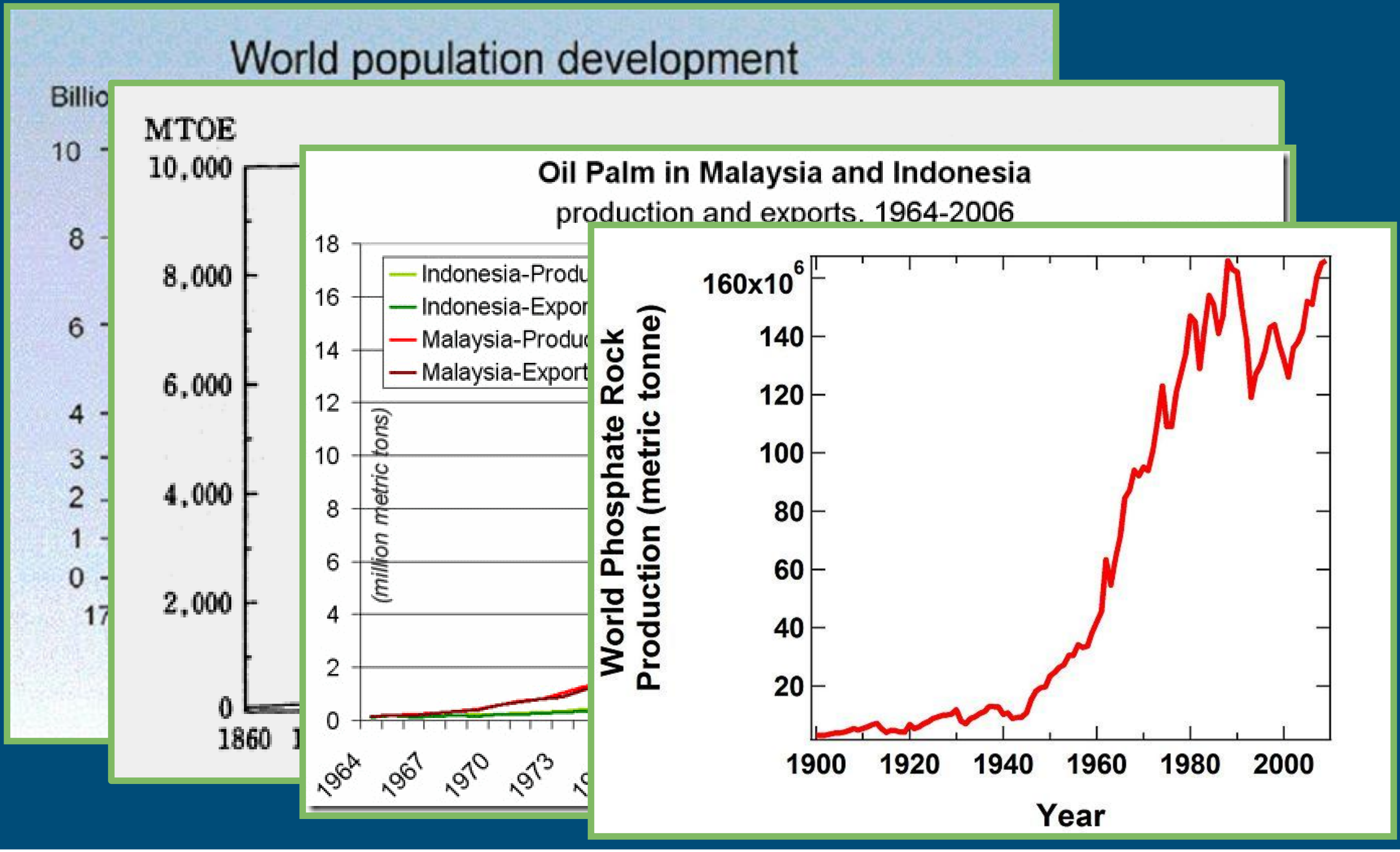
5%

- 80% positive about biobased economy
- 40% considers carreer / education in this field

Today's schedule

- Biobased economy
- Microalgae
- Economics
- Technological challenges
- Current research
- Discussion

Growth, consumption,...



Natural resource depletion / scarcity

Not today, not tomorrow, not?

Solution?

- Use renewable resources:
  - Sun
  - Water
  - Wind

Electricity alone is not enough

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The biobased economy

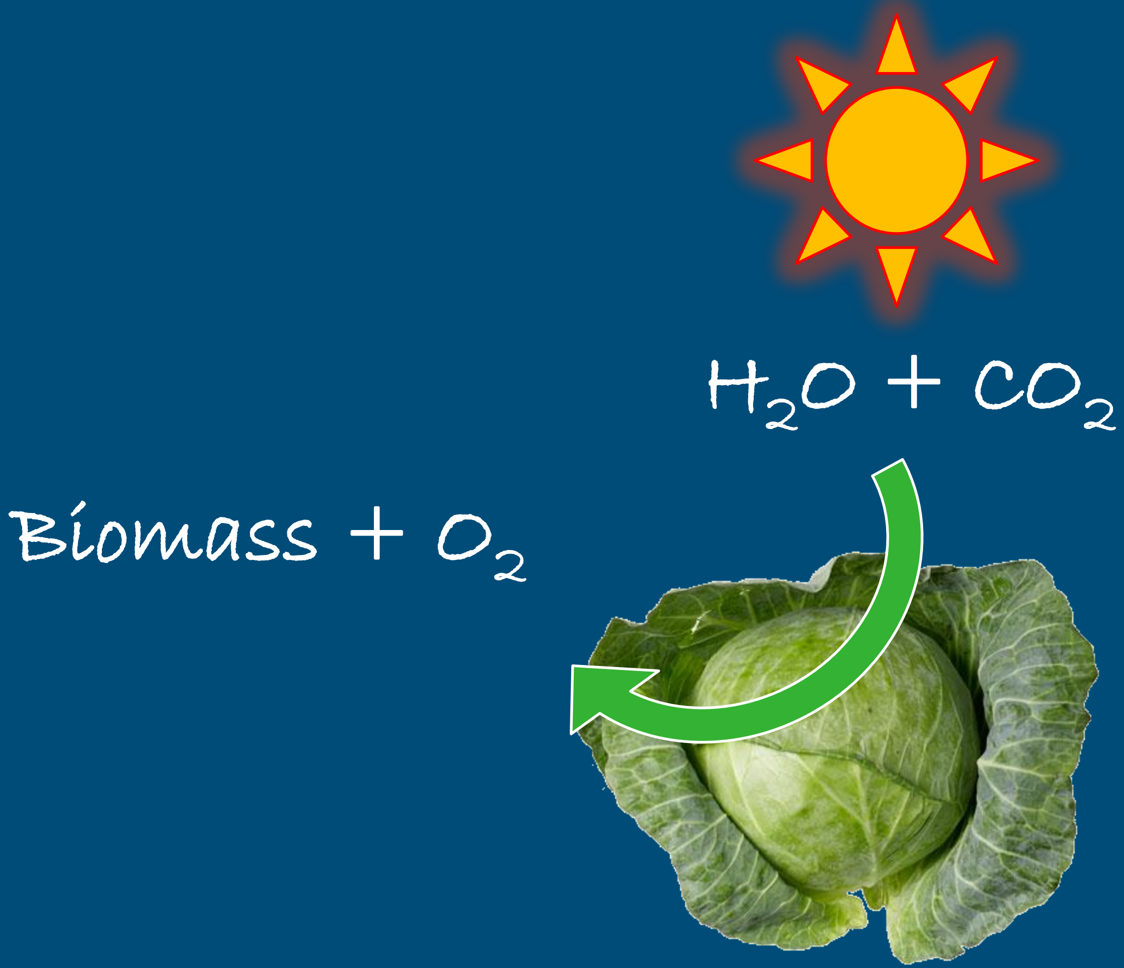
Production of ...

- fuels
- food and feed
- bulk and fine chemicals
- materials

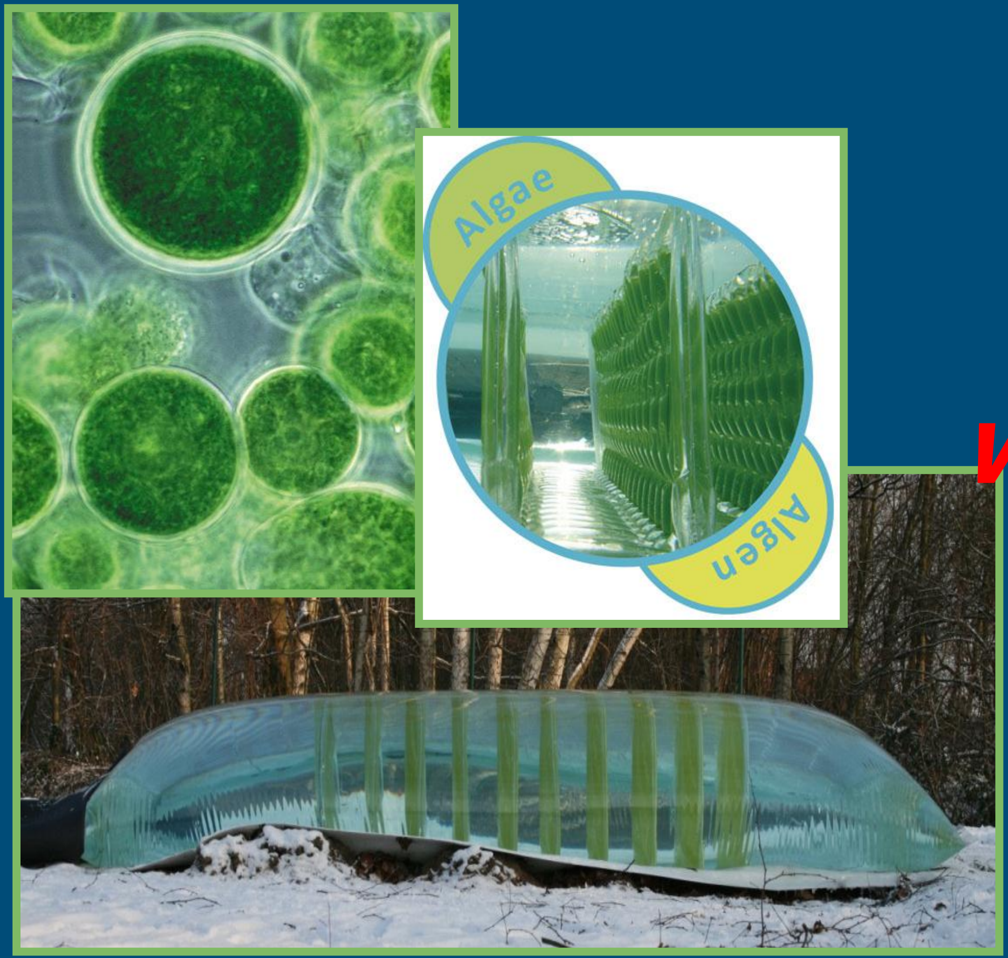
... using ...

- renewable resources
- waste streams
- biological production processes

Essential process: photosynthesis



Microalgae vs. plants

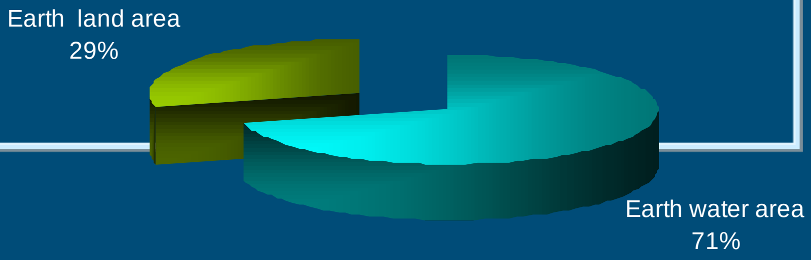


vs.

Drivers for (aquatic) Biomass

Biobased economy

- World population growth and increase in prosperity -> higher energy demand
- High energy prices
- Security of energy supply
- Climate change due to greenhouse gasses
- Rural development



Specific for aquatic biomass

- Increased competition for land for the production of food, chemicals and energy
- Limitations of land for agriculture
- Impact of global climate change on agricultural productivity

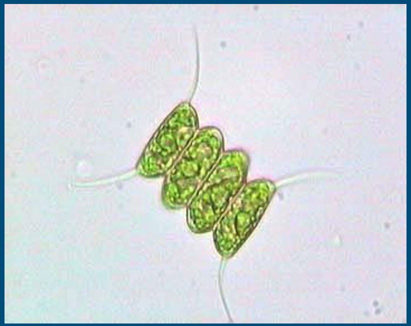
Microalgae vs. plants

vs.

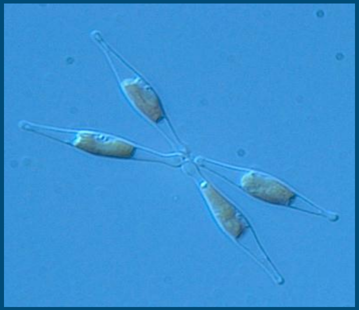
What are microalgae?

- Primitive plantlike organisms
- ~0.001 – 0.1 mm in size
- Fresh and salt water
- Photoautotrophic
- ≈ 80.000 species
  - Green algae
  - Chromista
    - Diatoms
    - Brown algae
  - Red algae
  - Euglenophyta

- *Spirulina*



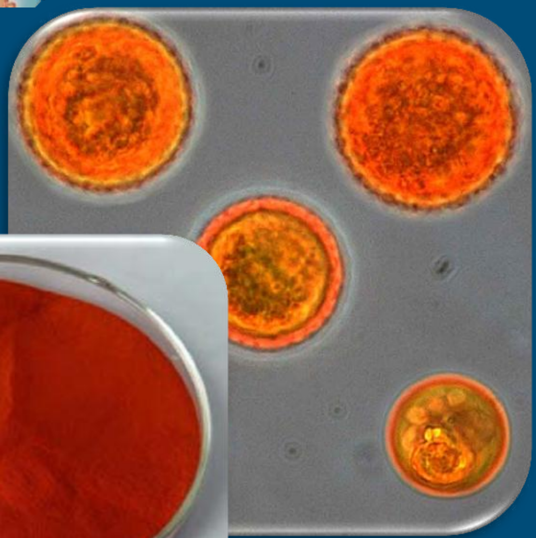
- *Scenedesmus*



- *Phaeodactylum*

Microalgal products

- Fish feed
- Biopolymers
- Fine chemicals (DHA, EPA)
- Functional proteins
- Medicines
- Pigments
- Fertilizers
- Oil



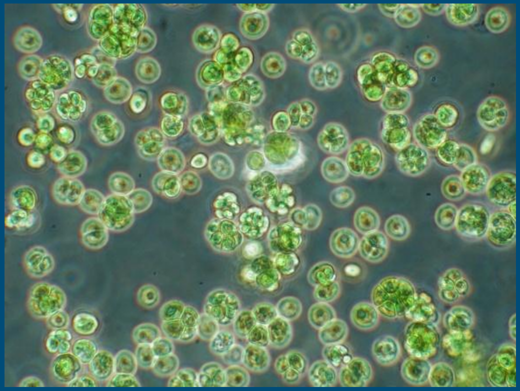
Why microalgae?

Feedstock	Oil Productivities L / ha /year
Corn	172
Soybeans	446
Sunflower	386
Rapeseed	1 250
Oil palm	5 950
Jatropha	1 892
Microalgae	
PE 3%; 30% lipids; NL	12 300
PE 3% ; 30% lipids; Bonaire	25 800
PE 6% ; 30% lipids; Bonaire	52 000

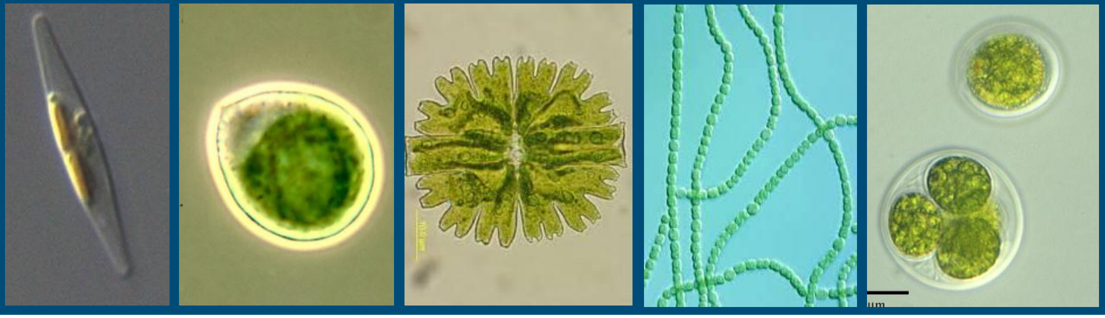
Where we are

Potential

More reasons:



- High areal productivities
- Can grow in seawater
- No competition for arable land
- Lower water foot print than agricultural crops
- Great variety in species -> variety in products!
- Ability to accumulate large amount of oils
- Possible to steer metabolism towards production of specific compound
- CO_2 mitigation
- Recycling nutrients (N & P)



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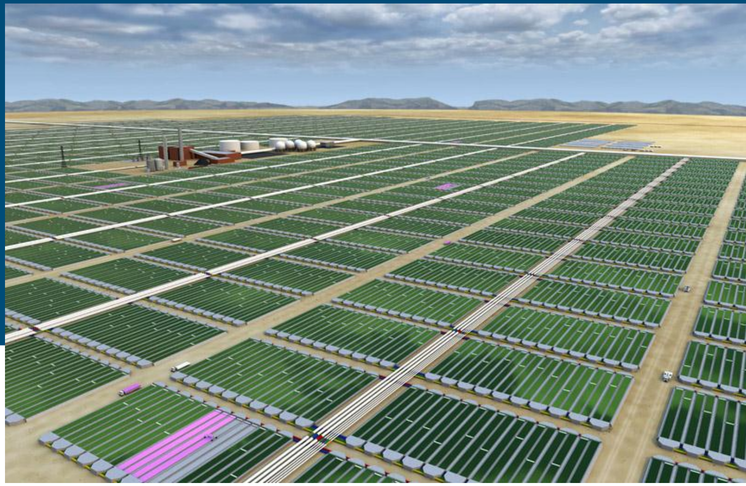
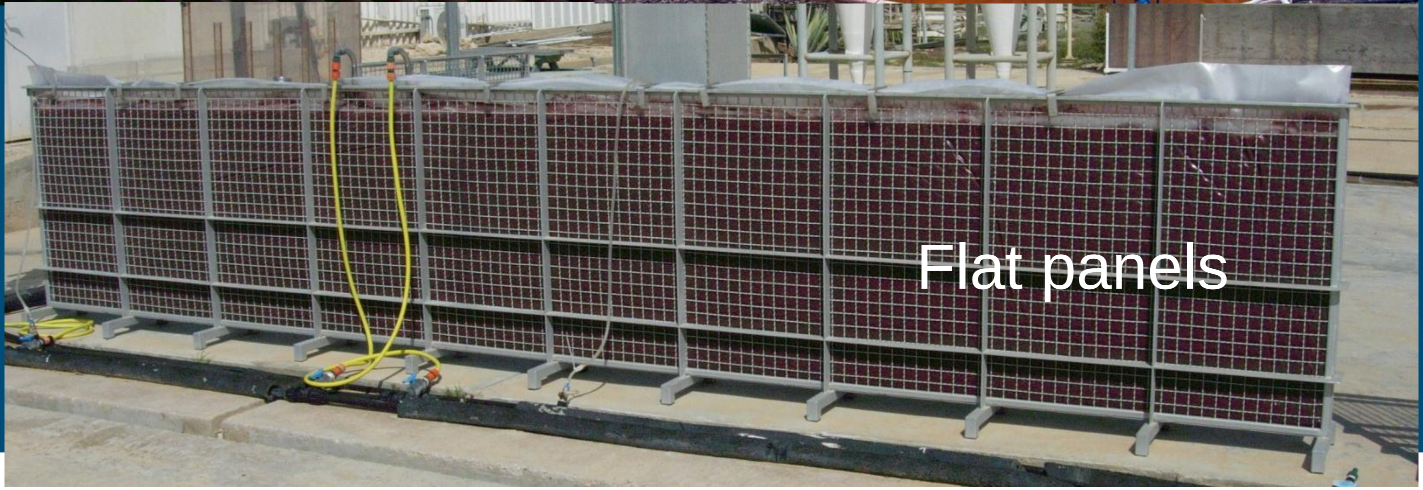
So… where are all the algae farms?

From a craft to an industrial process…

- Current global microalgae production: ~5000 tons of dry algal biomass
- High value products: carotenoids and ω-3 fatty acids
- Total market volume: €1.25 billion (av. market price: €250/kg dry biomass)
- World production of palm oil: ~40 million tons, market value: ~0.50 €/kg

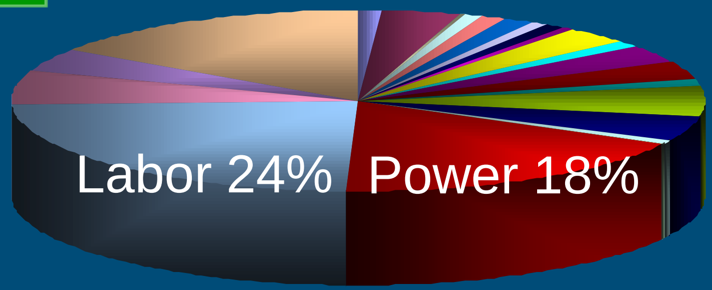


2007: Delta Feasibility Study

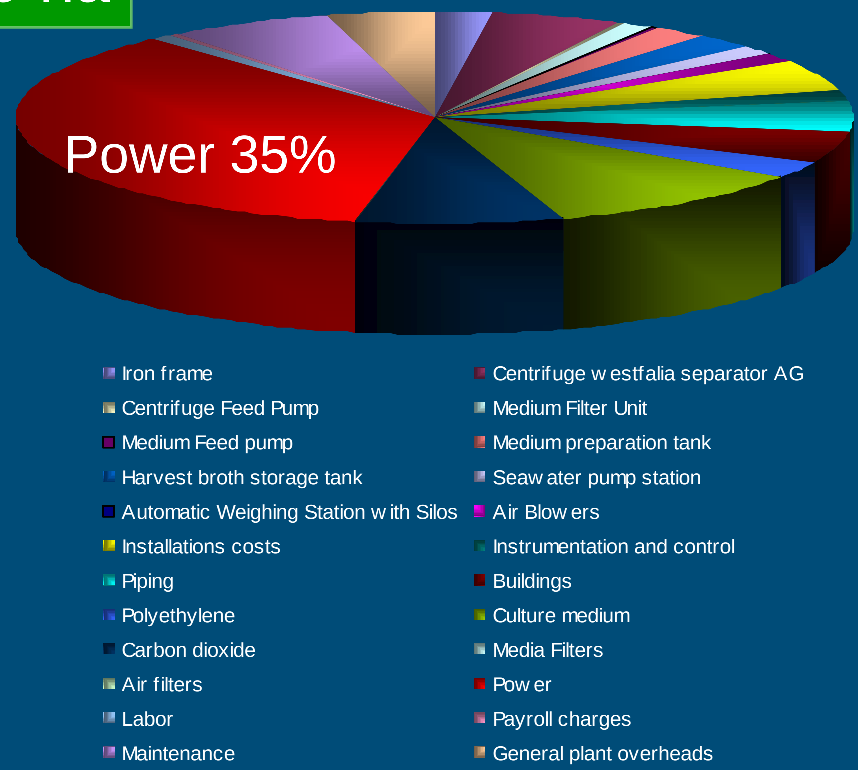


Delta feasibility study: production costs

1 ha



100 ha



- At 1 ha scale today: 10 €/kg
- At 100 ha scale today: 4 €/kg
- What will be possible: 0.70 €/kg

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Norsker N-.H., et al (2010) Microalgal production – a close look at the economics. ***Biotechnology Advances***

Conclusions feasibility study

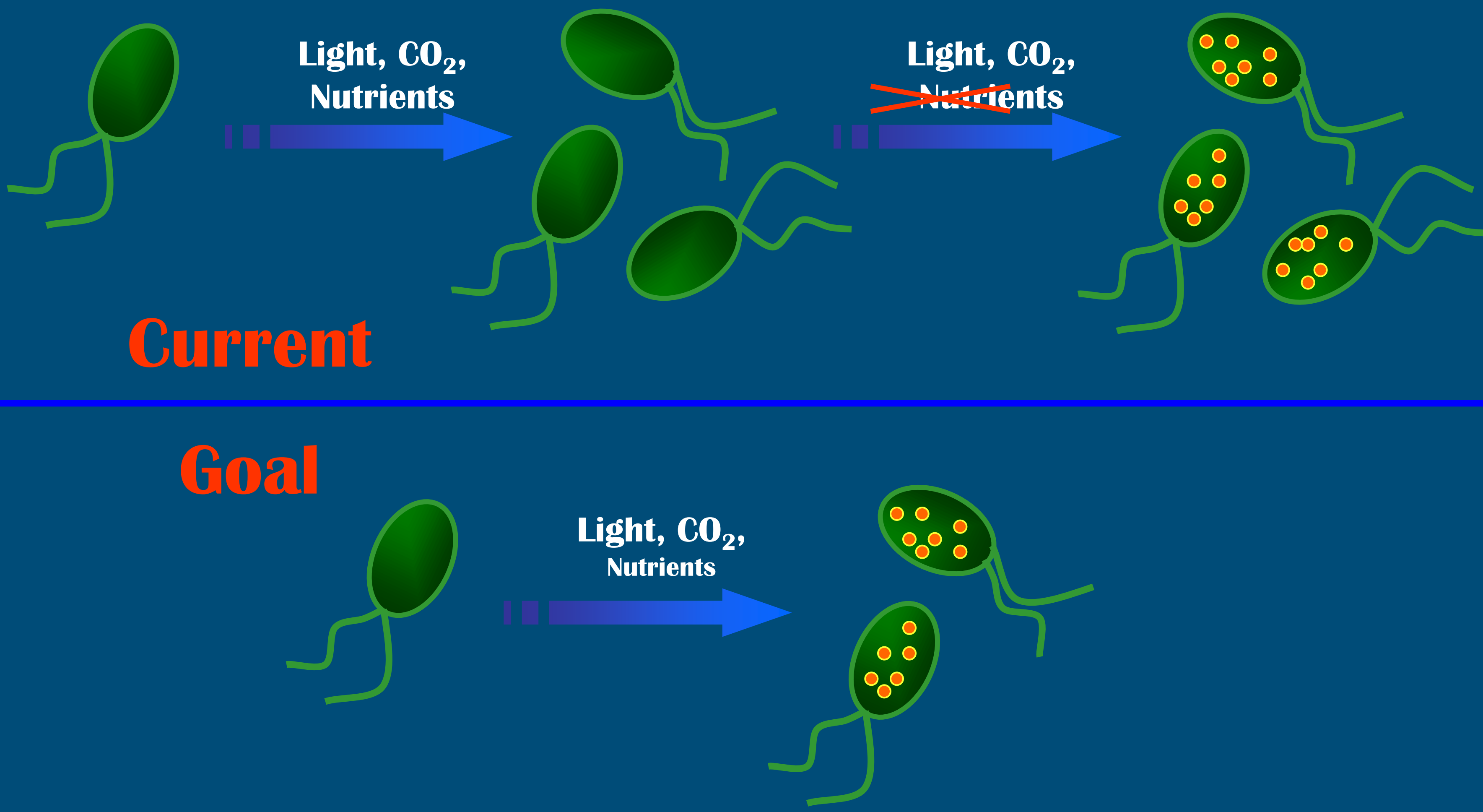
- Energy consumption is bottleneck
- Cost price reduction towards 0.70 €/kg possible
- No positive energy balance yet

- *Challenges*
  - Photosynthetic efficiency
    - Location
    - Reactor design
    - Cultivation conditions
    - Strain improvement / selection
  - CO_2 and other nutrients from waste streams
  - Biorefinery
  - Energy for mixing

Why (not) microalgae? Present challenges!

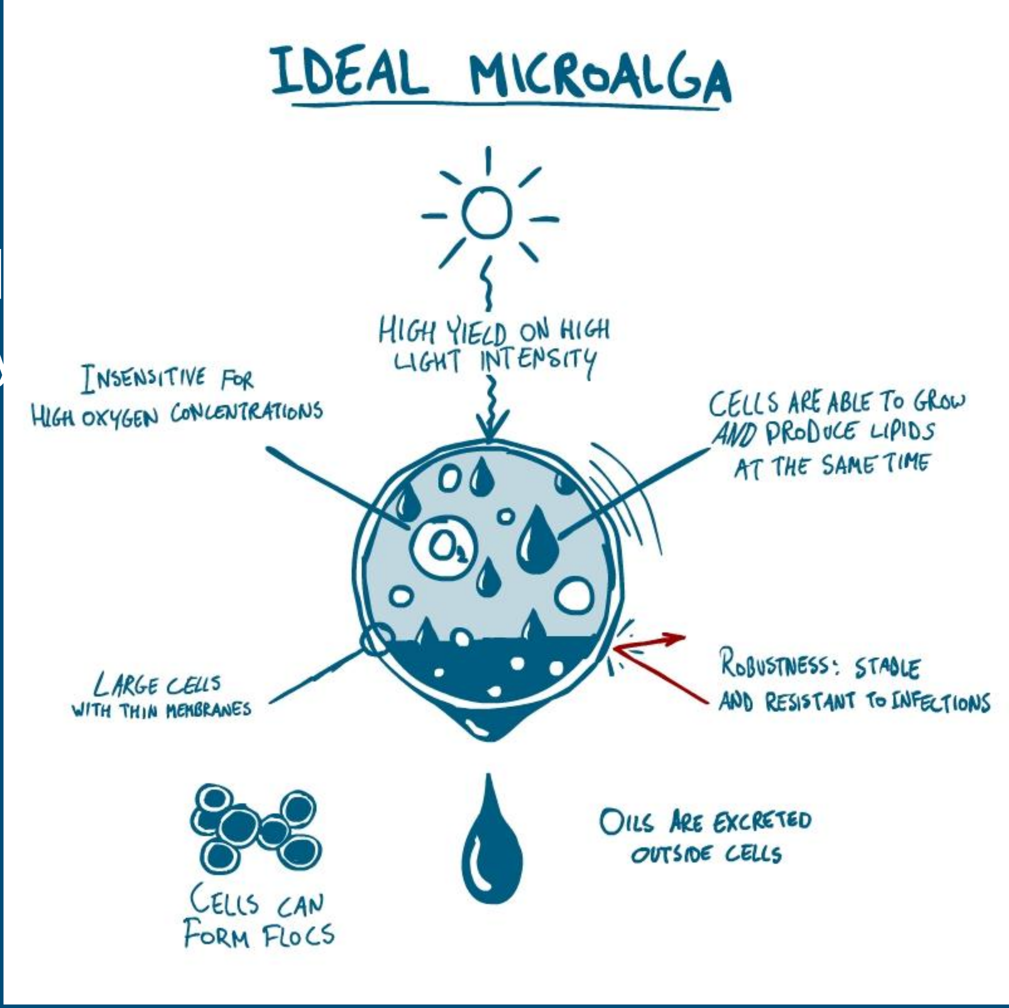
The choice of algae

Lipid production



The alga: no optimization on a single parameter

- High biomass productivity
- High productivity in required molecules (proteins, saturated neutral lipids, unsaturated fatty acids)
- Insensitive to high oxygen concentrations
- Possibility to grow under selective conditions
- Easy to harvest
- Mild extraction



Why (not) microalgae? Present challenges!

The process: efficiency in supply of nutrients and resources

Efficiency in supply and use of nutrients and resources

Sunlight

Water

CO_2, Nitrogen and Phosphorus

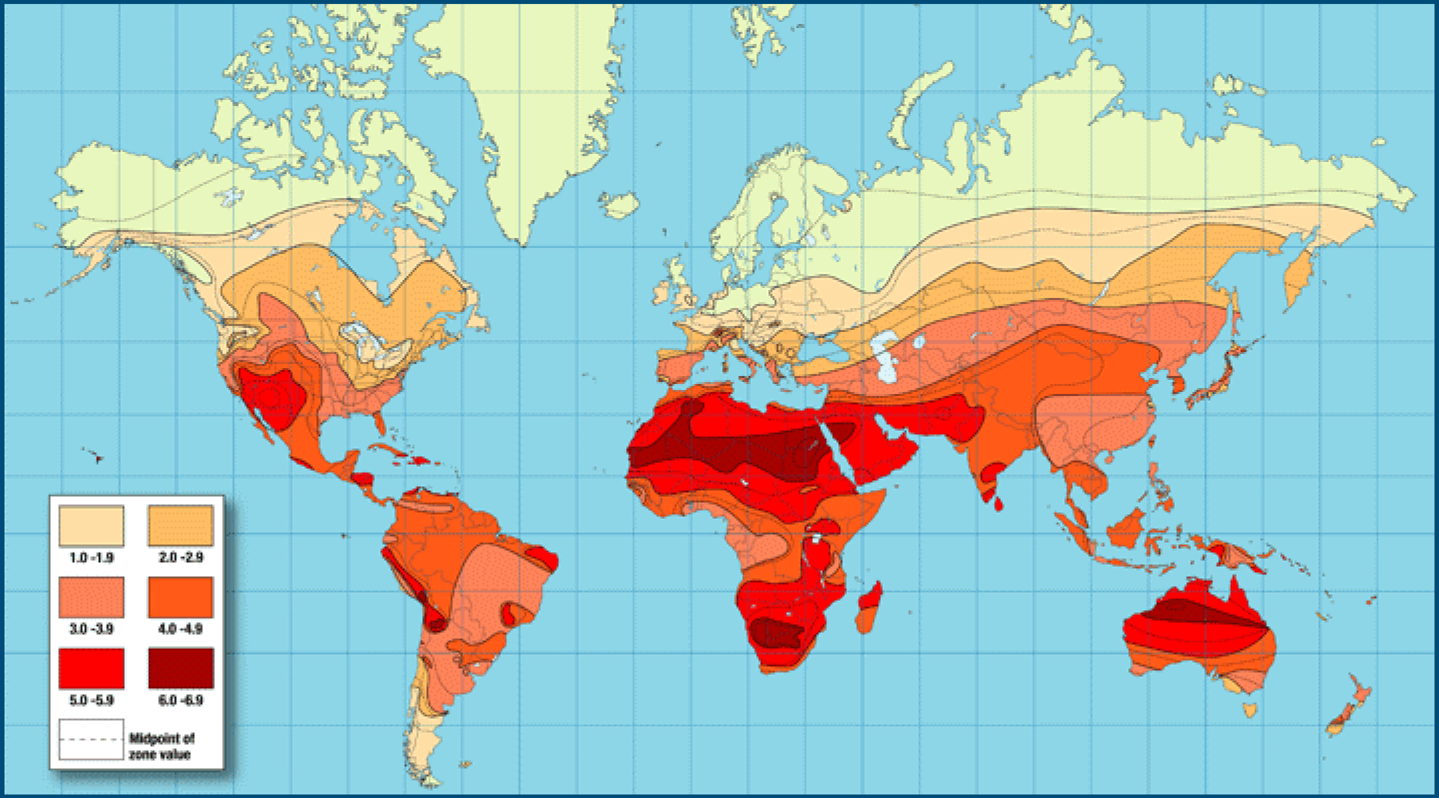
Efficiency in supply and use of nutrients and resources

Sunlight

Water

CO_2, Nitrogen and Phosphorus

Location: sunlight



Reactor design

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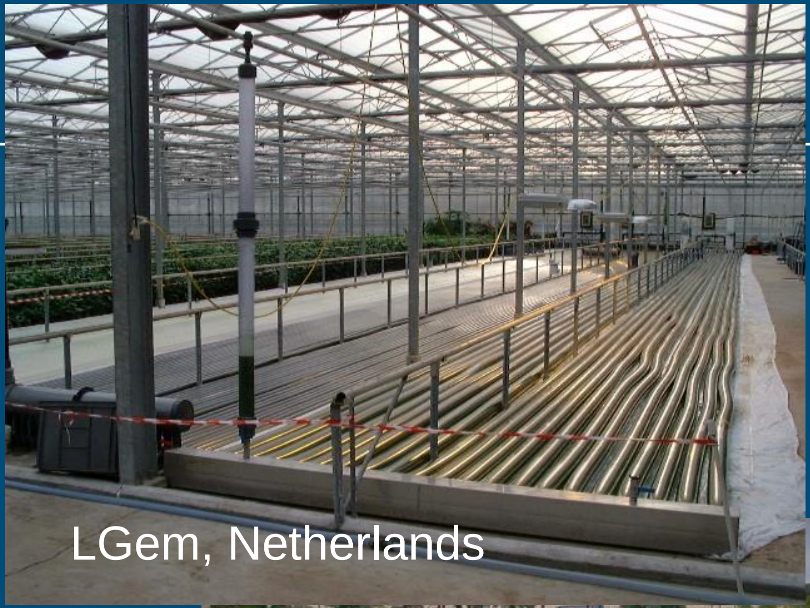
Tubular photobioreactors



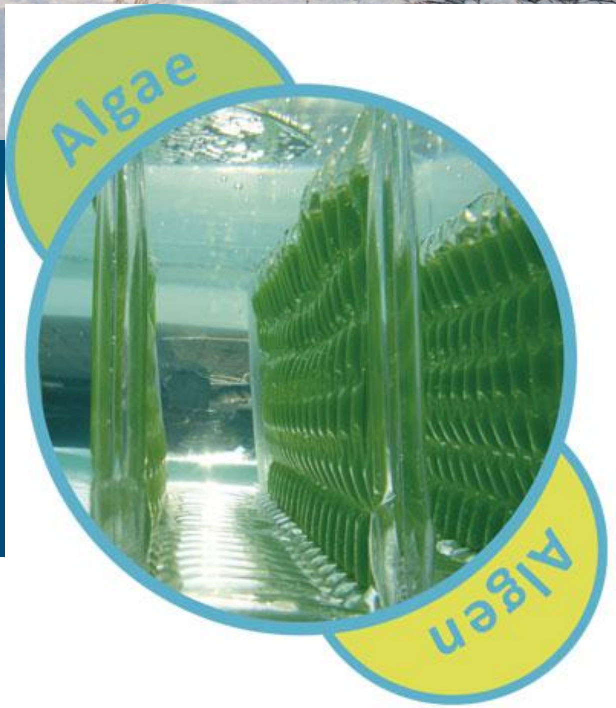
Stacked tubular photobioreactor

- Tubular fences

Plastic film photobioreactors

SOLIX
ALGAE TO ENERGY

Proviron
a human and ecological approach to chemistry



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Open ponds

NBT Ltd., Israel

Ingrepo, Netherlands

Comparison

	Raceway	Hor. tube	Vert. tube	Vert. panel	Vert. panel
Characteristics	Depth: 0.3 m	Diameter: 0.05 m Length: 50 – 100 m	Diameter: 0.05 m Length: 50 – 100 m	Depth: 0.1 m Height: 0.5 m Length: 10 m	Depth: 0.5 m Height: 1.0 m Length: 10 m
Ground coverage	Full ground coverage	Full ground coverage 20 tubes/m2	40 tubes/m2	5 panels/m2	2 panels/m2
Biomass concentration	0.1 – 0.5 g/L	1.0 – 5.0 g/L	0.5 – 2.5 g/L	1.5 – 7.5 g/L	0.5 – 2.5 g/L
PE	1.5%	3 – 4 %	4 – 6 %	4 – 6 %	4 – 6 %

Production costs:

Increasing Photosynthetic Efficiency – what margin do we have?

PE 9.0 %

↓ reflection on PBR

8.6 %

↓ night biomass loss

7.8 %

↓ maintenance

What's left ?... 7.4%

ca 50% reduction in production cost

Light saturation?

Nutrient limitations? CO_2

Inhibition? O_2, light

Practice?... 3 - 4%

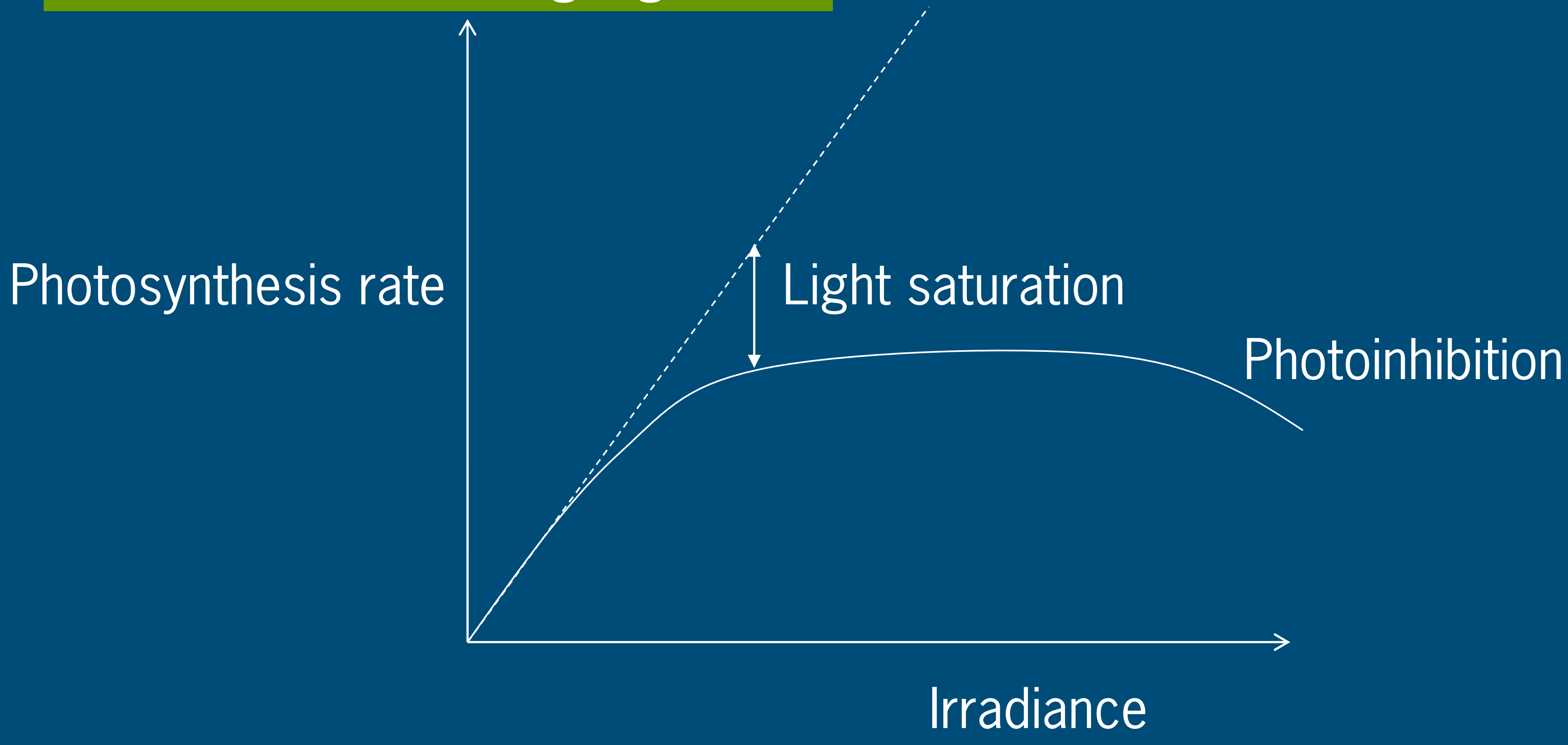
What's determining photosynthetic efficiency outdoors?

Measured / controlled parameters

- Incident light intensity
- Temperature
- O_2 partial pressure
- CO_2 partial pressure
- Gas flow rate / Liquid velocity
- Dilution rate
- pH
- Nutrients

Photosaturation and photoinhibition

Diluted cultures – no light gradient



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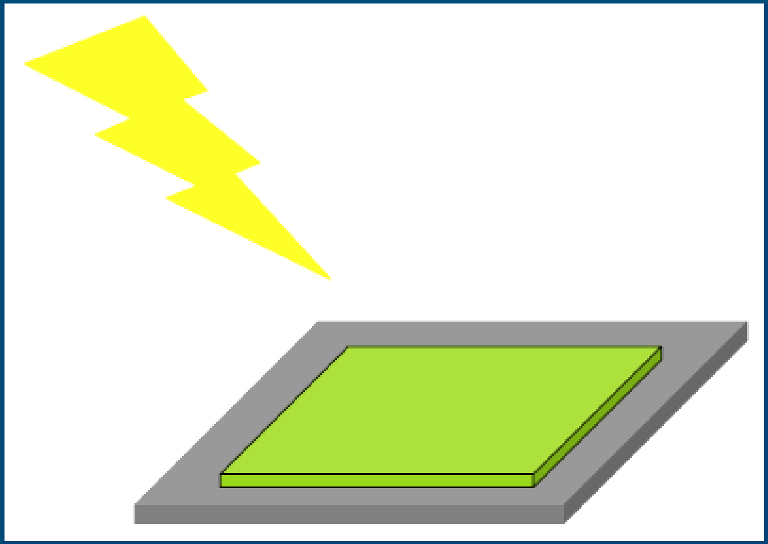
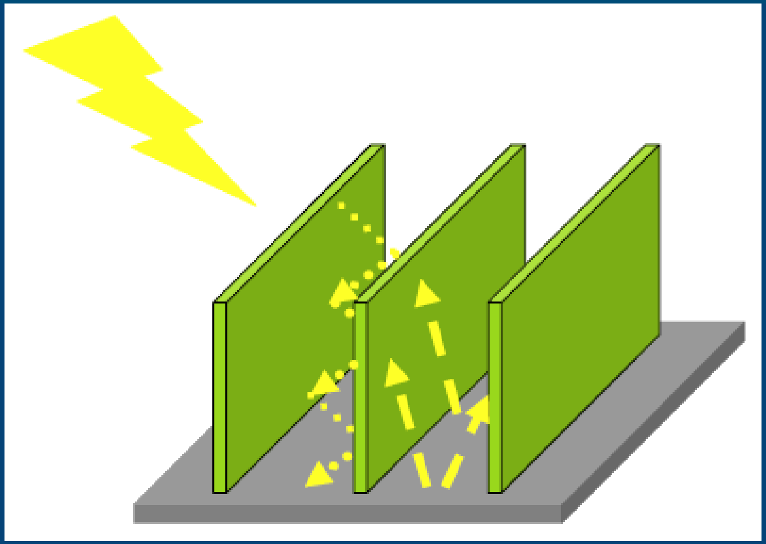
The principle of light dilution – go vertical!



I_{max}: 1800 μmol photons m^{-2} s^{-1}
(direct sunlight)



I_{max}: 400 μmol photons m^{-2} s^{-1}
(diluting effect)

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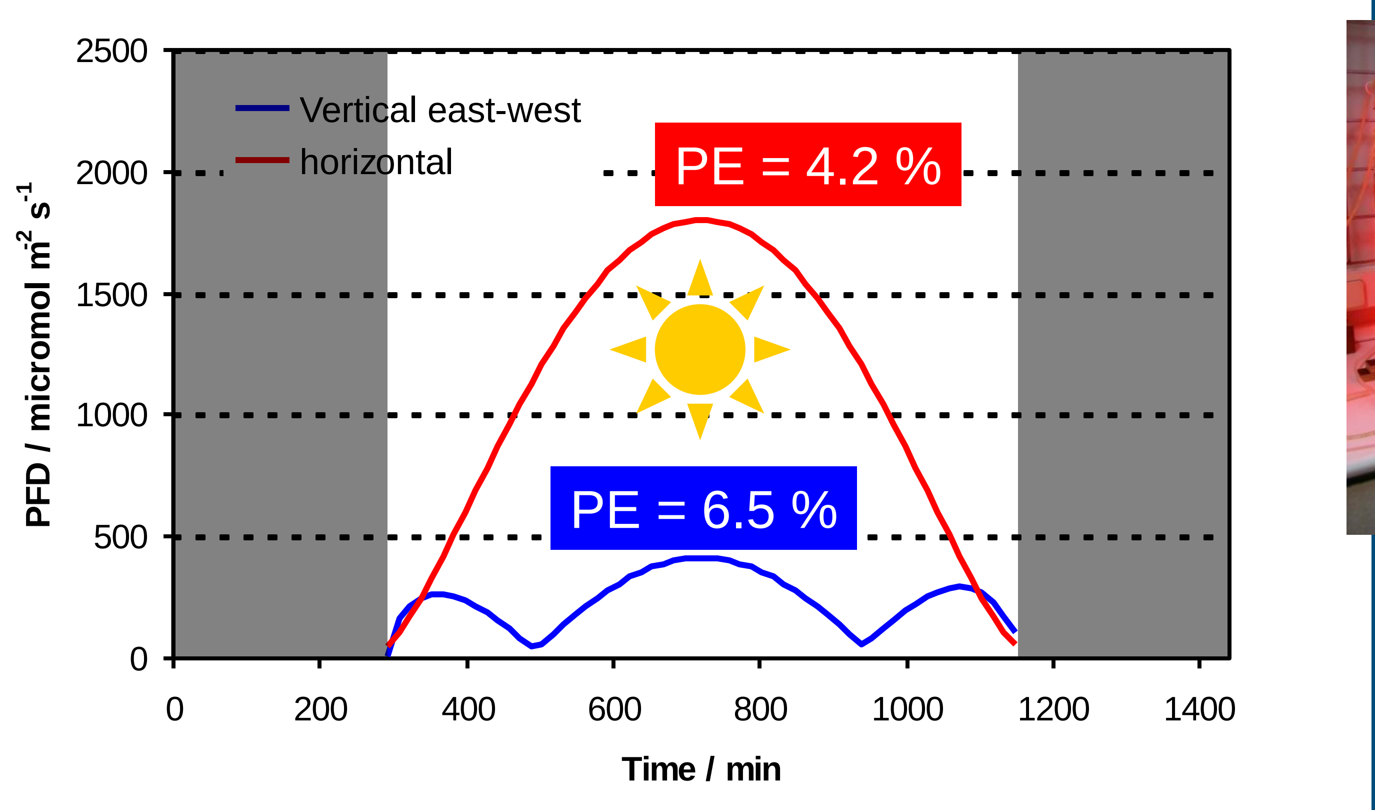
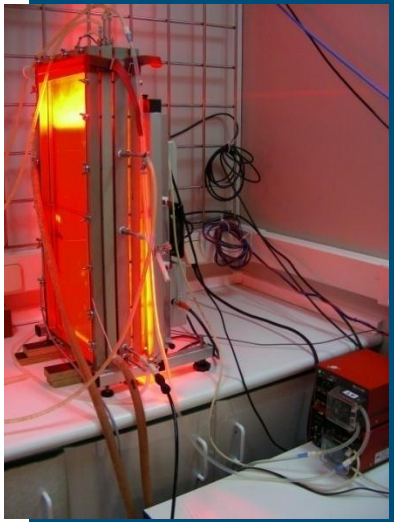
Light dilution in the lab





- At lab scale a photosynthetic efficiency of 6% seems to be within reach

Cuaresma et al., 2010

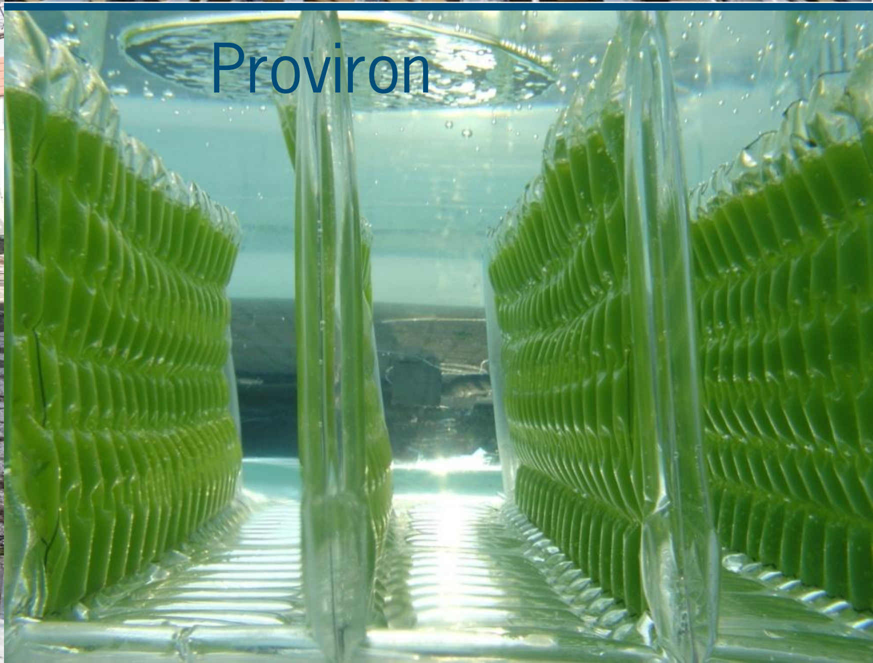
What about:

- Pilot scale 10 – 100 m^2
- Extended time > 1 yr

Light dilution in practice

Challenges

- Material lifetime
- Cleanability
- Reduce energy input (e.g reflect IR)



Efficiency in supply and use of nutrients and resources

Sunlight

Water

CO_2, Nitrogen and Phosphorus

Microalgae vs. plants

vs.

Main inputs in the process: Water

Photosynthesis : ~0.75 liter of water / kg of biomass

1.5 liters of water / liter of oil (50 % lipid content)

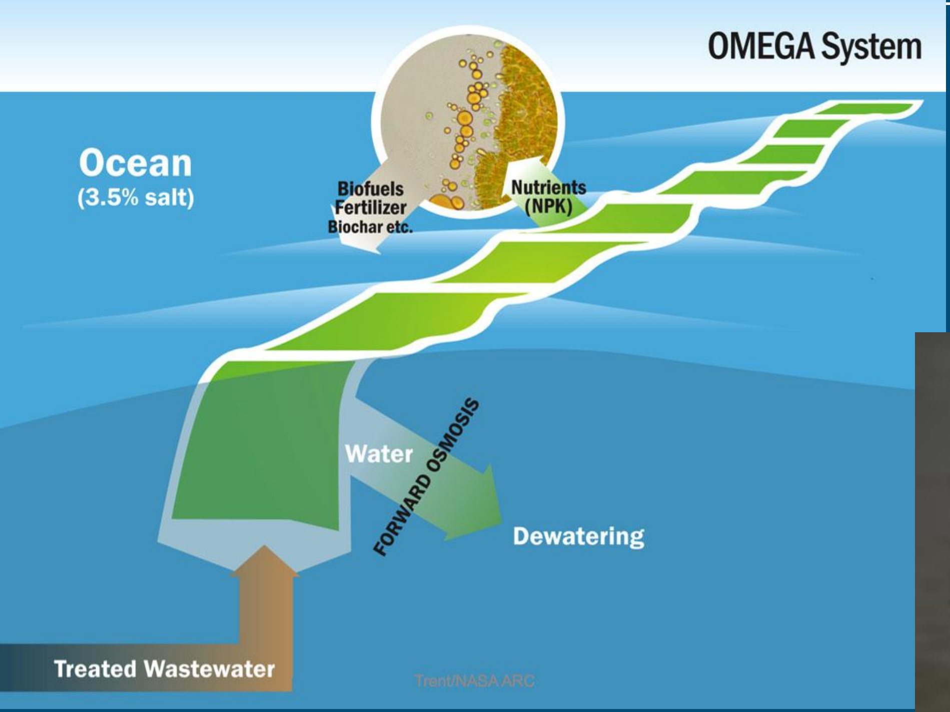
$$CO_2 + 0.93\ H_2O + 0.15\ NO_3^- \rightarrow CH_{1.72}O_{0.4}N_{0.15} + 1.42\ O2 + 0.15\ OH^-$$

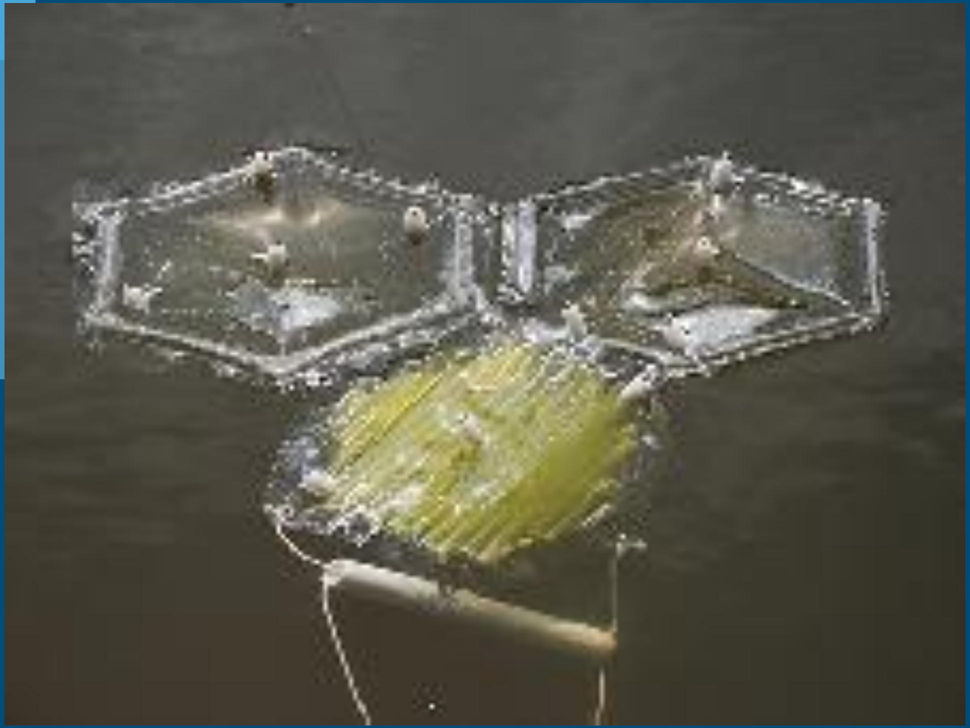
In practice consumption is much larger:

- cooling closed systems
- fresh water needs to be added to open ponds to compensate for evaporation.

- Cooling with large saltwater buffer
- Seawater species
- Growth on large water surfaces (lakes and seas)

NASA OMEGA Systems





Efficiency in supply and use of nutrients and resources

Sunlight

Water

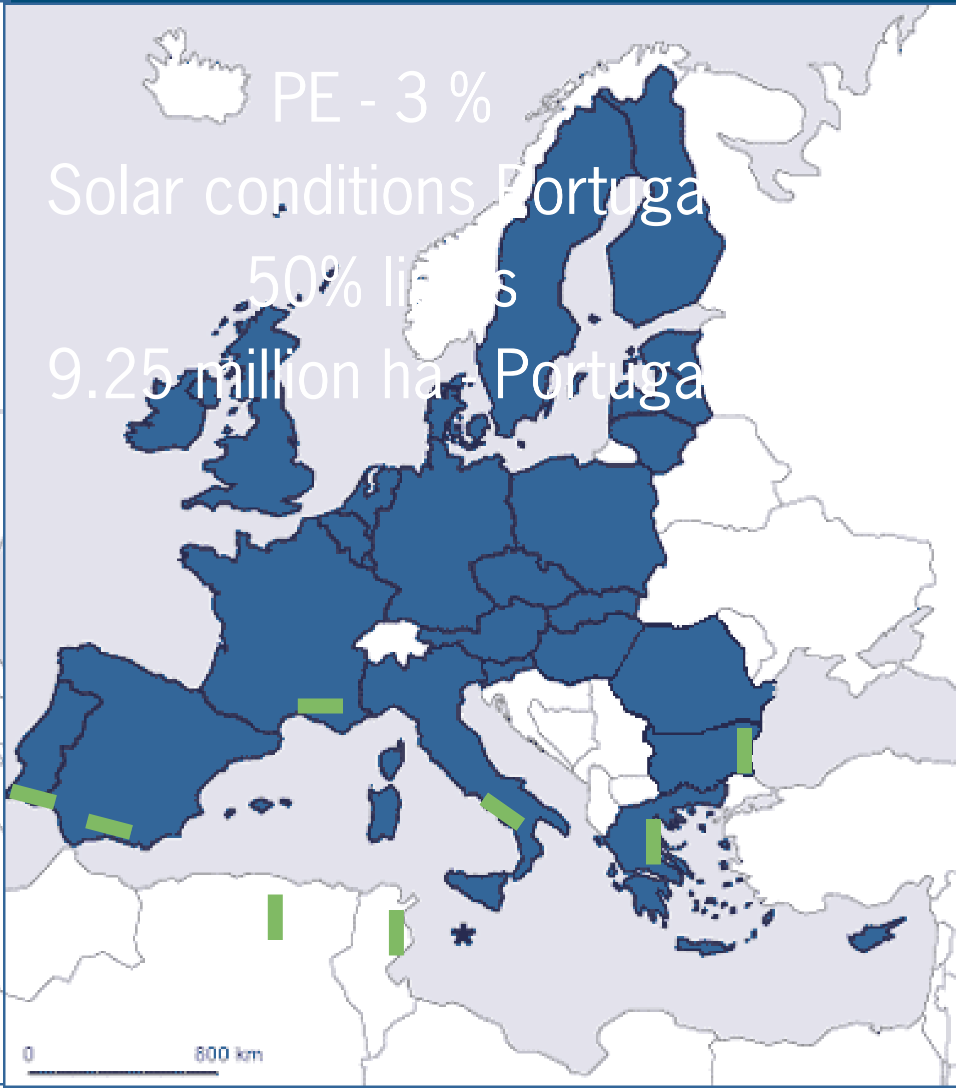
CO_2, Nitrogen and Phosphorus

Main inputs in the process

To produce 1 ton of algal biomass:

- 1.8 tons of CO_2 is needed
- 0.07 ton N
- 0.01 ton P

Transport Fuels in Europe - 0.4 billion m3



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Wijffels R.H., Barbosa M.J. (2010) An outlook on microalgal biofuels. ***Science*** 329: 796-799

Main inputs in the process CO_2

- 1.8 tons of CO2 is needed to produce 1 ton of algal biomass

- 1.3 billion tons of CO_2 for 0.4 billion m3 of biodiesel
- EU CO_2 production 4 billion tons of CO2

Logistics?

Main inputs in the process N & P

Biomass: 7% N

1 % P

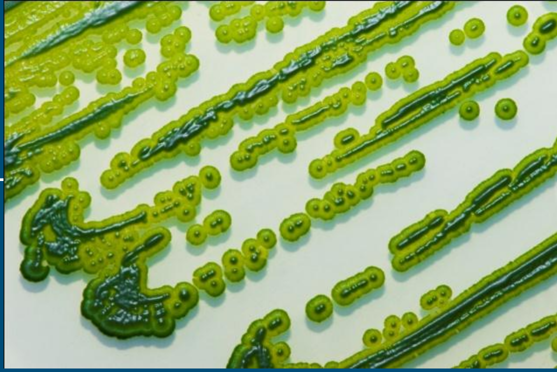
- ~25 million tons of nitrogen
- 4 million tons of phosphorus

Twice the amount that is presently produced as fertilizer in Europe

- Use residual nutrient sources (ca 8 million ton N in Europe)
- Recycle nutrients

How to optimize the process?

How to optimize the process?



- Increasing photosynthetic efficiency
- Integrate processes (free nutrients)
- Decreasing mixing
- Developing cheaper and less energy consuming harvesting technologies
- Choosing locations with higher irradiations

Scale up

Production costs

Energy requirement

AlgaePARC

Algae Production And Research Center

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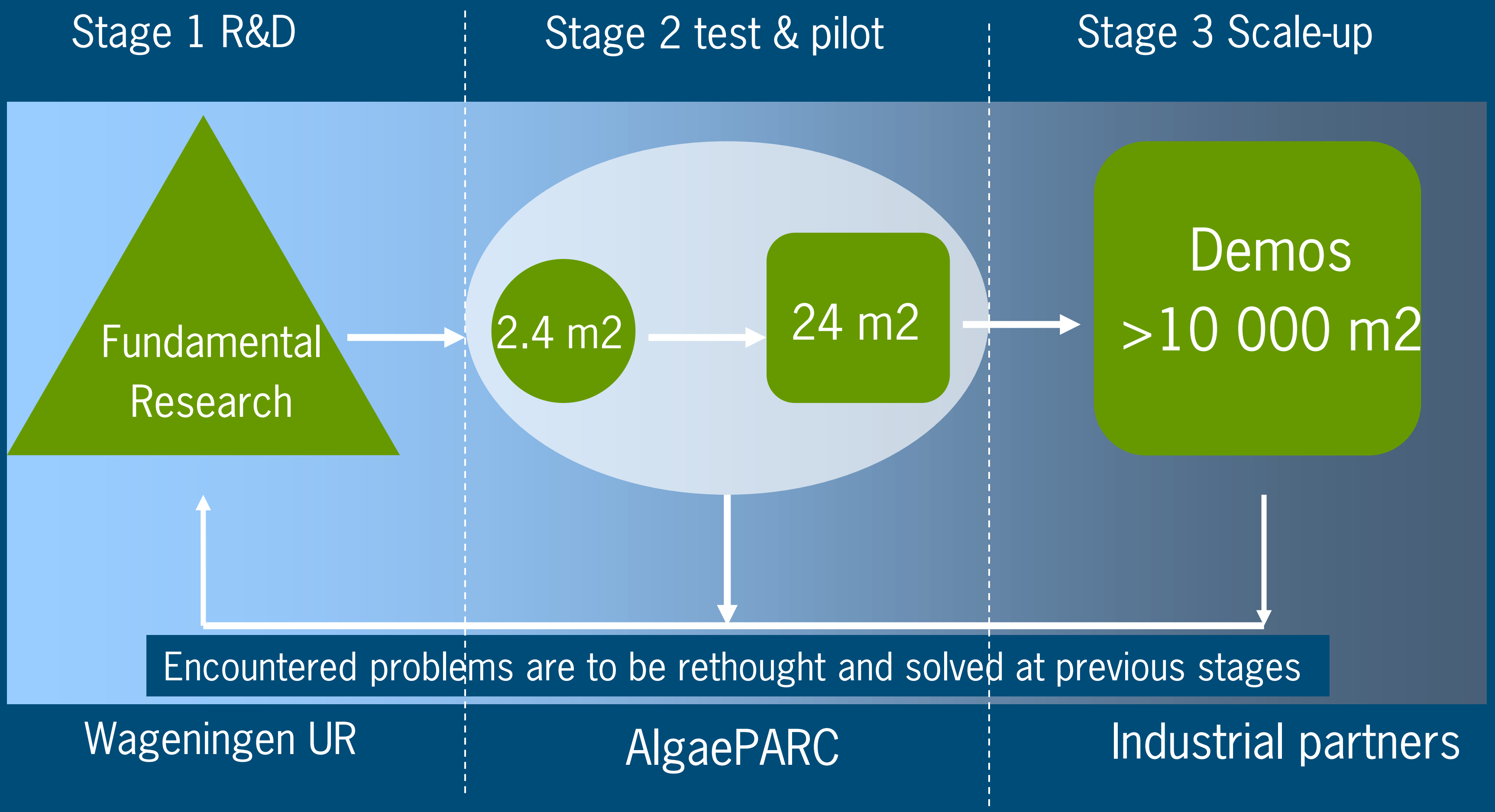
AlgaePARC

The main focus of AlgaePARC is to develop knowledge, technology and processes strategies to ***scale up*** microalgae facilities ***under industrial settings*** and to optimise product productivities under stress and controlled conditions outdoors.

Translate research towards applications



Cultivations systems (24 m^2)

Open pond
- Reference

Horizontal tubes
- high light intensity
- oxygen accumulation

Vertical stacked hor. tubes
- light dilution
- oxygen accumulation

Flat panels (Proviapt)
- light dilution
- no oxygen accumulation

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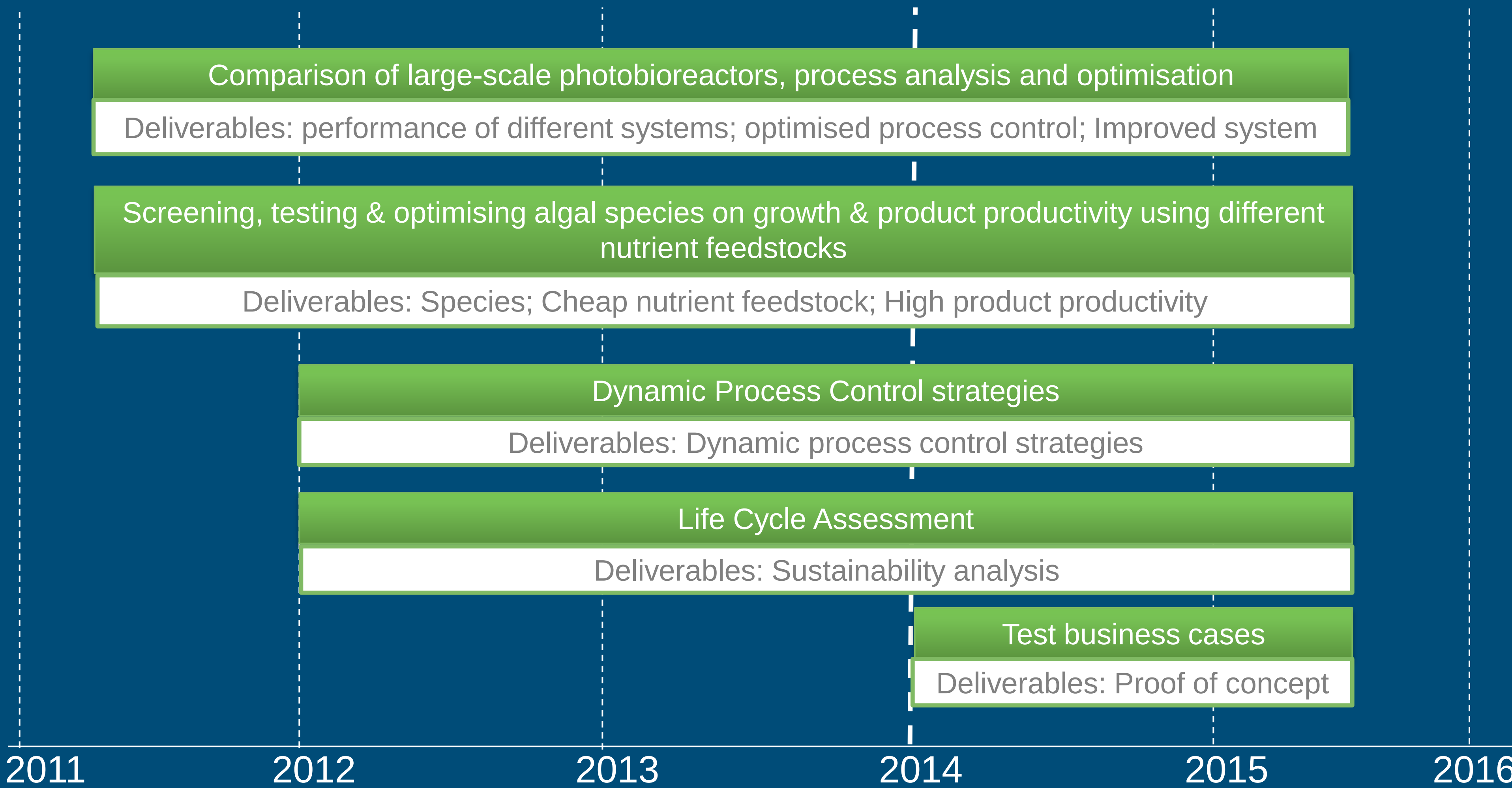
R&D activities AlgaePARC

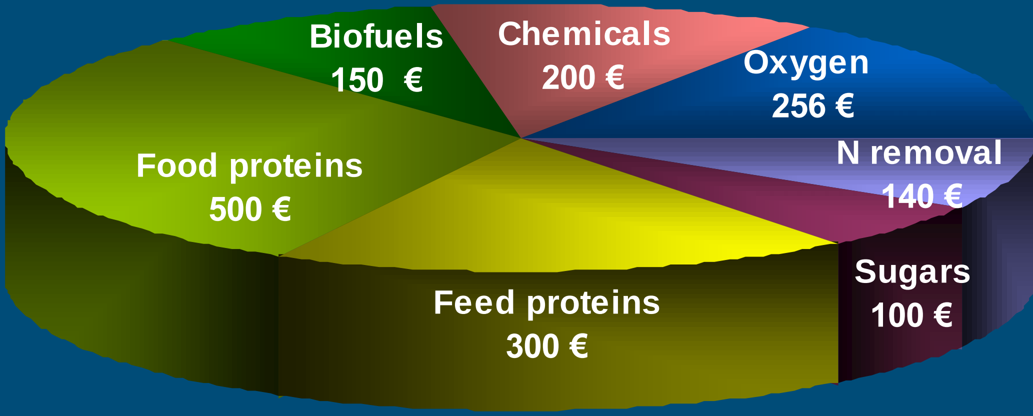


Funding AlgaePARC

- Facility financed by
  - Ministry EL&I
  - Province Gelderland
  - Wageningen UR
- Research program financed by

Next steps

- Development of demo projects
- Biorefinery
  - *Mild cell disruption techniques*
  - *Fractionation biomass with maintainance of functionality of proteins*
- From cell physiology to process strategies



Microalgae in a biobased economy?

- *What does he think?*

Microalgae in a biobased economy?

- *What do you think?*

Discuss proposition:

- Algae will be the feedstock of the future

Microalgae in a biobased economy?

- *What do I think?*
- Possibly
- 10 years R&D
- Need for trained personnel
- Educate

www.algae.wur.nl

www.AlgaePARC.com

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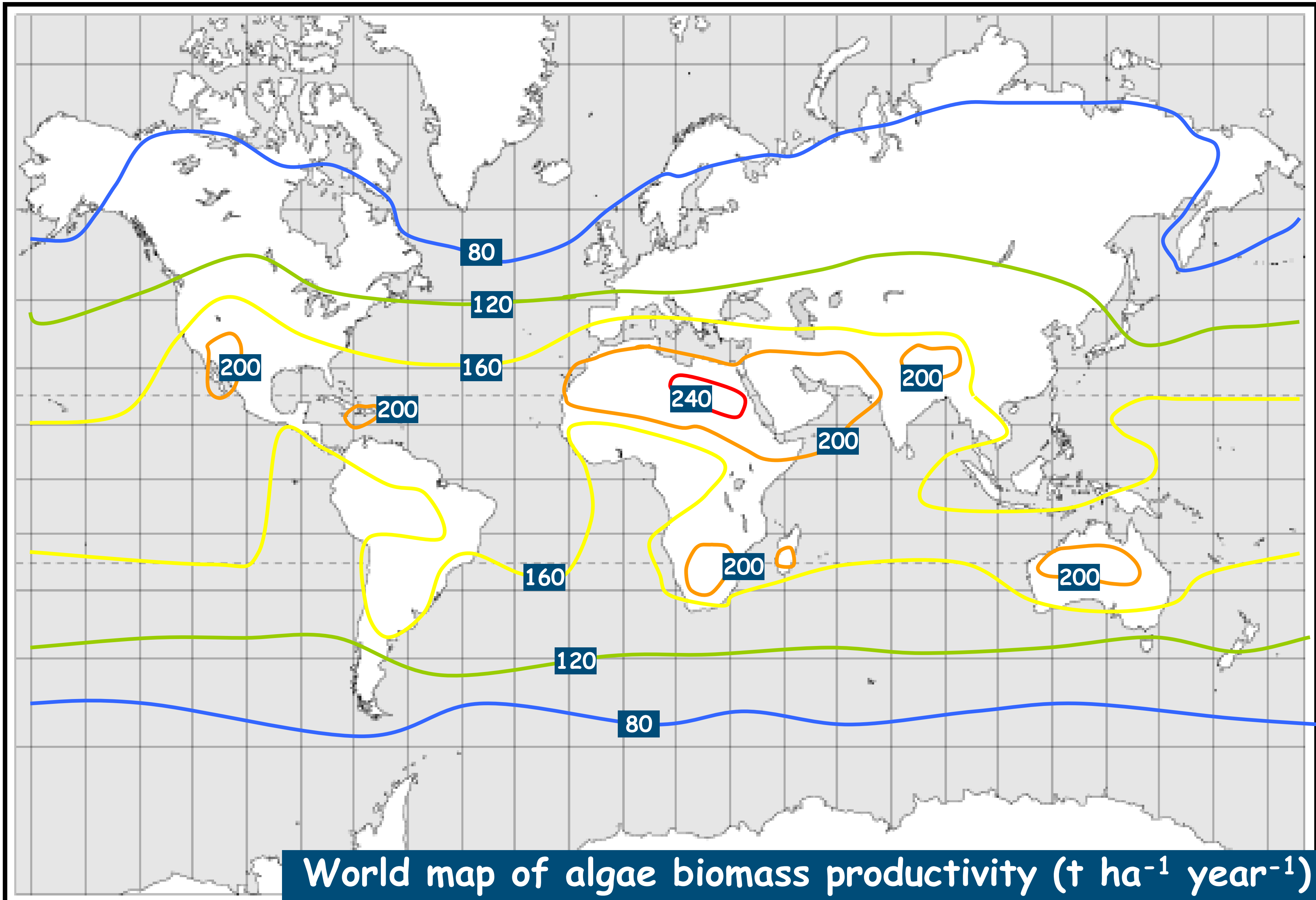


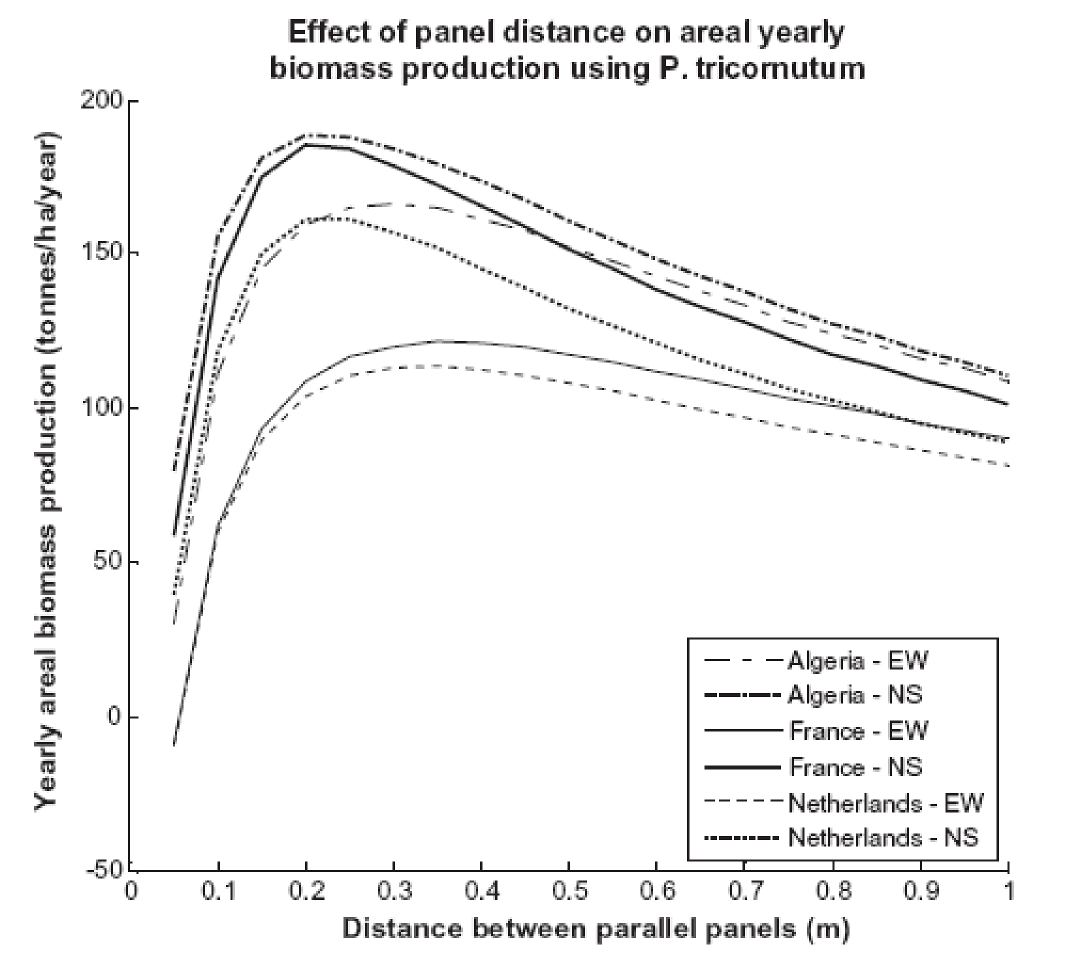
World map of algae biomass productivity (t ha^{-1} $year^{-1}$)

(at 5% photosynthetic efficiency and 20 MJ kg^{-1} dry biomass)

Source: Prof. Mario Tredici (Italy)

Scale-up: design studies

e.g Effect panel distance and orientation



Slegers et al. (2011) Applied Energy

Why (not) microalgae? Present challenges!

The process: harvesting

Harvesting techniques

- Centrifugation
  - Energy consumption is high
- Filtration
  - Only possible with large algae species (e.g. Spirulina)
- Flocculation
  - Good alternative for removal of water as first step

Flocculation

Chemical flocculation

- Multivalent metal salts
- Cationic polymers
- Chitosan

Autoflocculation

- Extreme pH
- Temperature
- Nutrient depletion

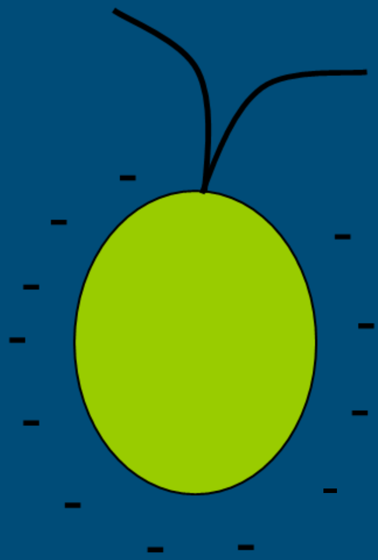
Bioflocculation

- Exopolysaccharides produced by microorganism

Dissolved/dispersed air flotation

Chemical flocculation

1. Multivalent metal salts
2. Cationic polymers
3. Chitosan



Important:

- Case 1, 2 and 3: Negative effect for downstream processing for production of biodiesel
- Case 2: flocculation using cationic polymers is inhibited by high ionic strength of sea water
- Case 1, 2, and 3: cost price too expensive for biodiesel production

Autoflocculation

1. Extreme pH
2. Temperature
3. Nutrient depletion

Important:

- Case 1: supposedly works for all algae
    - Time needed ranges from hours to days
    - pH range where flocculation occurs depends on strain
    - Effectiveness depends partially on growth phase
- Case 1: Much used in waste water plants
- Case 1, 2, 3: may cause cell composition changes
- Case 2, 3: generally considered too unreliable to be economical on a commercial scale

Bioflocculation

1. Capability of production of exopolysaccharides

Important:

- Environmental conditions are of influence
- Production strain is flocculating strain
- Other microalgal strain can be added to reactor as flocculant
- Other microorganisms (bacteria etc.) can be added to reactor as flocculant

Dissolved/disperged air flotation

1. Electrostatic interaction between cell and gas bubble/'collector'

Important:

- Strain dependent
- Usually use of added chemicals (inorganic coagulants)
- Often used in waste water treatment plants

Why (not) microalgae? Present challenges!

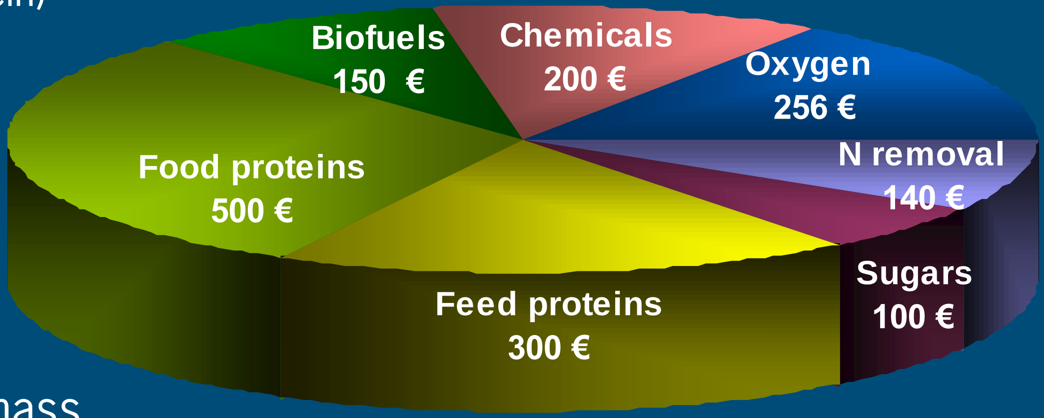
The process: what to do with the biomass

Microalgae: Importance of a biorefinery approach

- Varied and high quality composition of biomass
- Economic need to optimise valorization of the biomass by extraction of multiple products in addition to e.g fuels

Bulk chemicals and biofuels in 1,000 kg microalgae

- 400 kg lipids
  - 100 kg as feedstock chemical industry (2 €/kg lipids)
  - 300 kg as transport fuel (0.50 €/kg lipids)
- 500 kg proteins
  - 100 kg for food (5 €/kg protein)
  - 400 kg for feed (0.75 €/kg protein)
- 100 kg polysaccharides
  - 1 €/kg polysaccharides
- 70 kg of N removed
  - 2 €/kg nitrogen
- 1,600 kg oxygen produced
  - 0.16 €/kg oxygen
- Production costs: 0.40 €/kg biomass
- Value: 1.65 €/kg biomass



Complexity of biorefinery

- Business model in which different end users need to collaborate
- Market volumes must fit
- Highest value is obtained if functionality of molecules is maintained
- Biomass production and biorefinery depend on each other

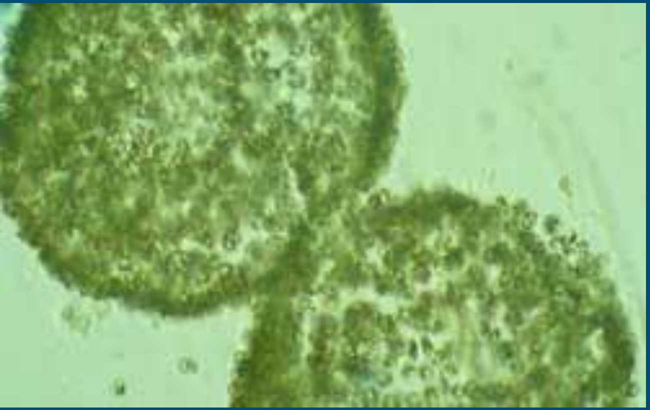
To replace all transport fuels in Europe

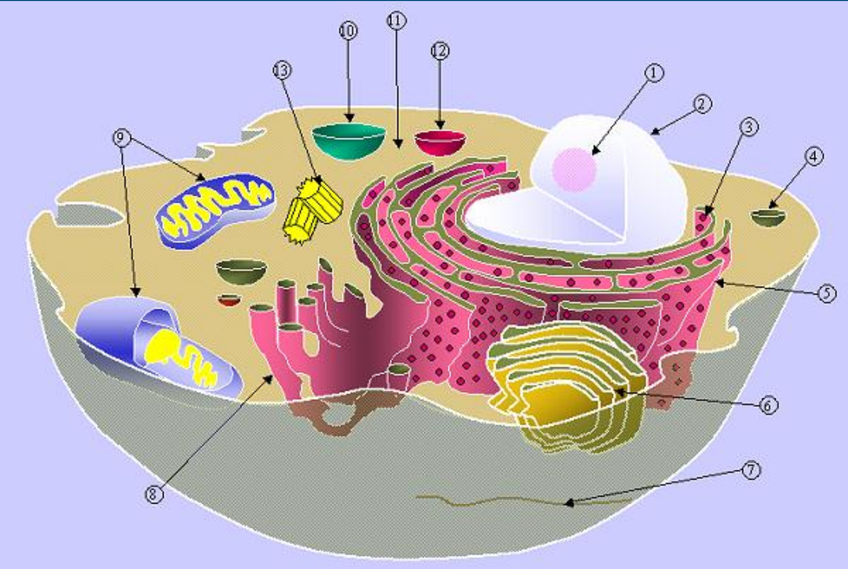
- 400 million m^3 lipids needed
- 9.25 million ha surface area
- Equivalent to surface area of Portugal
- 400 million tons of proteins produced
- 20 times the amount of soy protein imported in Europe

How can we make a more structure based approach for biorefinery?

- To fractionate all components
- Maintain their functionality
- At low energy input

Localization of components in different organelles in the cell





Molecular and Technological knowledge both needed

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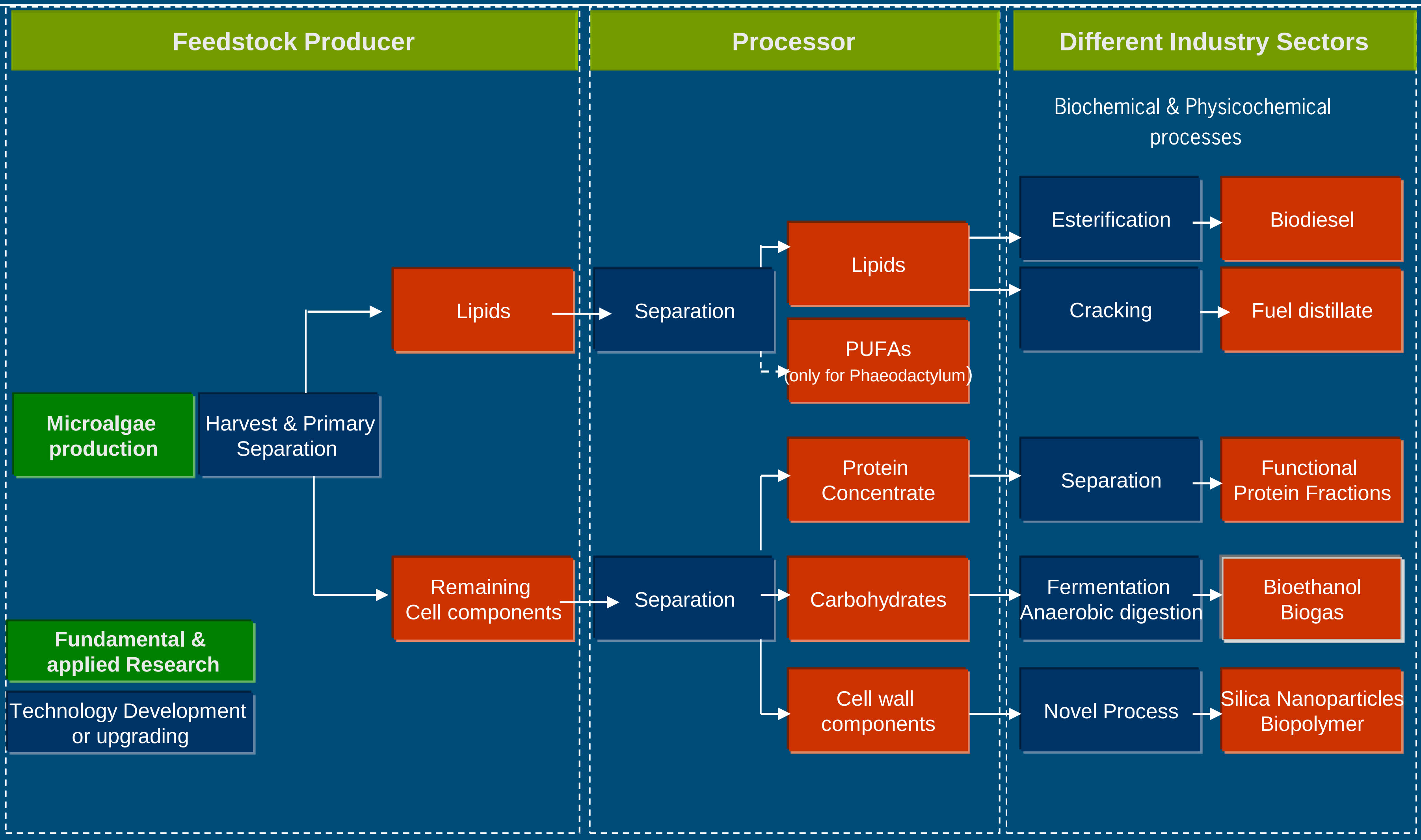
Specific developments required for a microalgae biorefinery

- Development of mild and efficient cell disruption, extraction and fractionation technologies
- Effective technologies for separation of carbohydrates, proteins and lipids
- Lipid/oil refining technologies
- Improvement of environmental performance, decrease in energy consumption and decrease of capital costs
- Integrate knowledge & facilities for oil, food and fine chemical industry
- Biomass provision (quantity and quality)

Present

- One process for one product

Chain Approach: from feedstock to end products



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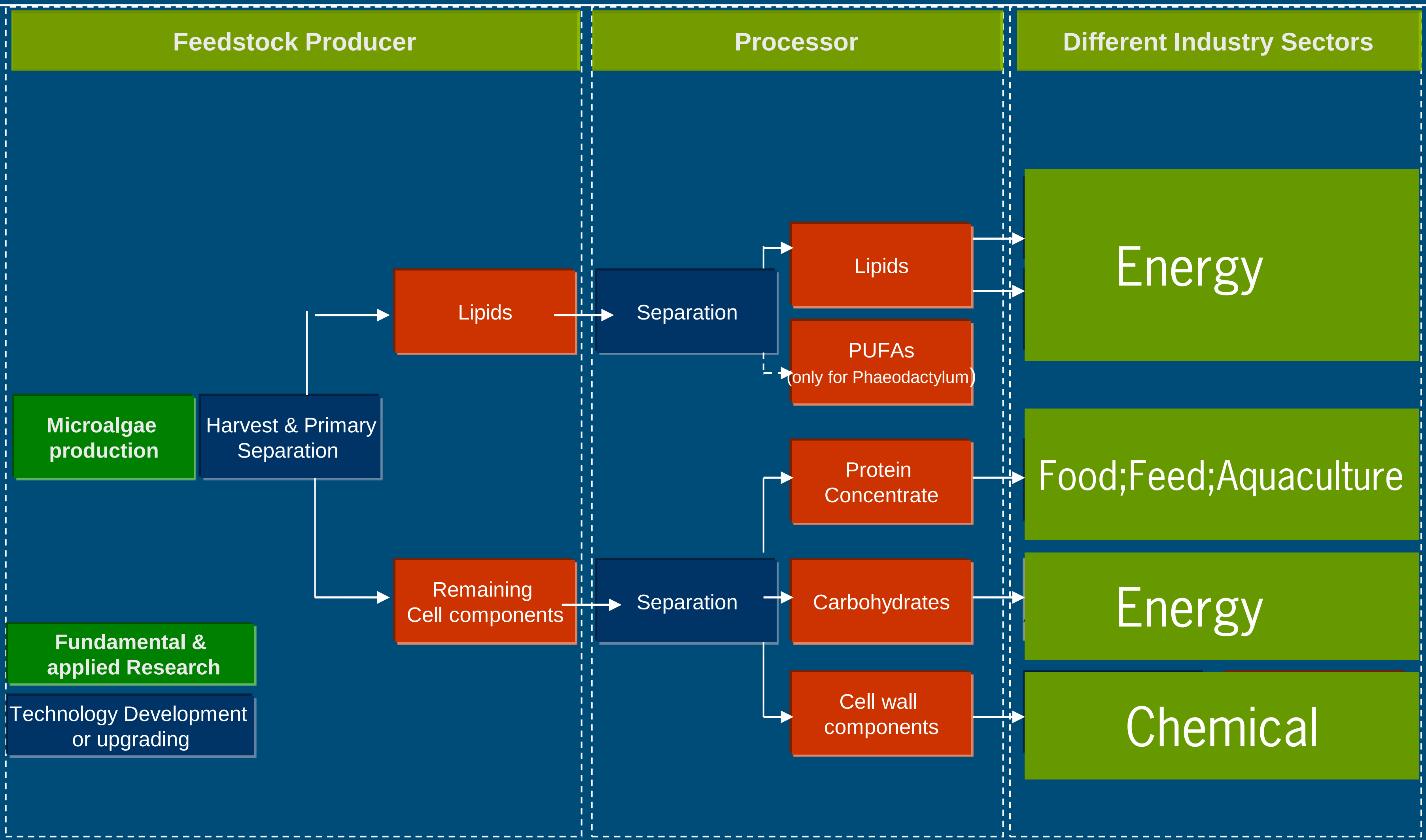
Chain Approach: from feedstock to end products



Why (not) microalgae? Present challenges!

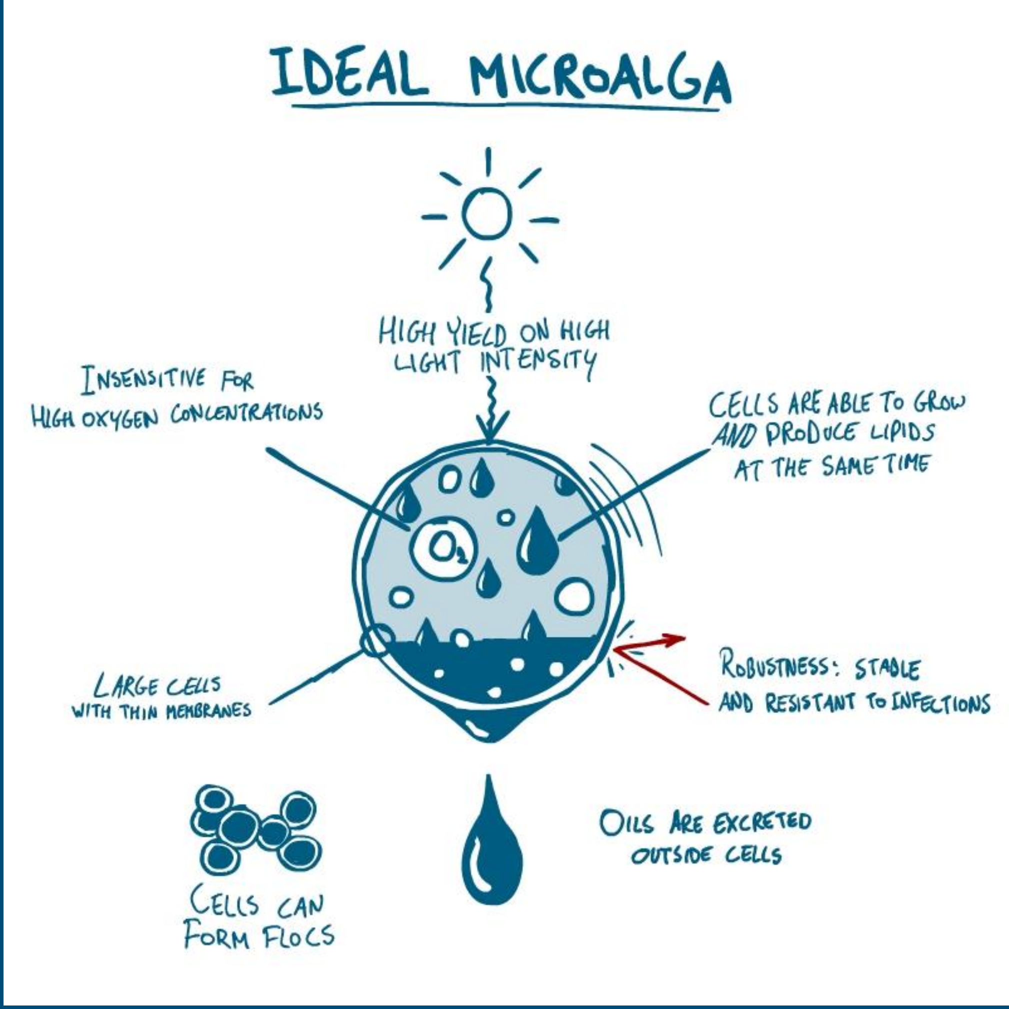
Furthermore....

Challenges in the entire chain

- High CAPEX, high running costs and energy consumption for cultivation, harvesting and product separation
- Large-scale cultivation of microalgae
- Current process technology does not allow the production of multiple products
- Lack of trained personnel
- Product development to commercial applications
  - Regulatory approval for use of algae in feed/food is lacking
  - Broad consumer acceptance of algae and seaweeds in food
  - The full range of potential products, best combinations and their market values is unclear

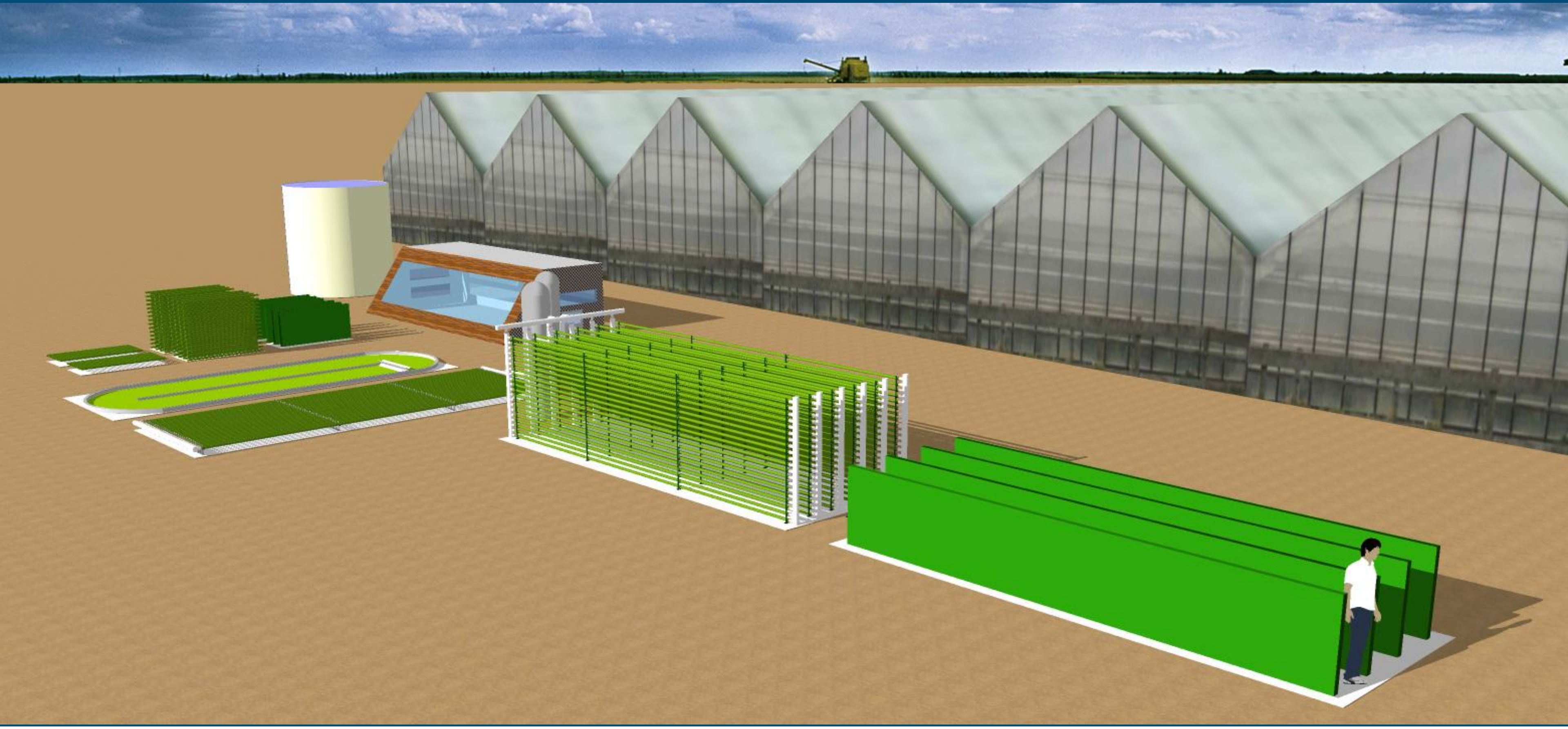
The alga: no optimization on a single parameter

- High biomass productivity
- High productivity in required molecules (proteins, saturated neutral, lipids, unsaturated fatty acids)
- Insensitive to high oxygen concentrations
- Possibility to grow under selective conditions
- Easy to harvest
- Mild extraction



AlgaePARC

Algae **P**roduction **A**nd **R**esearch **C**entre



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AlgaePARC

an international , open and independent centre for applied research on microalgae

The ultimate objective of AlgaePARC is to develop technology and process strategies for sustainable production of feedstock for fuel , chemicals, food and feed

R&D at AlgaePARC is aimed to fill the gap between fundamental research on algae and full-scale algae production facilities

Production costs

Scale-up

Energy requirement

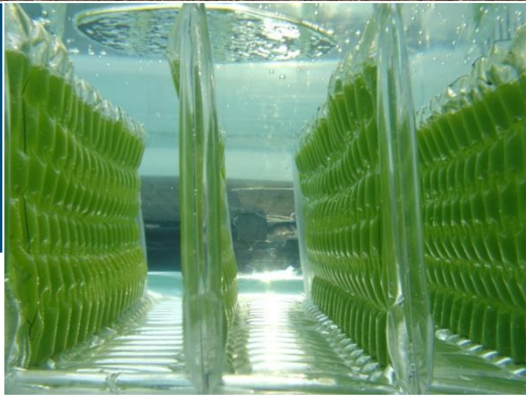
Cultivations systems (24 m²)

<ins>Open pond</ins>
- Reference

<ins>Horizontal tubes</ins>
- high light intensity
- oxygen accumulation

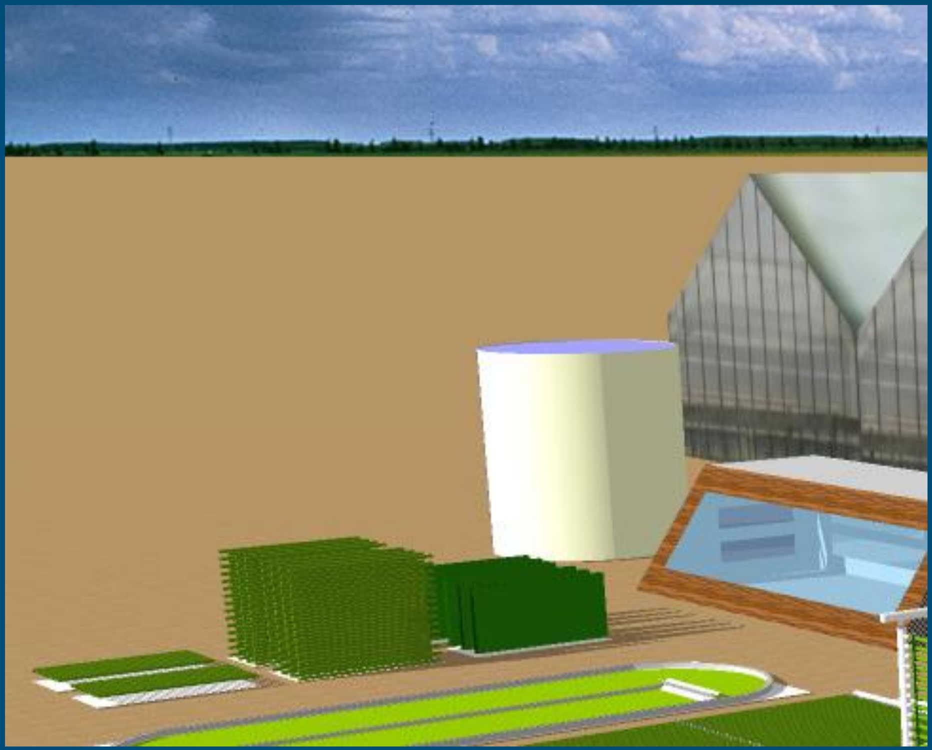
<ins>Vertical stacked hor. tubes</ins>
- light dilution
- oxygen accumulation

<ins>Vertical plastic films (Proviapt)</ins>
- light dilution
- no oxygen accumulation



2.4 m^2 systems

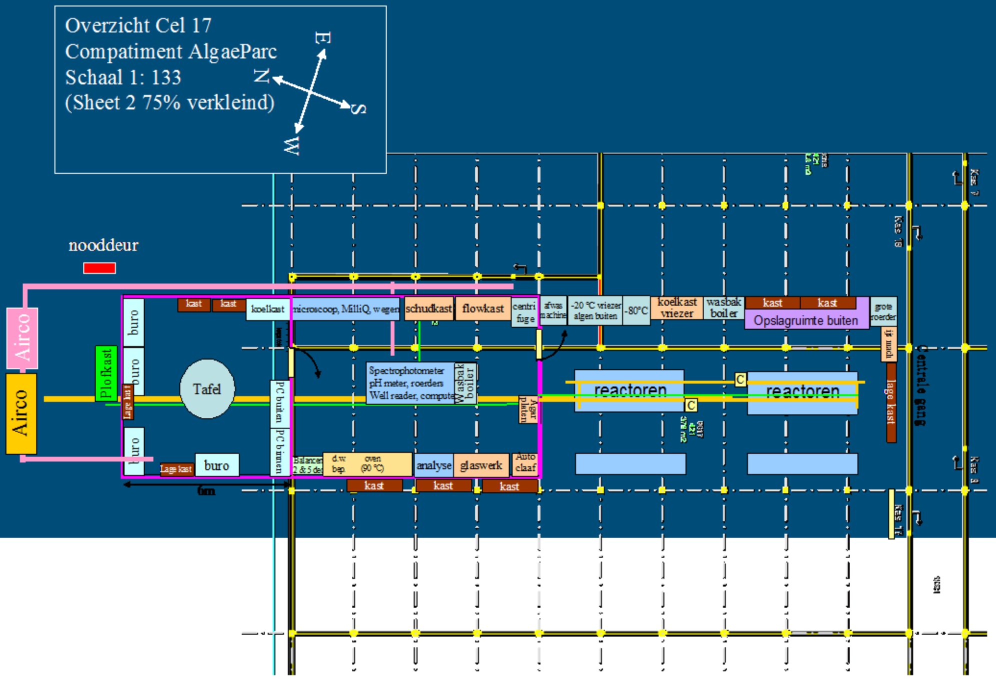
- Phase between lab and pilot
- Test things where you are not sure of
- Different strains
- Different feed stocks
- Adaptations in design
- New systems
- If successful
  - To 25 m^2 scale
- If not successful
  - More experiments
  - Reject



...and a Lab

- Storage of strains
- Medium optimisation
- Initial test of feedstocks
- Screening
- Analytics
- Support for outdoors

mL ->m3 *in situ*



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