Maximal photosynthetic efficiency of microalgae in photobioreactors and the minimal requirement for gas transfer

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What's determining PE outdoors?

- Light intensity
- Temperature
- Oxygen partial pressure
- Carbon dioxide partial pressure
- pH
- Nutrients

Low controllability

High controllability

Biomass growth

- Sunlight driven production of carbohydrates:

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

10 hν

- Carbohydrates yield biomass:

$$1.18\ CH_2O + 0.12\ NH_4^+ \rightarrow CH_{1.78}O_{0.36}N_{0.12} + 0.18\ CO_2 + 0.47\ H_2O + 0.12\ H^+$$

- Taken together:

$$CO_2 + 0.71\ H_2O + 0.12\ NH_4^+ \rightarrow CH_{1.78}O_{0.36}N_{0.12} + 1.18\ O_2 + 0.12\ H^+$$

11.8 hν

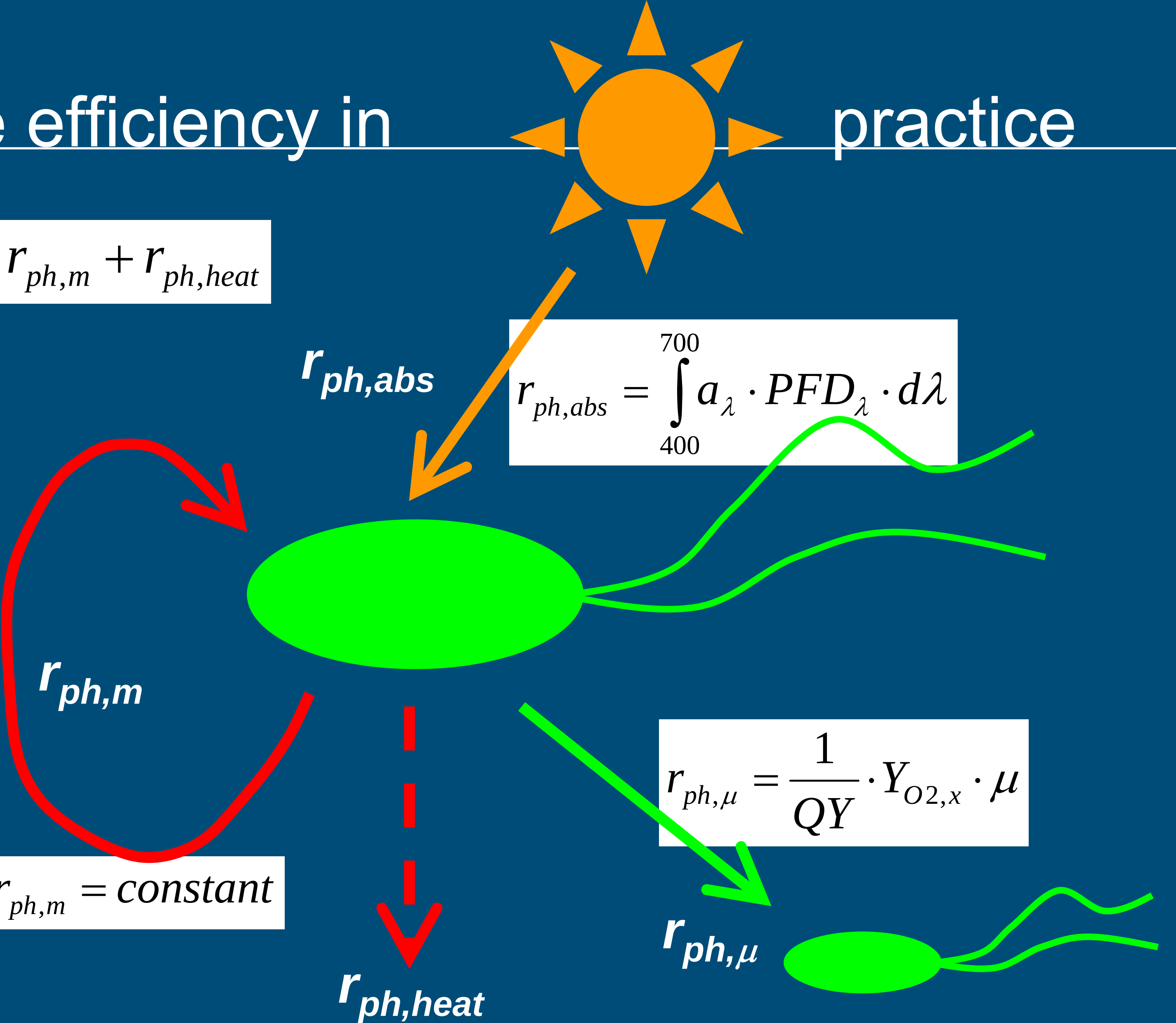
Theoretical maximal photosynthetic efficiency (PE)

N-source	QR_{CO2} mol Cmol^{-1}	$Y_{x,E}$ g mol^{-1}	PE_{PAR} % PAR	PE %
NO_3^-	14.2	1.50	19	8
NH_4^+	11.8	1.80	21	9
No nitrogen *	10	1.96	21	9

* Hypothetical situation of biomass solely accumulating carbohydrates $(CH2O)_n$

Light use efficiency in practice

$$r_{ph,abs} = r_{ph,\mu} + r_{ph,m} + r_{ph,heat}$$



$$r_{ph,abs} = \int_{400}^{700} a_\lambda \cdot PFD_\lambda \cdot d\lambda$$

$$r_{ph,m} = constant$$

$$r_{ph,\mu} = \frac{1}{QY} \cdot Y_{O2,x} \cdot \mu$$

PE in SLP panel photobioreactors?

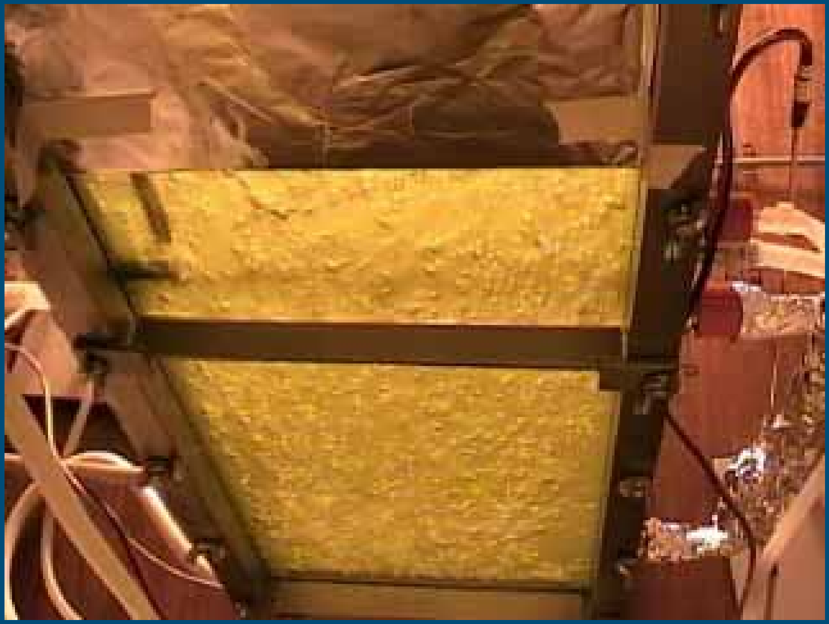
Short light-path

Turbulence

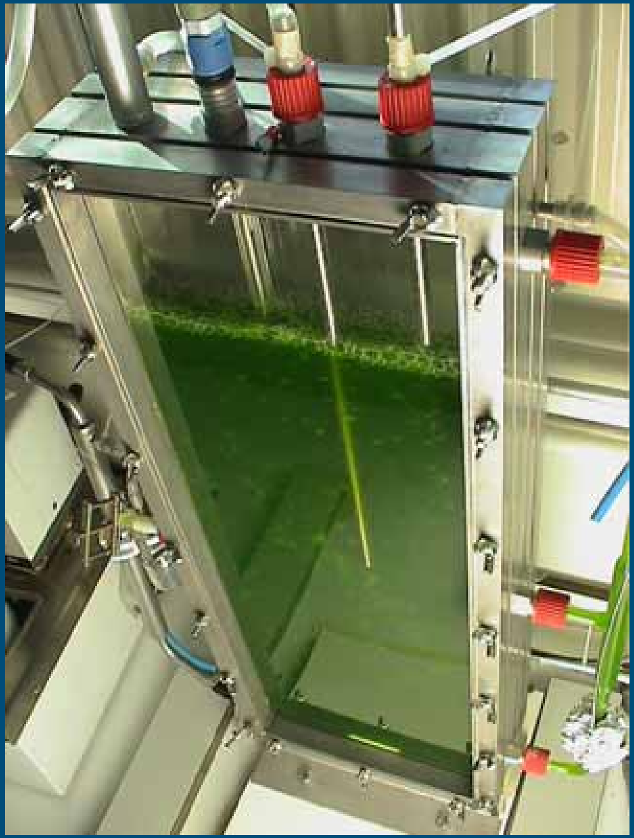
Species	I (μmol $m^{-2}s^{-1}$)	Light path (cm)	$Y_{x,E}$ (g mol^{-1})
	Theoretical maximum ⇒		1.50
Spirulina	1800	2.6	1.42
Spirulina	2x1050	1.4	1.62
Chlorococcum	2x1000	1.0	0.53
Nannochloropsis	2000	1.0	0.37

WUR-BPE research focused on…

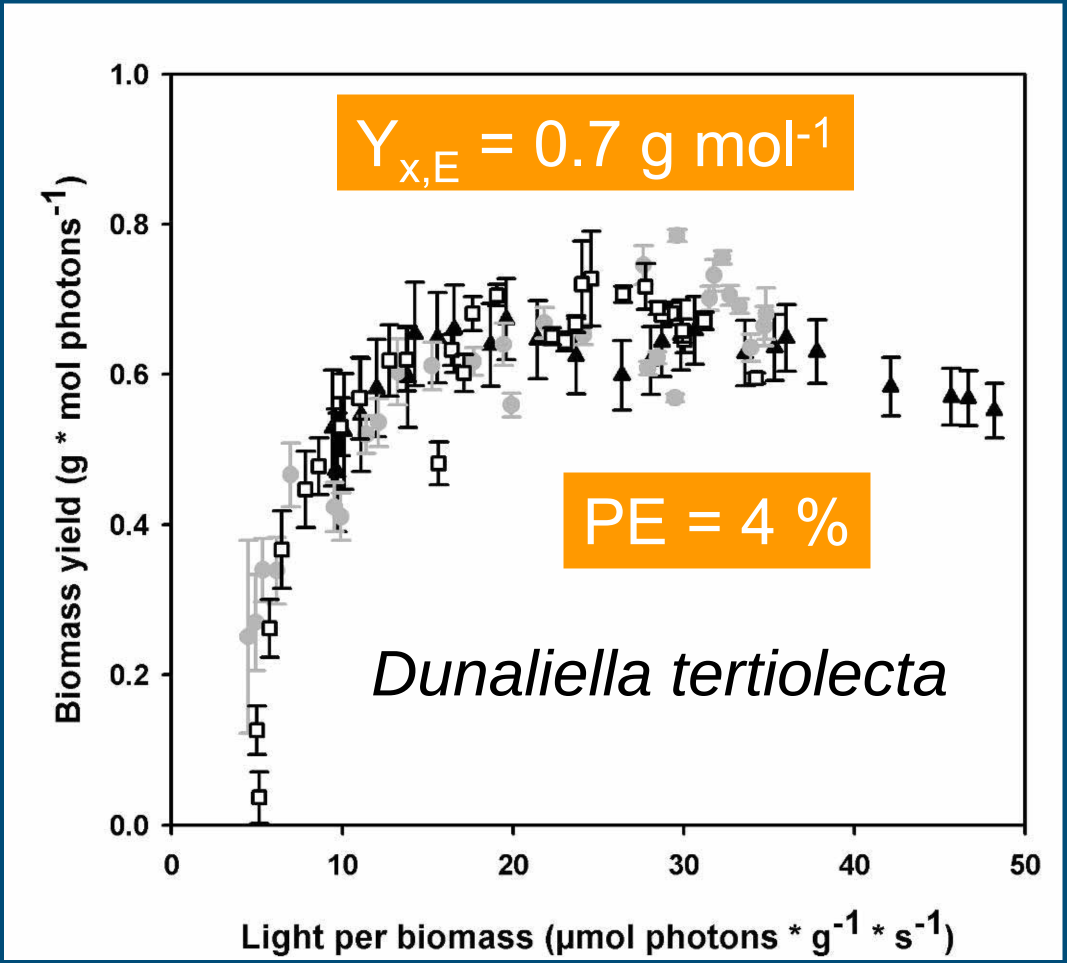
- High PE at high light intensity PFD by:
  - Short light path
  - Turbulent mixing
  - High biomass density



Panel reactors and saturating light, 950 $\mu mol\ m^{-2}\ s^{-1}$



1, 2 and 3 cm Light path



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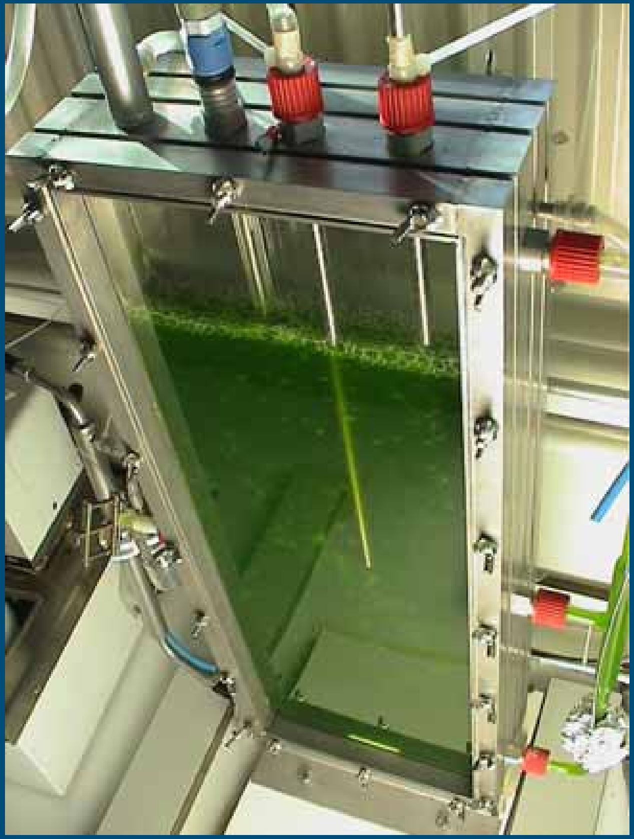
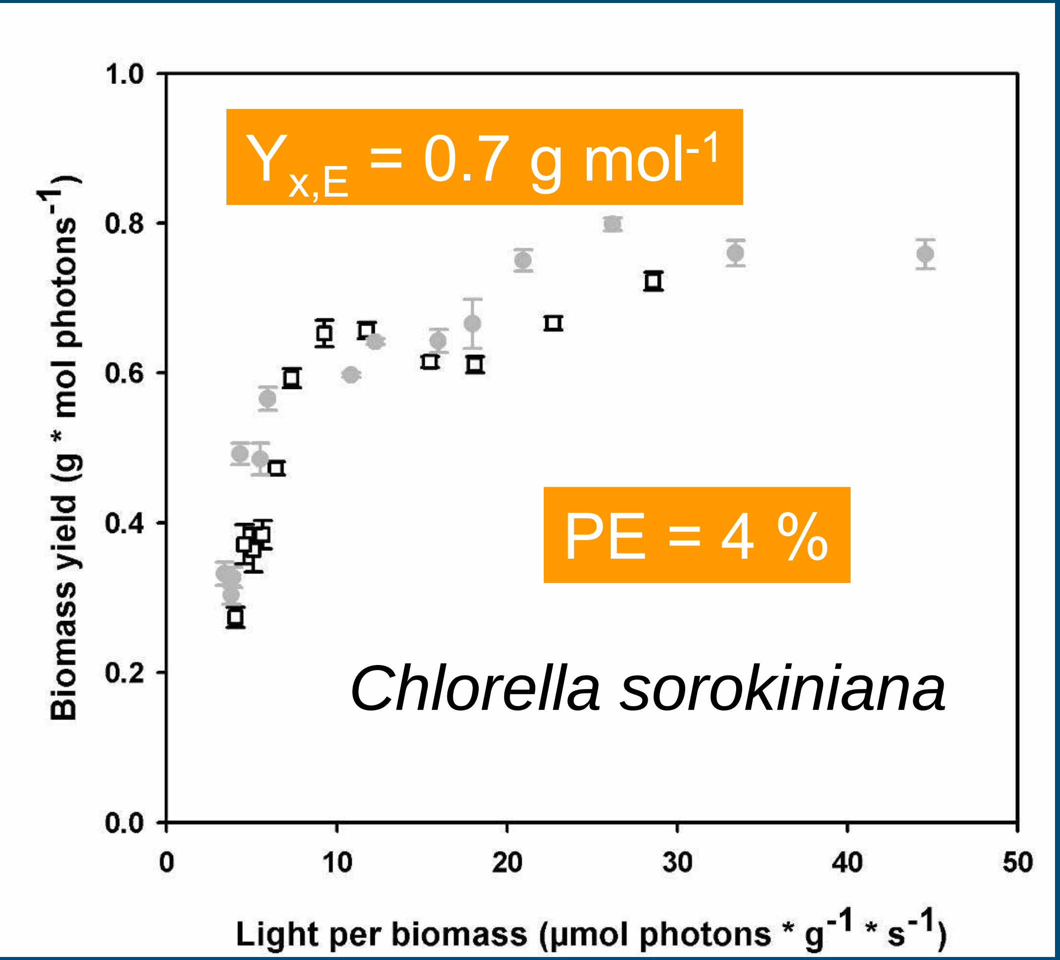
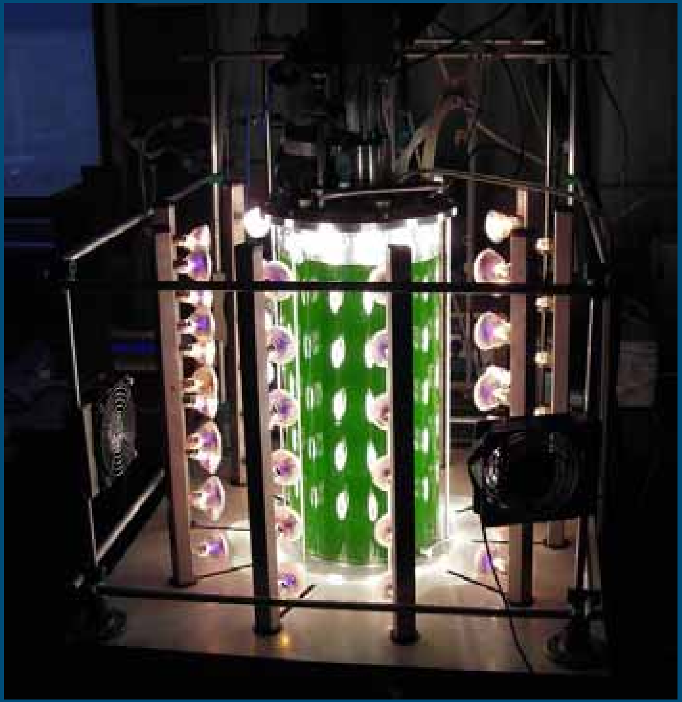
Panel reactors and saturating light, 950 μmol m^{-2} s^{-1}



1, 2 and 3 cm Light path

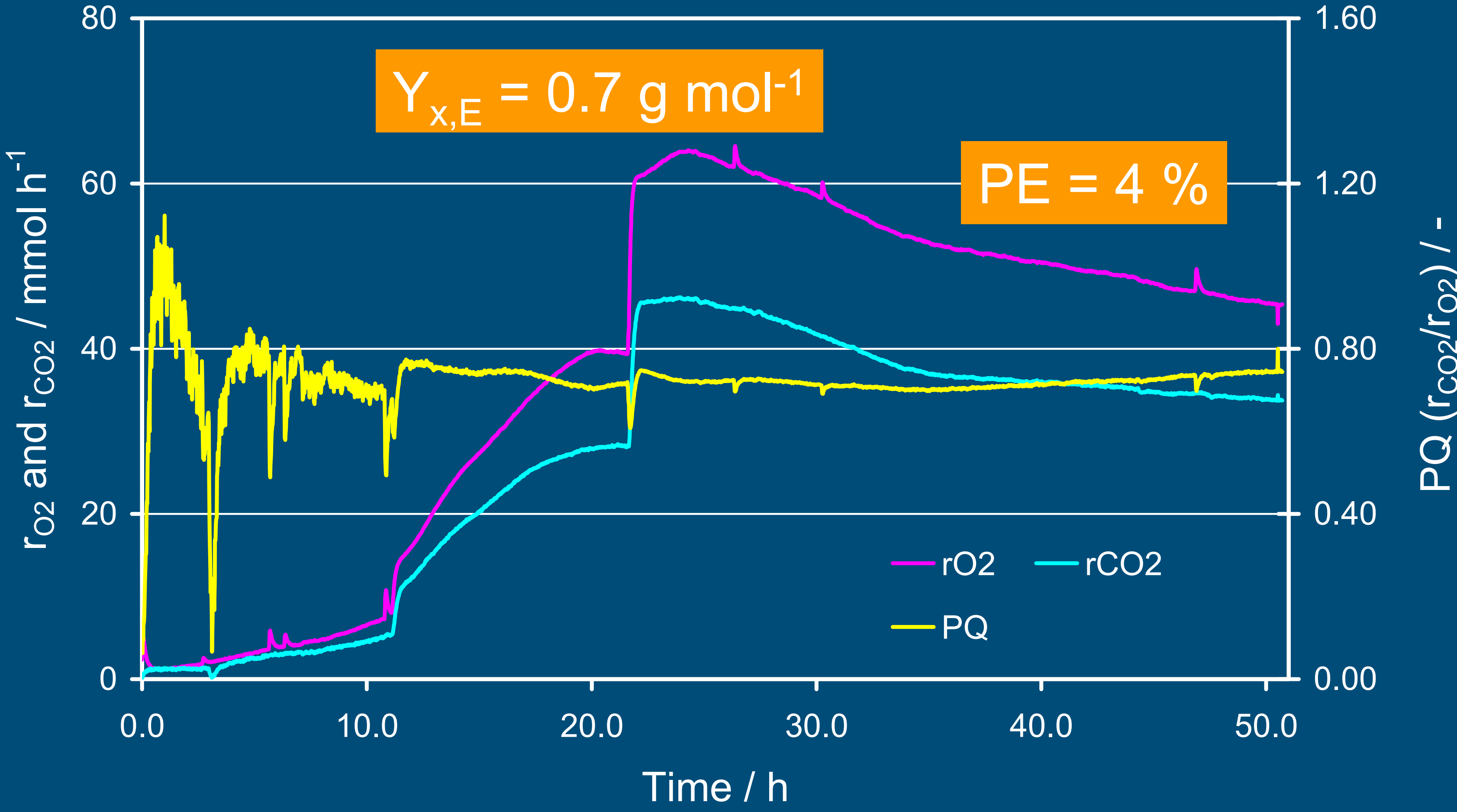


Spinning Tube-in-Tube photobioreactor

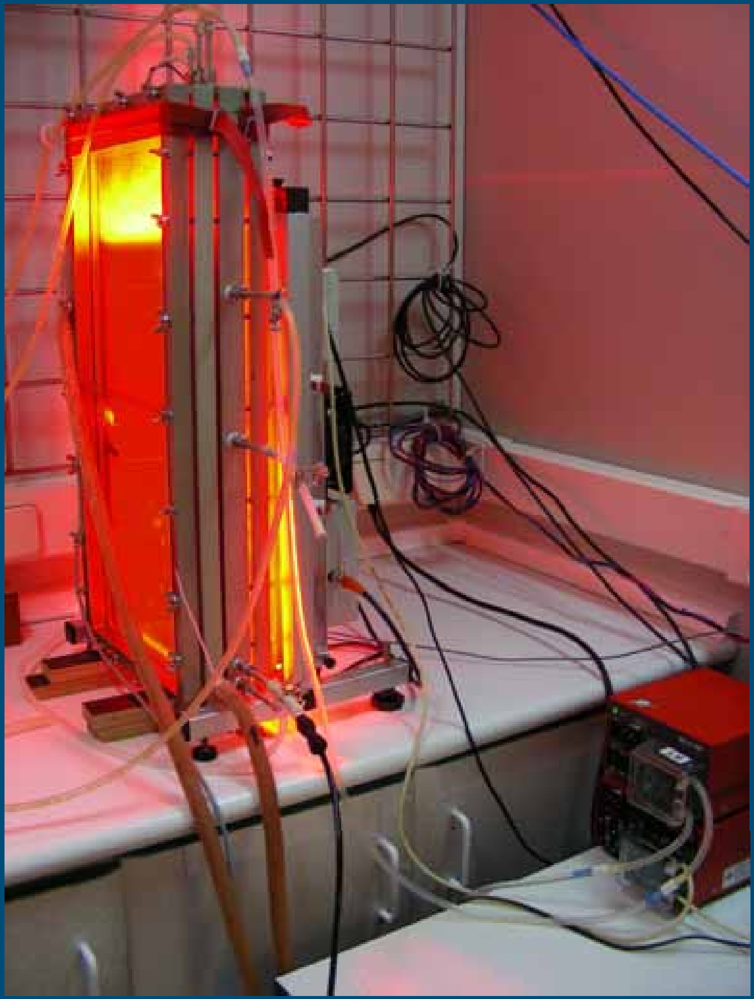


- *Chlorella sorokiniana*
- 1 cm light path, variable mixing
- 1500 micromoles m^{-2} s^{-1}

Over-saturating light, 1500 μmol m^{-2} s^{-1}

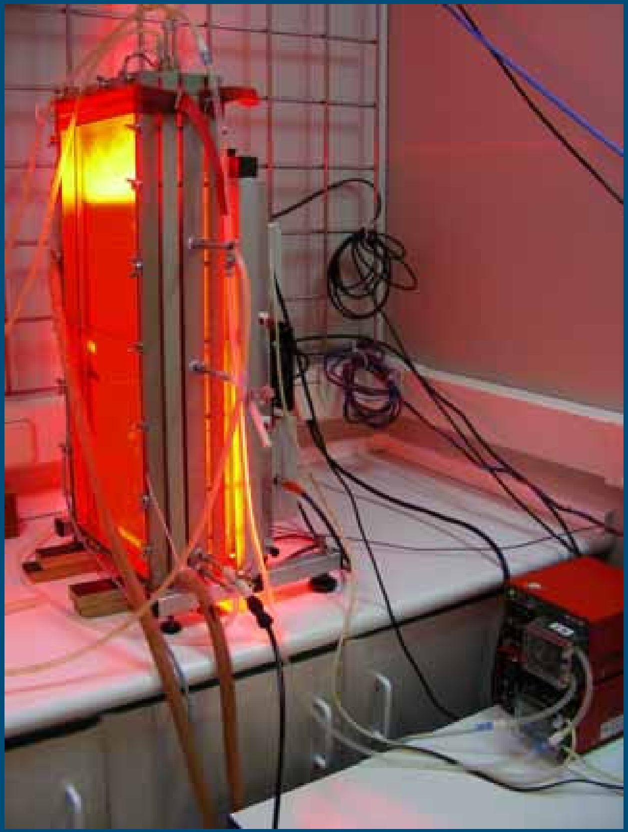


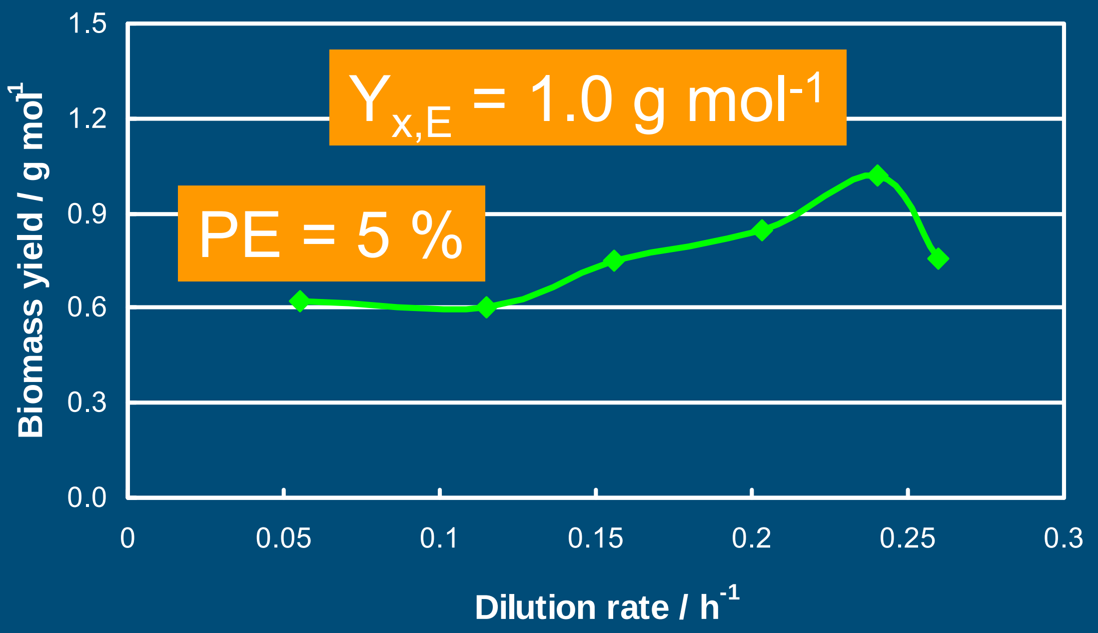
Over-over saturating light



- *Chlorella sorokiniana*
- 1.4 cm panel reactor
- Variable dilution rate
- 2100 μmol m^{-2} s^{-1}

Over-over saturating light, 2100 μmol m^{-2} s^{-1}





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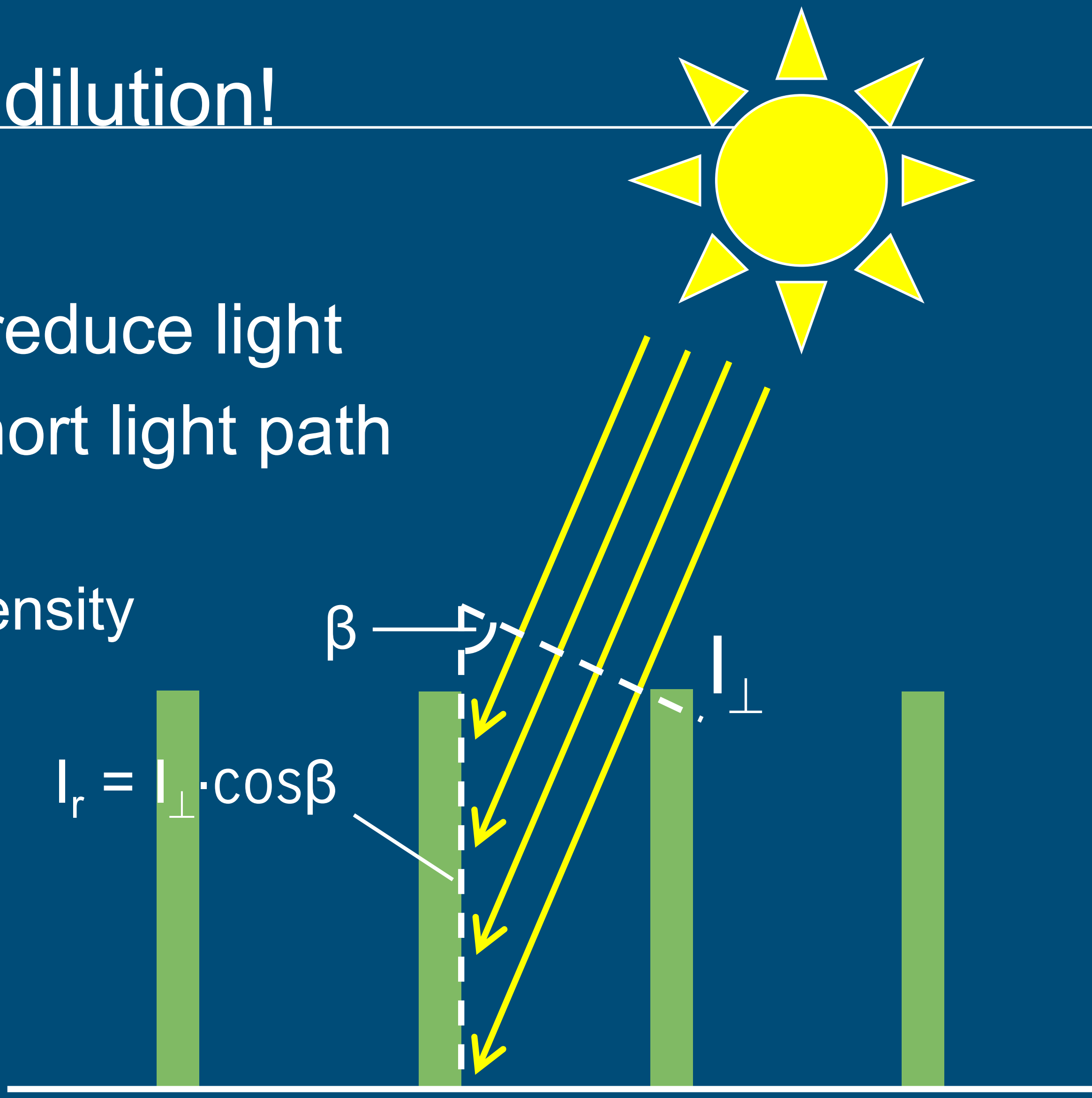
Conclusions photosynthetic efficiency

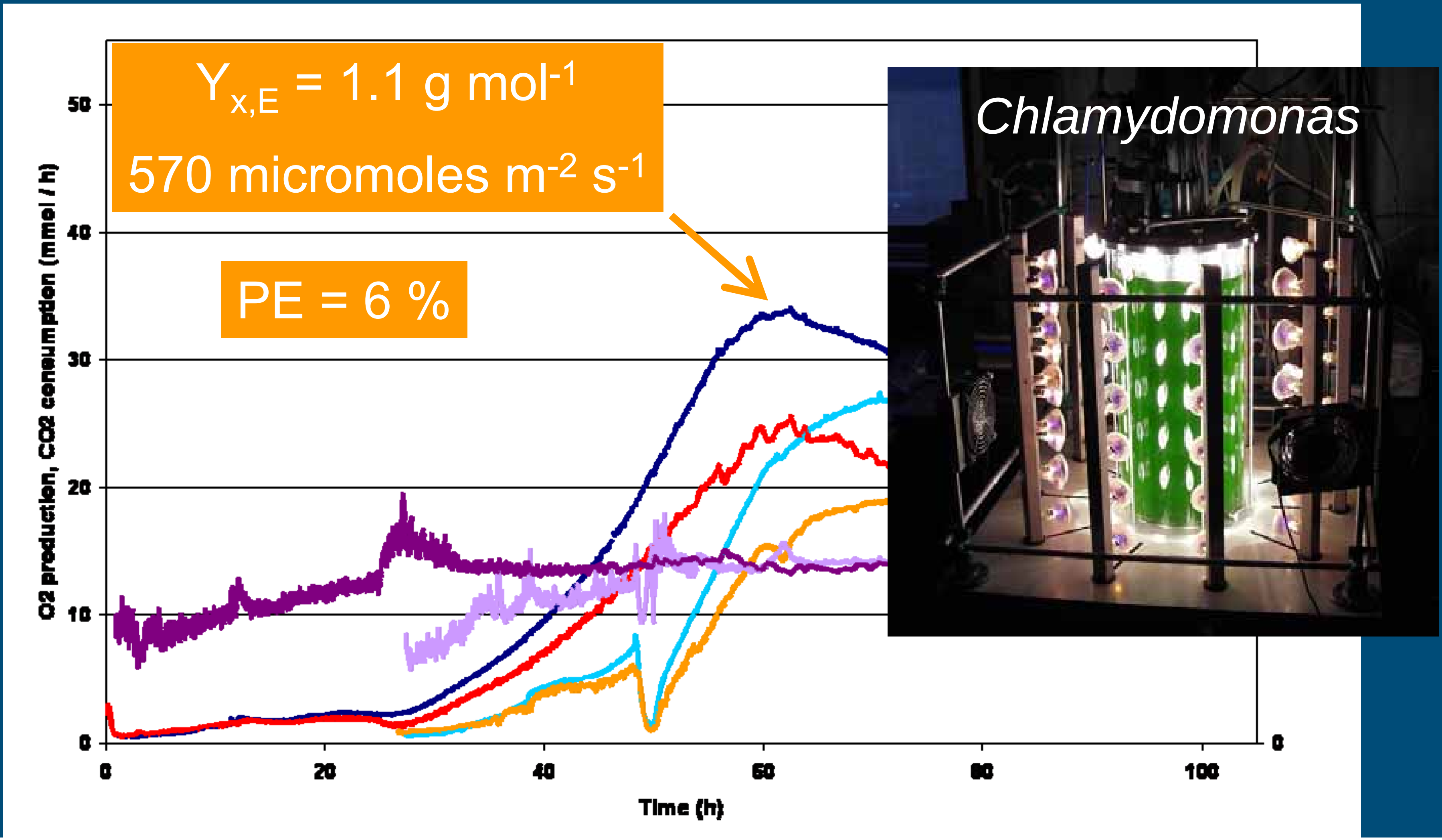
- PE of 4% possible under high PFD
- Biomass concentration 1 - 10 g L^{-1}
- High mixing does not help much…?
- …and takes too much energy!

High PE?... Light dilution!

- Go vertical and reduce light
- Combine with short light path systems
  - High biomass density



PE at moderate light intensity



Outlook

- A Photosynthetic efficiency of 7% seems to be within reach for closed photobioreactors…
  - When corrected for night biomass loss 6% is a reasonable target for real life

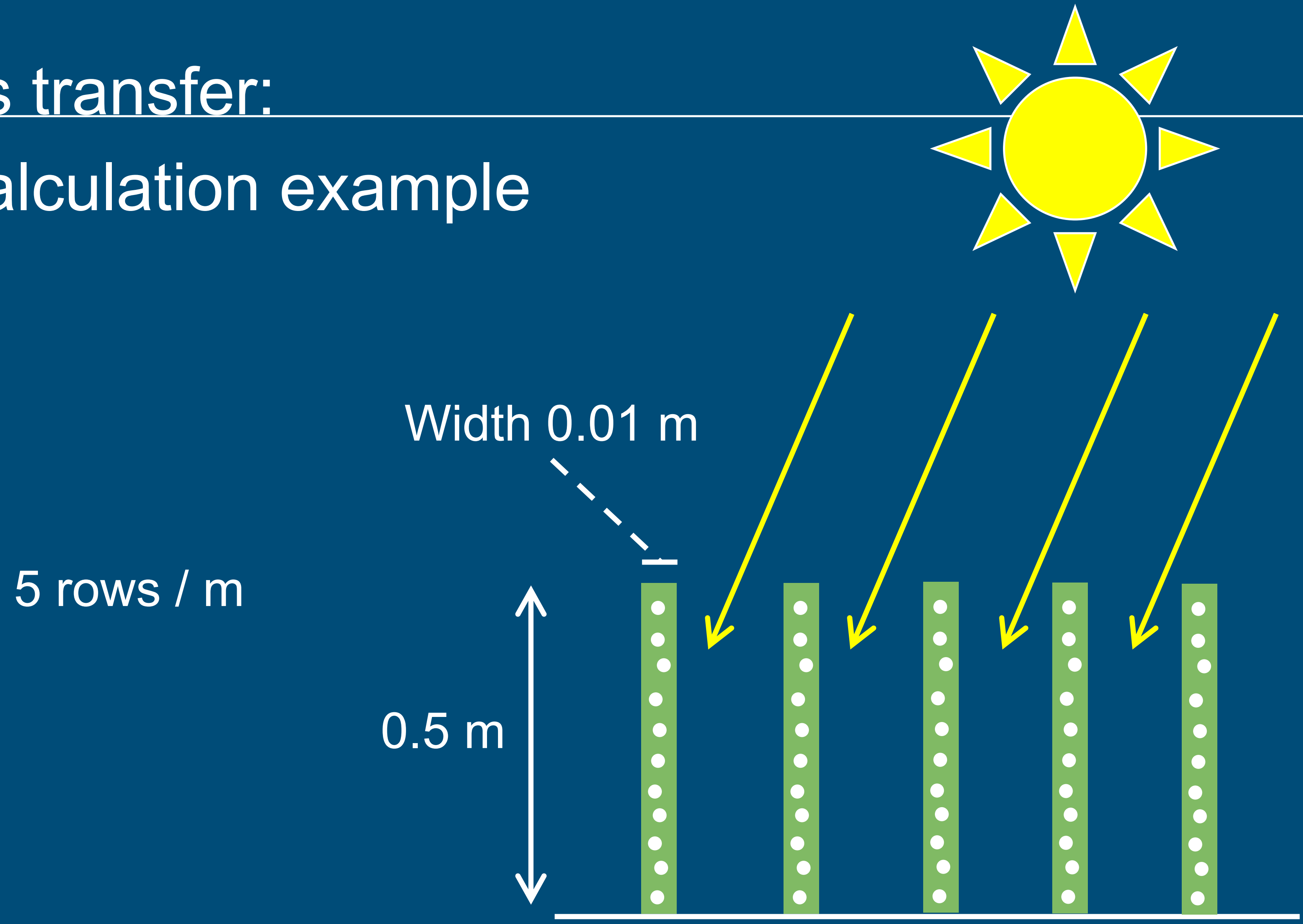
- What will it cost…?
  Materials / construction

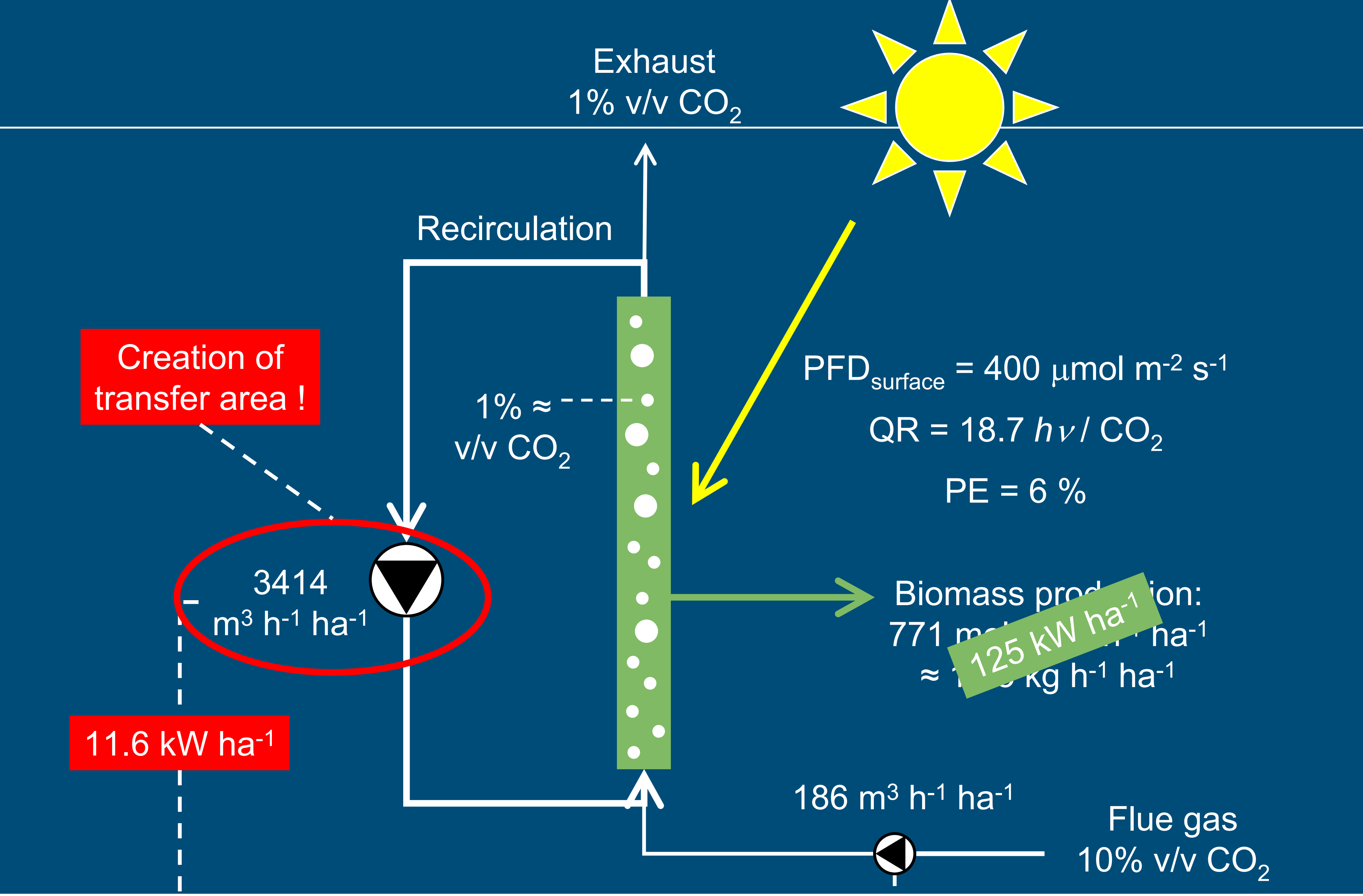
Mixing/gassing for CO_2 and O_2 transfer

- Gassing needs to be minimized, but:
  - CO_2 and O_2 transfer capacity must need demands
  - Sedimentation must be prevented

- Important for any system, closed PBRs and open ponds!
- What is the energy requirement?

Gas transfer:
a calculation example





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CO_2 transfer rate (CTR) and gas flow rate

PFD
QR_{CO2}
V_r
A_r

0.35 mM $CO_2 \triangleq$ 1% v/v CO_2

0.1 mM CO_2

$$CTR = k_{l,CO2} \cdot a \cdot (C_{CO2,interface} - C_{CO2,bulk}) \quad [\text{mol } CO_2 \text{ m}^{-3} \text{ s}^{-1}]$$

$$k_{l,CO2} \cdot a = 0.96 \cdot k_{l,O2} \cdot a = 0.96 \cdot 0.32 \cdot v_{gs}^{0.7}$$

Superficial gas velocity

Bubble column
Coalescing, non-viscous
bubble diameter ≈ 6 mm

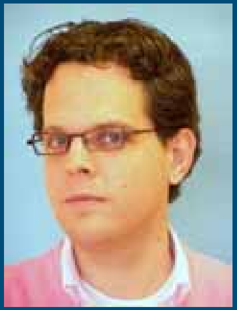
25 °C, pure water, pH 7

Conclusions gas transfer

- Liquid mixing and CO_2 supply can be combined
- O_2 can be removed too
  - O_2 will accumulate to ≈ 2 times air saturation
- Amount of energy is needed equivalent to 10% of sunlight energy fixed inside the biomass
  - independent of photosynthetic efficiency or light input
  - Also algal ponds need to be gassed

Acknowledegments

- Jan-Willem Zijffers



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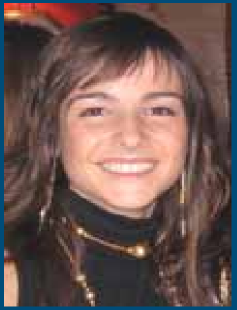

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Thank you for your attention

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Biomass growth versus lipid accumulation

$$CO_2 + 0.71\ H_2O + 0.12\ NH_4^+ \rightarrow CH_{1.78}O_{0.36}N_{0.12} + 1.18\ O_2 + 0.12\ H^+$$

11.8 hν

50% w/w fatty acid (C_{16}) accumulation/excretion:

$$CO_2 + 0.88\ H_2O + 0.05\ NH_4^+ \rightarrow CH_{1.91}O_{0.23}N_{0.05} + 1.32\ O_2 + 0.05\ H^+$$

13.2 hν

$$CO_2 + 0.95\ H_2O + 0.12\ NO_3^- \rightarrow CH_{1.78}O_{0.36}N_{0.12} + 1.42\ O_2 + 0.12\ OH^-$$

14.2 hν

50% w/w fatty acid (C_{16}) accumulation/excretion:

$$CO_2 + 0.98\ H_2O + 0.05\ NO_3^- \rightarrow CH_{1.91}O_{0.23}N_{0.05} + 1.43\ O_2 + 0.05\ OH^-$$

14.3 hν