Bio-H_2-Erzeugung mit einzelligen Grünalgen

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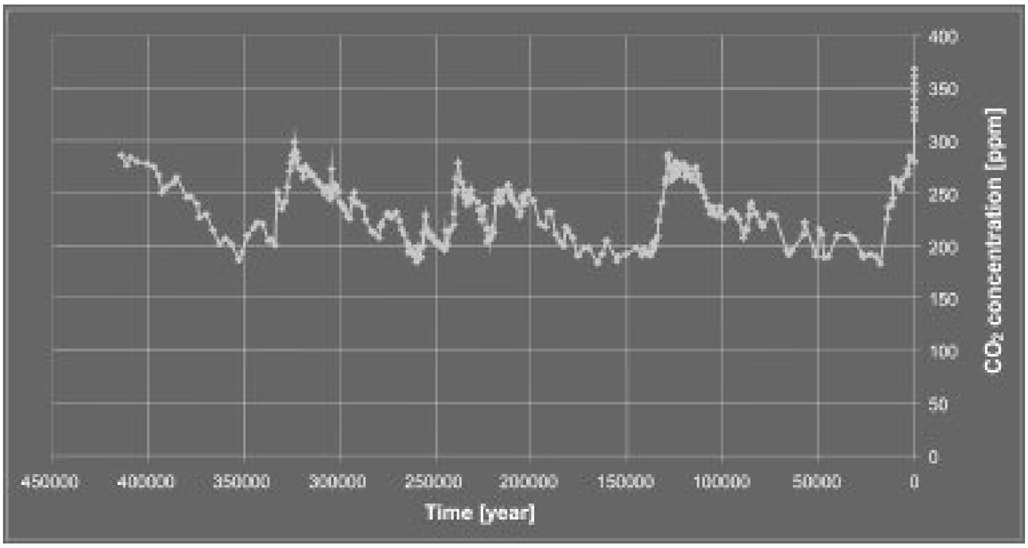
Die Entwicklung sauberer und leicht verfügbarer Energiequellen ist von vitaler Bedeutung für Gesundheit und globalen Wohlstand, mehr als alle anderen Herausforderungen, denen sich die Menschheit heute gegenüber sieht. Aus Wasser gewonnener Wasserstoff wurde dabei als die größte potenzielle Quelle für die saubere Energie der Zukunft identifiziert. Eine zukünftige Wasserstoffökonomie hängt dabei kritisch von der Entwicklung effizienter und nachhaltiger Wasserstoff-Produktionsverfahren im großen Maßstab ab.

Climate Change

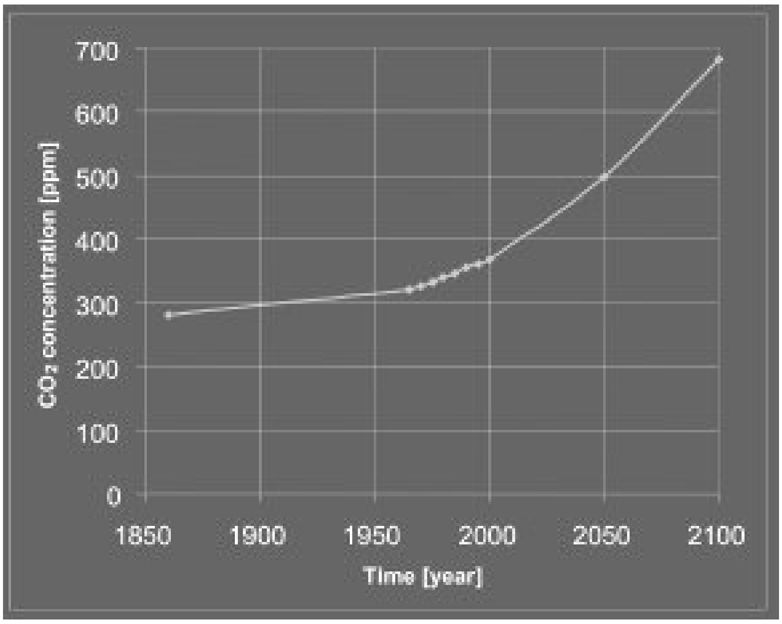
Last 400,000 years: Atmospheric CO_2 (200-280 ppm)



Petit et al., Nature 2004

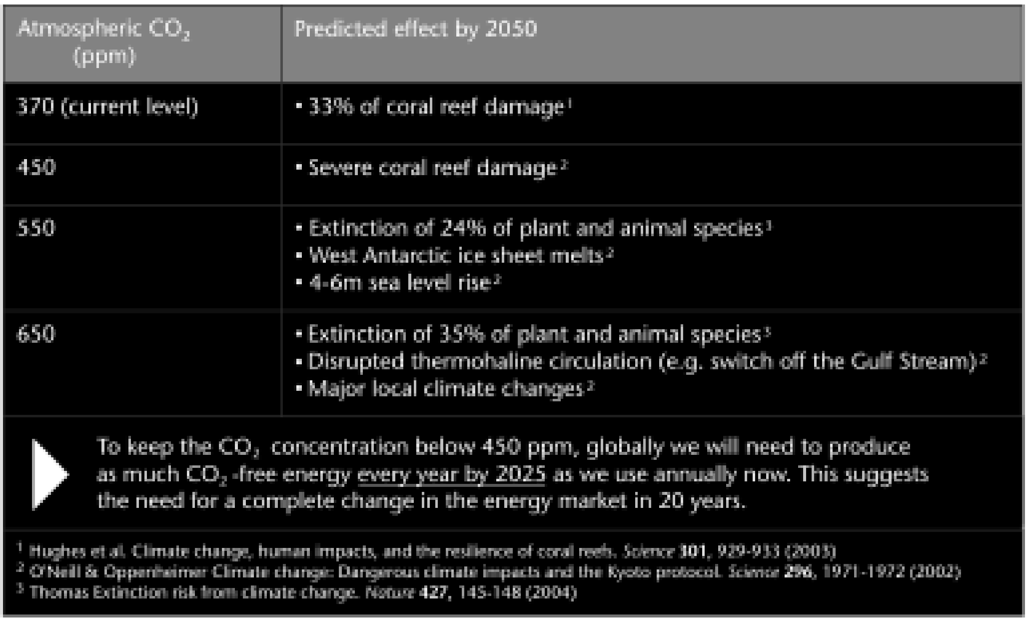
Climate Change

1860-2000: 280-375 ppm CO_2



Petit et al., Nature 2004

CO_2 emission constraints: Global climate change impact

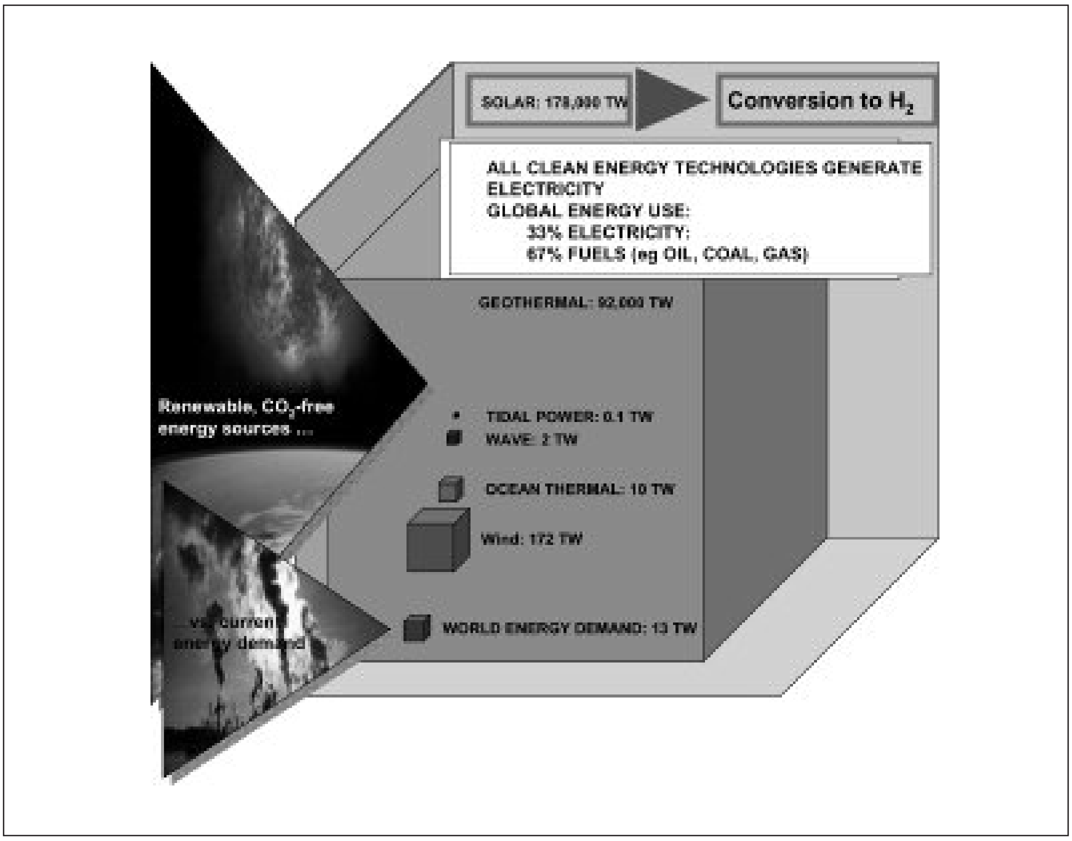


Atmospheric CO_2 (ppm)	Predicted effect by 2050
370 (current level)	▪ 33% of coral reef damage[1]
450	▪ Severe coral reef damage[2]
550	▪ Extinction of 24% of plant and animal species[3] ▪ West Antarctic ice sheet melts[2] ▪ 4-6m sea level rise[2]
650	▪ Extinction of 35% of plant and animal species[3] ▪ Disrupted thermohaline circulation (e.g. switch off the Gulf Stream)[2] ▪ Major local climate changes[2]

▶ To keep the CO_2 concentration below 450 ppm, globally we will need to produce as much CO_2-free energy every year by 2025 as we use annually now. This suggests the need for a complete change in the energy market in 20 years.

[1] Hughes et al. Climate change, human impacts, and the resilience of coral reefs. *Science* **301**, 929-933 (2003)
[2] O'Neill & Oppenheimer Climate change: Dangerous climate impacts and the Kyoto protocol. *Science* **296**, 1971-1972 (2002)
[3] Thomas Extinction risk from climate change. *Nature* **427**, 145-148 (2004)

Alternatives



SOLAR: 178,000 TW

Conversion to H_2

ALL CLEAN ENERGY TECHNOLOGIES GENERATE ELECTRICITY
GLOBAL ENERGY USE:
33% ELECTRICITY;
67% FUELS (eg OIL, COAL, GAS)

GEOTHERMAL: 92,000 TW

Renewable, CO_2-free energy sources ...

TIDAL POWER: 0.1 TW
WAVE: 2 TW

OCEAN THERMAL: 10 TW

Wind: 172 TW

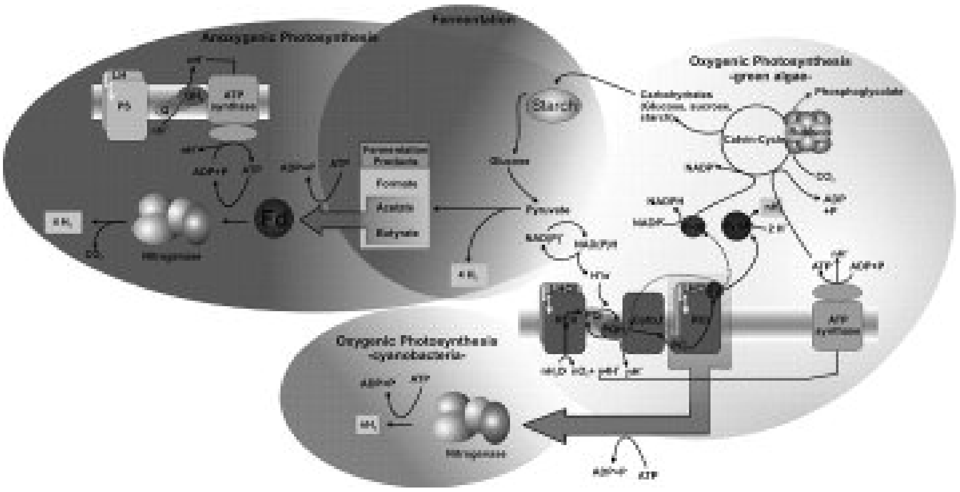
... vs. current energy demand

WORLD ENERGY DEMAND: 13 TW

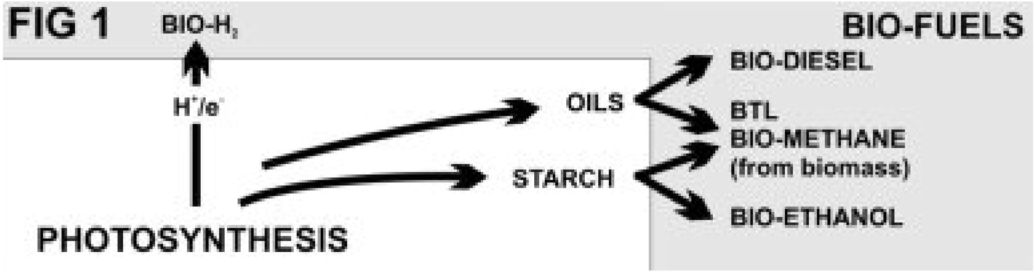
Alternatives of CO_2-free H_2 production:

1. CO_2-free generated energy coupled to electrolysis
    - Solar power used directly for electrolysis through photovoltaic systems
    - Nuclear or wind energy coupled to electrolysis
2. Sunlight-collecting microorganisms combining sunlight energy collection and energy conversion into H_2
3. Biomimetic approaches producing hydrogen from sunlight and water by artificial photosynthesis

The Biochemistry Of Solar Powered H_2 Production



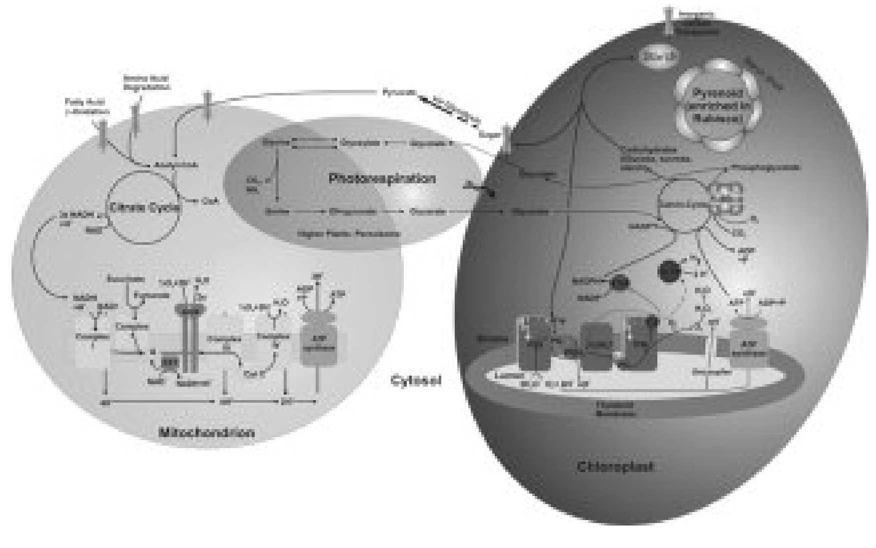
Advantages of direct H_2 production

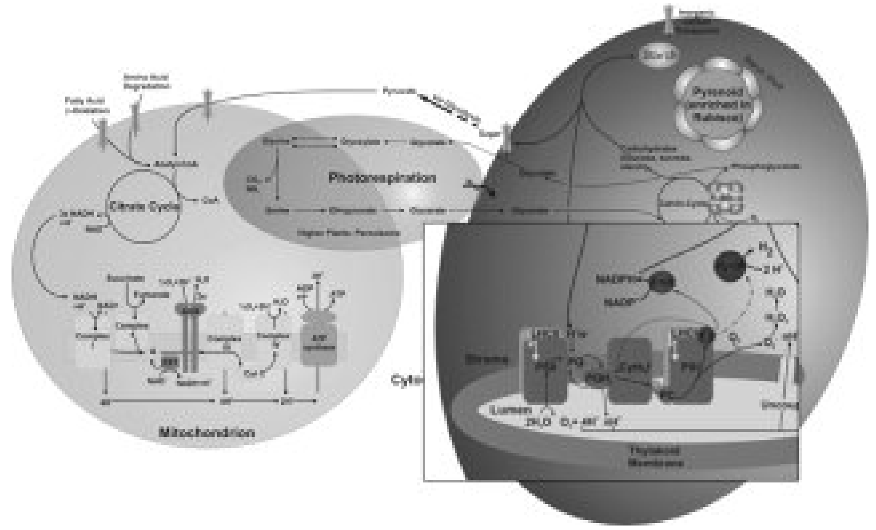


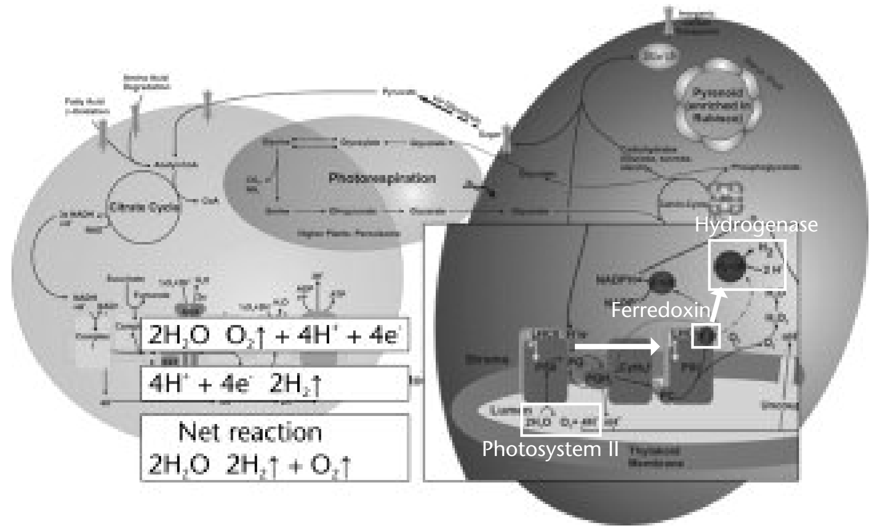
Advantages of direct H_2 production:

- Reducing arable land use for bio-fuel production
- Reducing H_2O use in agriculture
- Coupling clean fuel production to desalination

Hydrogen Pathway
Light energy can drive metabolite and bio-fuel production
(1-3)







$2H_2O \quad O_2\uparrow + 4H^+ + 4e^-$

$4H^+ + 4e^- \quad 2H_2\uparrow$

Net reaction

$2H_2O \quad 2H_2\uparrow + O_2\uparrow$

Bestimmte einzellige Grünalgen und Cynobakterien haben die Fähigkeit entwickelt, H_2 direkt ohne Abbau der Biomasse aus Wasser und Sonnenlicht zu produzieren. Besonders die Mikroalge *Chlamydomonas reinhardtii* wird für diesen Zweck eingesetzt. Aufgrund der hohen Kapazität der beteiligten Hydrogenasen kann die theoretische Effizienz der photosynthetisch getriebenen Umwandlung von Sonnenlichtenergie in H_2 (PCE-Rate) sehr hoch sein und bei kompletter Optimierung die Effizienz photovoltaischer Zellen erreichen (PCE bis zu 15 %).

Biophotolytic Hydrogen

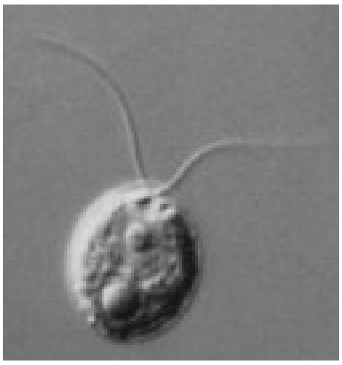
Biophotolytic Hydrogen:

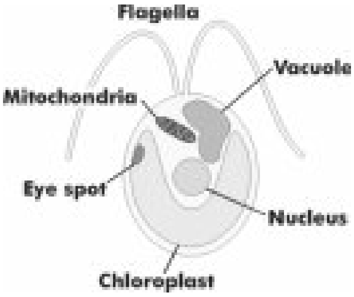
Green algae and cyanobacteria can use water-splitting photosynthetic processes to generate molecular hydrogen rather than fix carbon, the normal function of oxygenic photosynthesis.

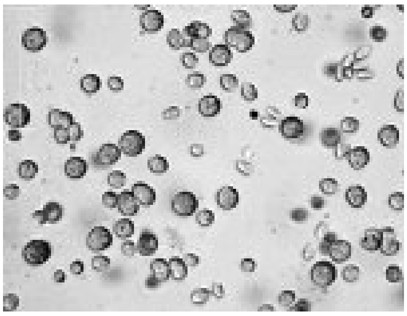
Reengineering microbial systems for the direct production of hydrogen from water eliminates inefficiencies associated with carbon fixation and biomass formation.

The maximal energetic efficiency for direct biophotolysis is about 10-15% compared with a maximum of about 1% for hydrogen production from biomass.

Chlamydomonas reinhardtii – the green yeast –







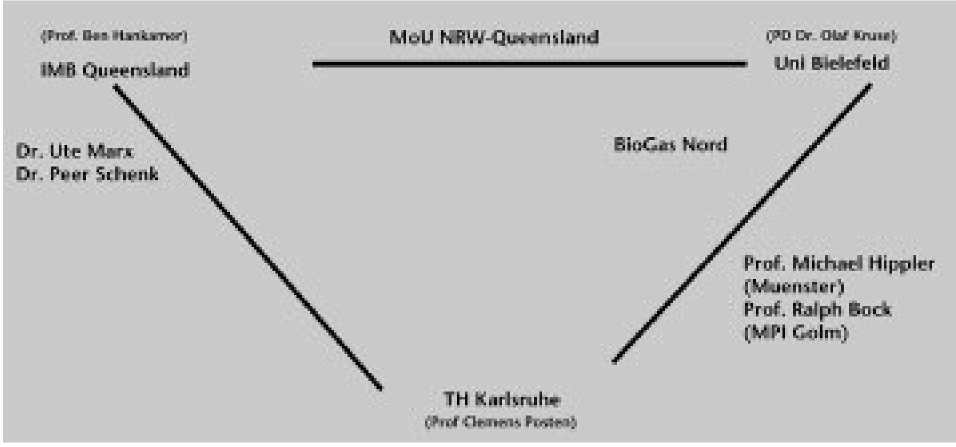
Focus: Economic solar-powered H_2 production from H_2O using engineered green algal cells

- ➔ Solar-driven H_2 production discovered in algae in 1939 (H. Gaffron)
- ➔ Hydrogenase is ~100x more efficient than known bacterial enzymes, but oxygen-sensitive
- ➔ Major breakthrough: Two-phase process (A. Melis, 2000)
  >>> Separation of O_2 producing & O_2 sensible processes

1. SOLAR-H	**NEST-EU FP6 activity**
2. Solar Bio-Fuels	**Australian-German Consort.**
1. US-Airforce	**US consortium**
2. DOE	**US consortium**
3. BMBF-H2	**German consortium**
4. Bio-H2	**French consortium**
5. Solar to Fuel	**ESF platform**

White paper: http://www.ssnmr.leidenuniv.nl/index. php3?m=12&c=34

Consortia working on H_2O to H_2


(Prof. Ben Hankamer)
IMB Queensland

MoU NRW-Queensland

(PD Dr. Olaf Kruse)
Uni Bielefeld

Dr. Ute Marx
Dr. Peer Schenk

BioGas Nord

Prof. Michael Hippler
(Muenster)
Prof. Ralph Bock
(MPI Golm)

TH Karlsruhe
(Prof Clemens Posten)

Prof Giovanni Finazzi (CNRS Paris)

Prof Charles Dismukes (Princeton)

Consortium Solar Bio-Fuel®

Is a Algal Solar-powered H_2 Production Feasible?

- ➔ **Fossil fuel and climate change studies**
- ➔ **‘Photosynthesis: A blue print for solar energy capture and biohydrogen production technologies‘**

  (Olaf Kruse, Jens Rupprecht, Jan H. Mussgnug, G. Charles Dismukes and Ben Hankamer, PPS 2005)
- ➔ **Industrial Feasibility Study Thiess Ltd 2004 NRELFeasibility study: 2002**

Die Wildform von *C. reinhardtii* ist jedoch derzeit nur in der Lage eine maximale Effizienz von ca. 0.1 % in einem eingeschränkten Zeitfenster unter bestimmten (anaeroben) physiologischen Voraussetzungen zu erreichen. Über gentechnische Ansätze ist es nun unserem Konsortium *Solar Bio Fuels* (Universität Bielefeld, IMB Queensland, TH Karlsruhe) gelungen, zwei Mutanten aus *C. reinhardtii* (Stm6 und Stm6Glc4) mit ungewöhnlich hohen H_2-Produktionsraten und Effizienzen (PCE-Rate von bis zu ca. 1.5 %) zu konstruieren. Die Mutante Stm6glc4 ist zudem in der Lage, durch Zuckeraufnahme die Wasserstoffproduktion über externe Zuckerressourcen weiter zu steigern. Damit erschließt sich die Möglichkeit, H_2 aus Grünalgen sowohl direkt aus Sonnenlicht als auch indirekt über die Verwertung von zuckerhaltigem (photosynthetisch hergestelltem) Pflanzenmaterial einzusetzen.

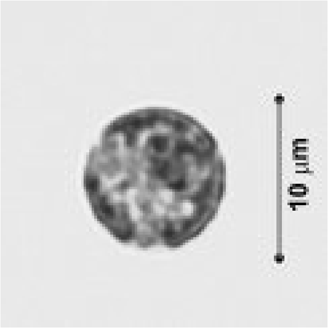
Die Ziele sind nun eine weitere Optimierung der Zellkulturen durch sinnvolle Umsteuerungen intrazellulärer Flüsse und eine enge Verzahnung im Sinne einer integrierten Bioprozessentwicklung sowie der Aufbau und Betrieb eines 250L-Pilotreaktors zum Nachweis der technischen und ökonomischen Machbarkeit der Wasserstoffproduktion mit Hilfe von Mikroalgen.

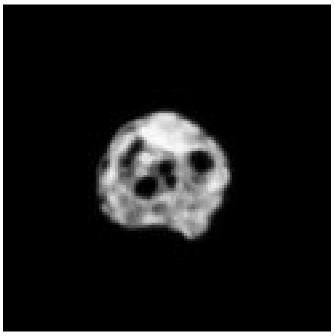
Improved Photobiological H_2 Production in Engineered Green Algal Cells

Chlamydomonas reinhardtii

➔ Problem: Conversion efficiency of collected photons to H2 is too low (PCE rate of 0.1%) due to:

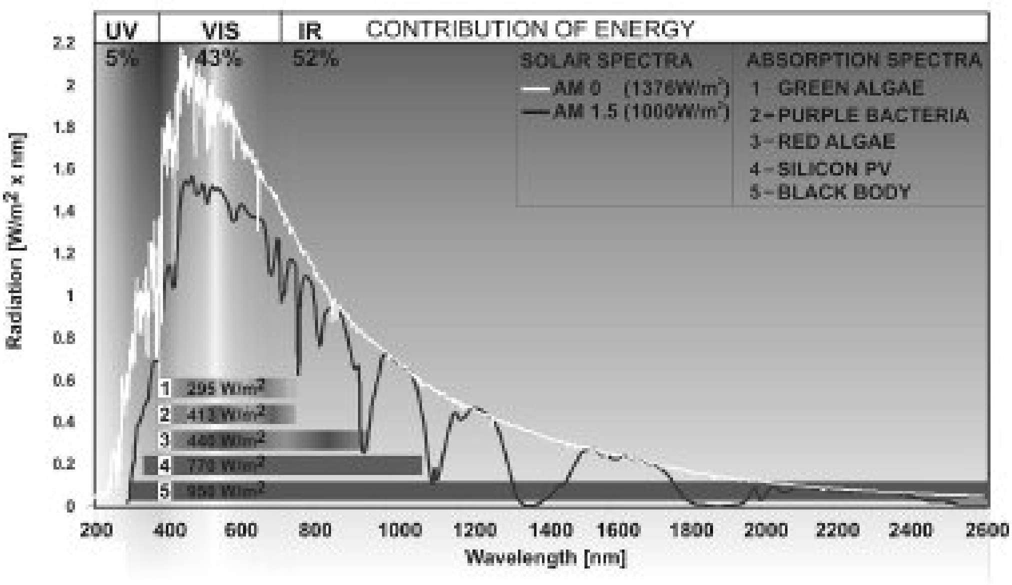
- absorption spectrum limited to 400-700nm
- energy loss
- suboptimal substrate supply





Chlorophyll auto-fluorescence

SOLAR ENERGY SPECTRUM



Current projects and future constraints

1. **Bottom up research areas:**
   - Systematic analysis of hydrogen production pathways by omics-research and bioinformatic modelling to identify new gene targets for genetic manipulation
2. **Top down research areas:**

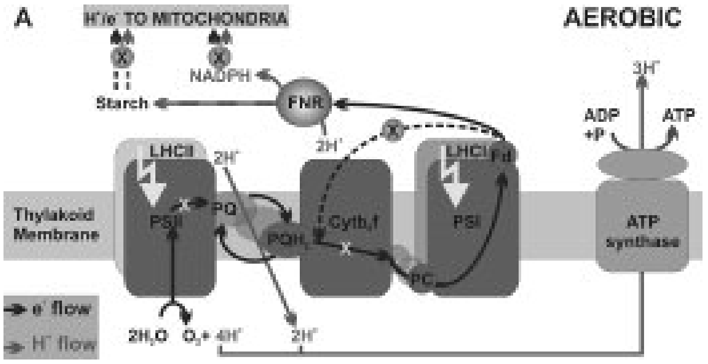
Improving H_2 production capacities in high H_2 production mutants and set up of photo bio-reactor prototypes by

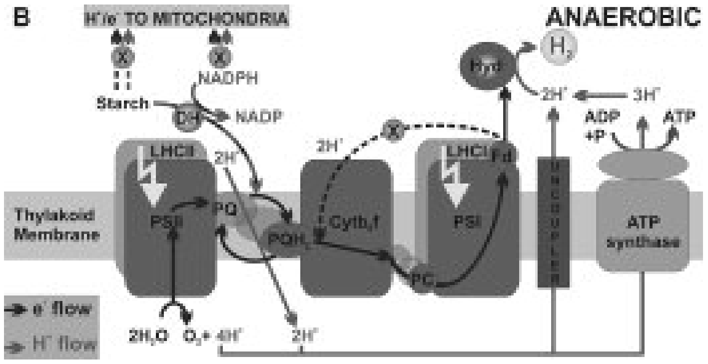
- genetic engineering of gene targets in the metabolite supply system
- genetic engineering in the sunlight collection system
- genetic engineering in the catalytic hydrogen production system

biochemical approaches to improve growth conditions and/or to setup chemostat cultures

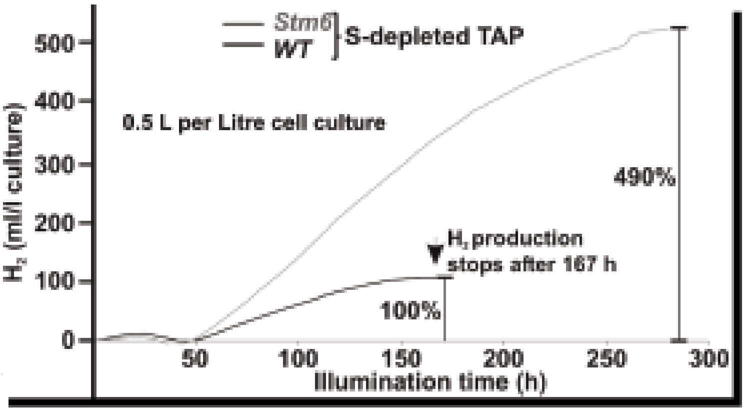
biotechnological developments to come from labscale photo- bioreactors to outdoor prototypes

Aerobic/Anaerobic





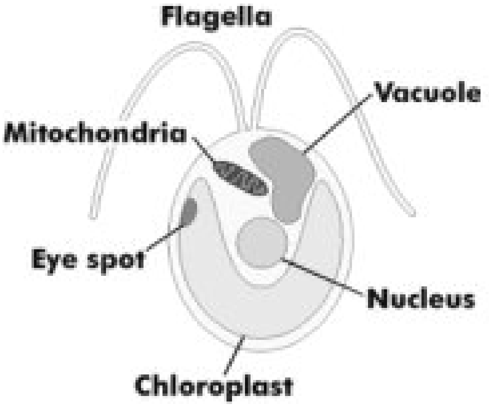
Results

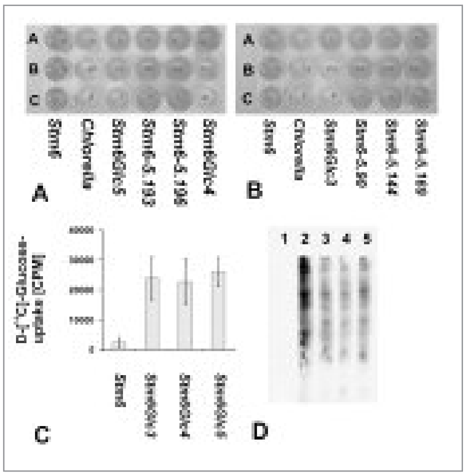


- ➔ Considering the light intensity used, corresponding to ~2,0% Energy Conversion Efficiency
- ➔ If efficiency of 7-10% at high solar levels can be achieved, then economically viable

Olaf Kruse, Jens Rupprecht, Klaus Peter Bader, Peer Martin Schenk, Giovanni Finazzi, and Ben Hankamer, JBC 2005

Results:
Insertion of a sugar transporter to facilitate external feeding and to increase H_2 production rates





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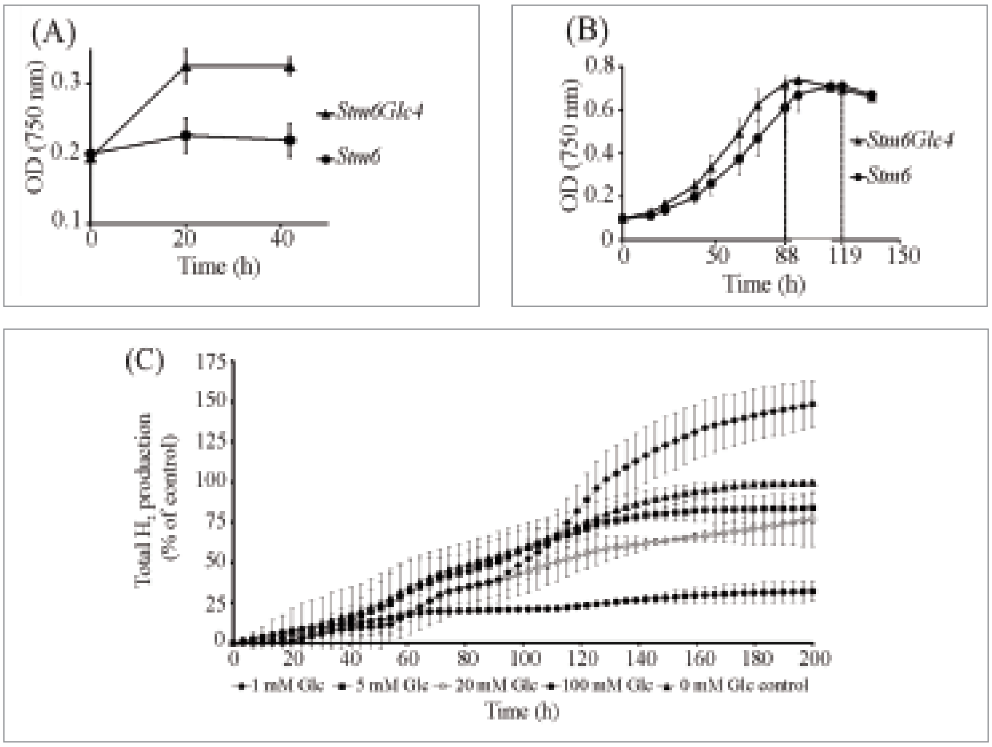
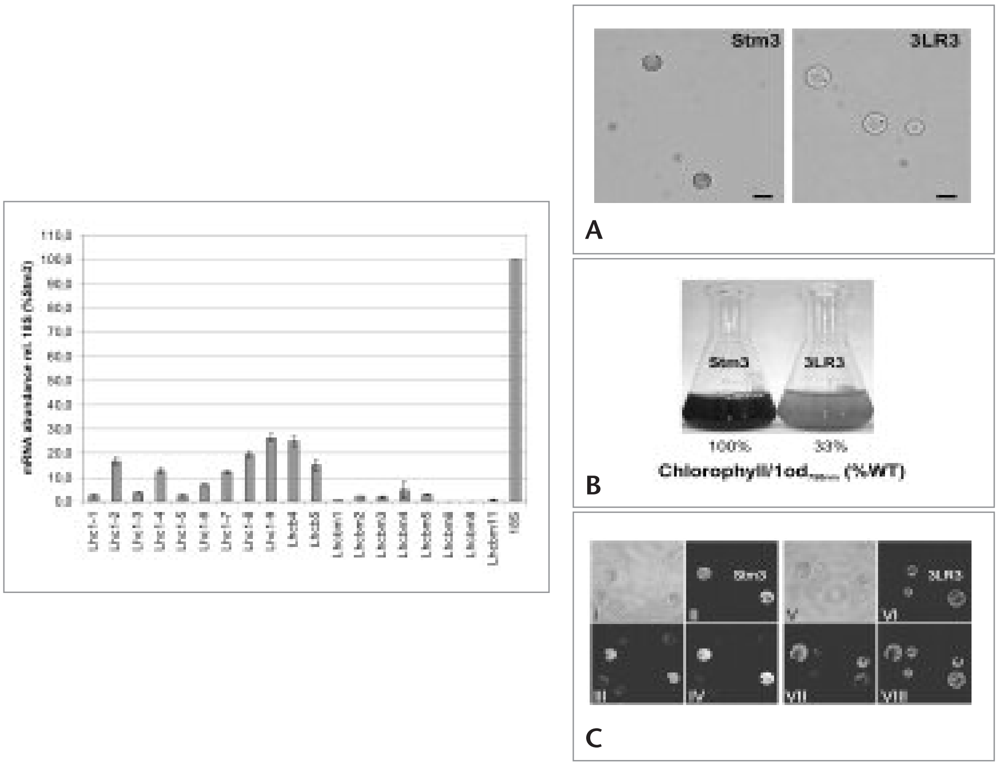
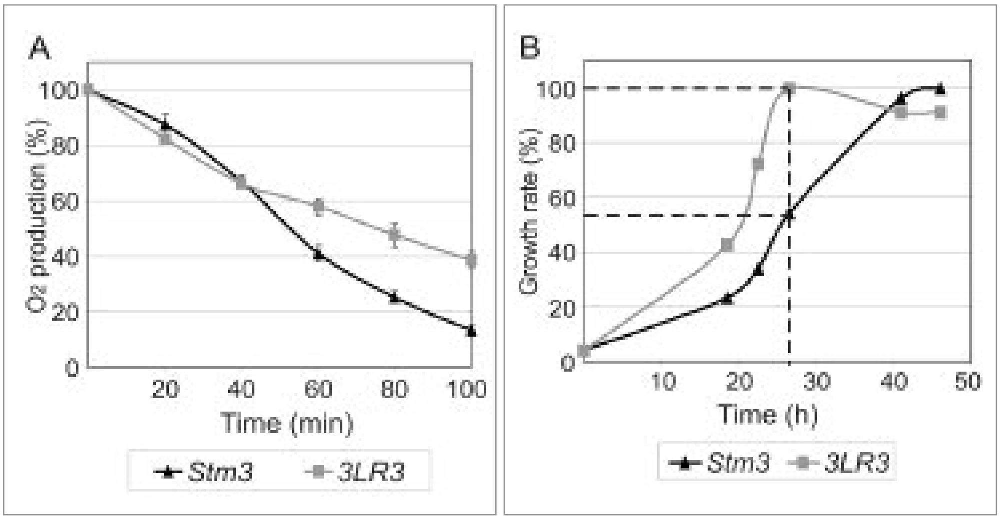


Results:
Overcoming energy loss by optimizing the LHC antenna





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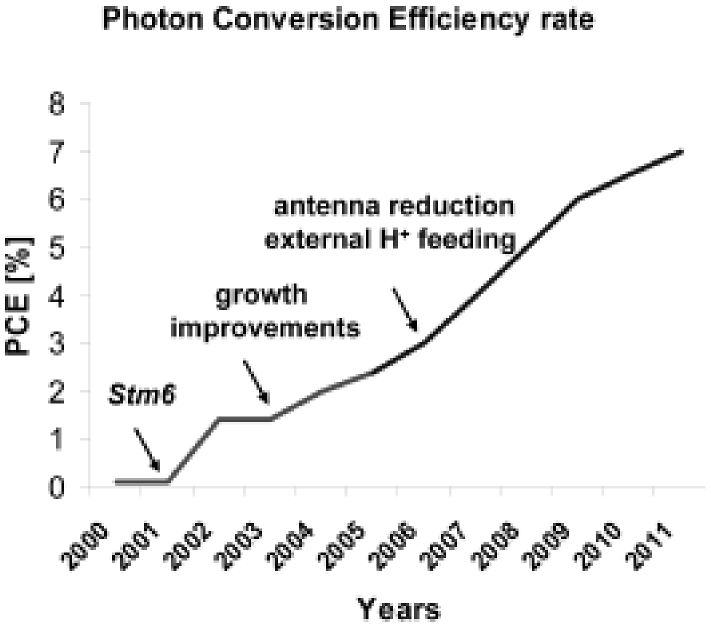


Results:
The way to return of investment

Current photon conversion efficiencies at natural light levels

A maximum of 9.94·103 kJ solar energy can be absorbed
per square metre per day (230 W/m^2)

This solar energy input could be converted into 0.695 mol H_2 by
an algal *Stm6* culture with a photon conversion efficiency of 2%.

This corresponds to a H_2 production rate of 1.39 $g·m^{-2}·d^{-1}$

Plant size at current efficiency levels

A production plant with a culture surface area of 1000 m² could for example yield 1.39 kg hydrogen per day, which is equivalent to 15 568 l at standard conditions.

If it is possible to enhance the photon conversion efficiency to 5% by means of genetic engineering and process optimization, this would result in a hydrogen production rate of 3.48 $g·m^{-2}·d^{-1}$.
Thus the plant would produce 38 976 l hydrogen per day.

If the upper photon conversion efficiency limit of 10.6% could be reached, the production rate could be as high as 7.37 $g·m^{-2}·d^{-1}$, equivalent to 82 523 l hydrogen per day.

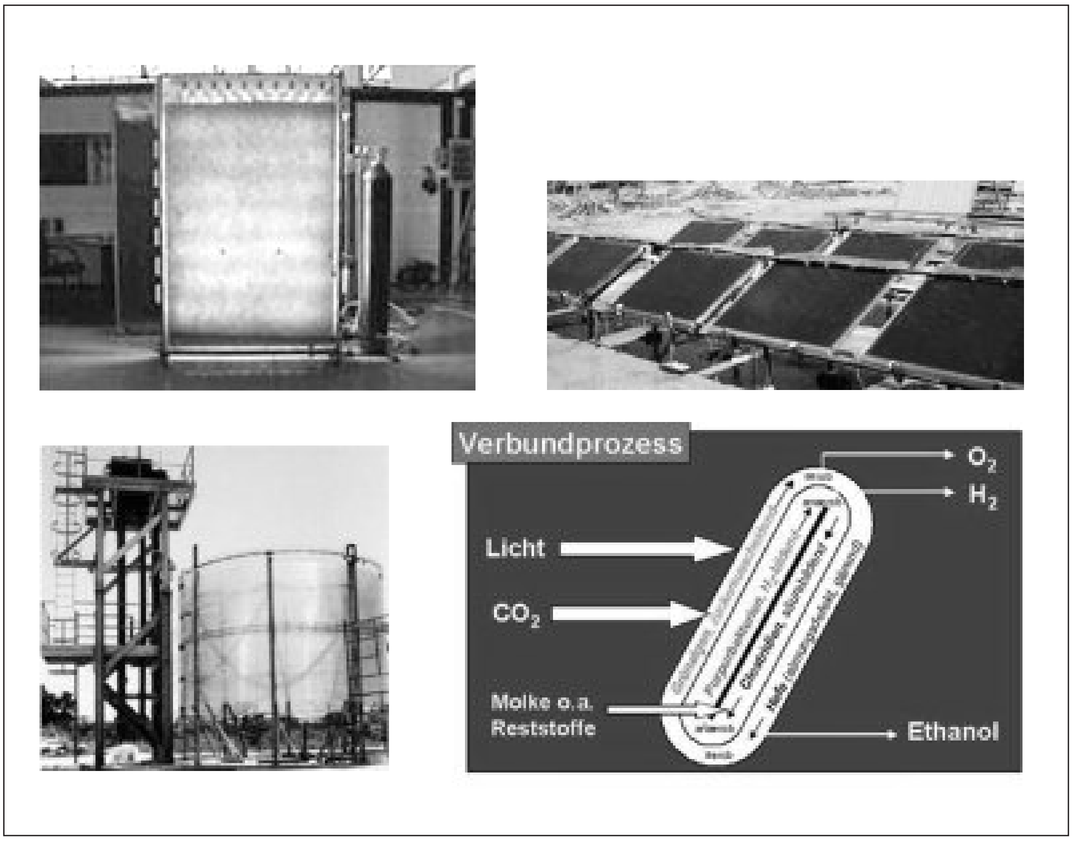
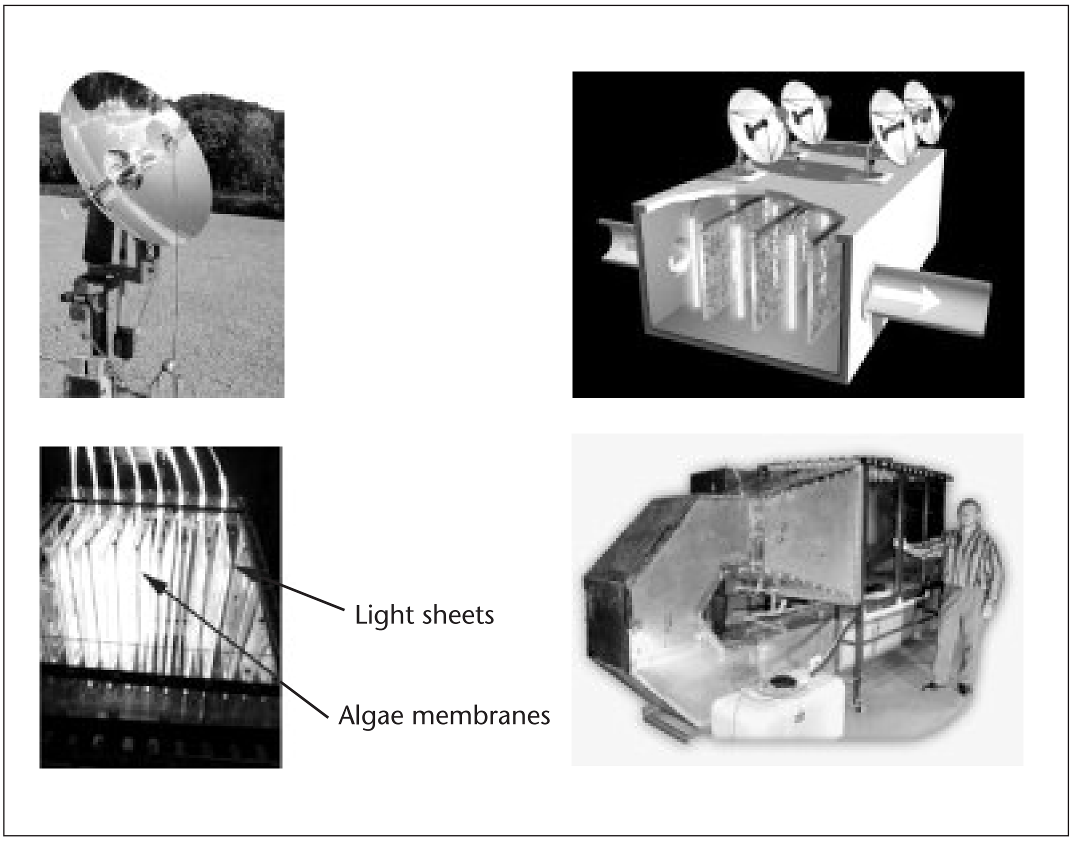


Plate reactors (TH Karlsruhe, Prof. Posten)



Rührkessel mit Lichtführung

Hybrid System

Anlage in Klötze bei Wolfsburg

- 500 km Rohre
- Ca. 700 m3
- 130 t Algen p.a.

Vergleich Lichteintrag

Ziel: Gleichmäßige Lichtverteilung bis zur Sättigung an Reaktoroberfläche

Vorteile:

- sehr gute Lichtverteilung und Abschwächung
- Sterilisation, Mischung
- UV, IR auskoppelbar

Nachteile:

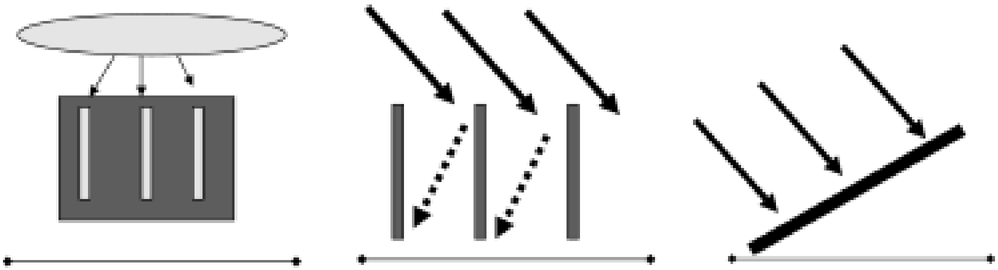
- teuer
- 50 % Lichtverluste

Vorteile:

- billig, da Verteilung über Luftschächte
- Lichtabschwächung über Anstellwinkel

Nachteile:

- Konzentrationsgradienten unflexibel nach Aufbau



Biohydrogen: Advantages, Possibilities and Limitations

ADVANTAGES

1. TARGETS CHEMICAL FUEL MARKET (67%)
2. SELF ASSEMBLING PHOTOCOLLECTORS
3. ASSEMBLY ABSORBS CO_2
4. H_2 PRODUCTION CAN BE COUPLED TO WATER PURIFICATION (MARINE ORGANISMS)
   SEA WATER > $H_2 + O_2$ (GAS PHASE) > COMBUSTION (FRESH H_20)
5. SEAWATER IS A PLENTIFUL RESOURCE
6. H_2 DRIVES FUEL CELL, YIELDING EFFICIENCY GAINS

POSSIBILITIES

1. COULD TARGET LOW COST END OF THE MARKET.
   THIS IS EFFICIENCY, BIOLOGY & ENGINEERING DEPENDENT.

CURRENT LIMITATIONS

1. EFFICIENCY IS KEY
   BIOLOGICAL SOLUTIONS: MOLECULAR BIOLOGY/ ALGAL SELECTION & CULTURE
   ENGINEERING SOLUTIONS: BIOREACTOR DESIGN, GASIFICATION (?) OF BIOMASS, GAS EXTRACTION, COLLECTION, CLEAN UP & STORAGE