Photosynthesis: 150 TW!!

\[ \text{CO}_2 + \text{H}_2\text{O} + \text{light} \rightarrow \text{biomass} + \text{O}_2 \]

We: 16 TW
105 billion tons per year of biomass is produced by photosynthesis
= two great pyramids of Giza per hour... every hour of biomass
Photosynthesis involves two light reactions in series: Photosystem 1 to reduce CO$_2$ and Photosystem 2 to oxidize H$_2$O.
Lessons From Nature For Solar Fuels

1. A plant in your windowsill absorbs all the incident light:

on an average sunny day \(10^6\) photons per second thanks to highly concentrated chlorophylls in proteins organized in the thylakoid membrane
Lessons From Nature For Solar Fuels

1. A plant in your windowsill absorbs all the incident light: $10^6$ photons per second thanks to highly concentrated chlorophylls in proteins.

2. A photosynthetic excitation can be transferred over 1000s of chlorophylls without getting lost thanks to superposition states and coherence.
Delocalized Excitations

\[ \phi_i \quad \text{vs} \quad \psi_k = \sum_{i=1}^{N} c_{ki} \phi_i \]

localized \hspace{1cm} \text{delocalized}
2D-ES to reveal Coherence

![Diagram with graphs and molecular structures indicating frequency distribution and population time graphs with coherence analysis at different times (25 fs, 35 fs, 55 fs).]
1. A plant in your windowsill absorbs all the incident light: $10^6$ photons per second thanks to highly concentrated chlorophylls in proteins

2. A photosynthetic excitation can be transferred over 1000s of chlorophylls without getting lost thanks to superposition states and coherence

3. Reaction centers separate charges by electron tunneling on a picosecond timescale
BioSolar Cell: The Reaction Center

Electron transfer = Electron Tunneling

4 nm
Lessons From Nature For Solar Fuels

1. A plant in your windowsill absorbs all the incident light: $10^6$ photons per second thanks to highly concentrated chlorophylls in proteins

2. A photosynthetic excitation can be transferred over 1000s of chlorophylls without getting lost thanks to superposition states and coherence

3. Reaction centers separate charges by electron tunneling on a picosecond timescale

4. Plants extract electrons from H$_2$O with a ‘hole efficiency’ of 1 using an ingenious complex management of electrons and protons
Photosystem Two: The water splitting enzyme

\[
2\text{H}_2\text{O} \rightarrow 4\text{H}^+ + 4\text{e}^- + \text{O}_2
\]

Ferreira et al. Science 2004
Lessons From Nature For Solar Fuels

1. A plant in your windowsill absorbs all the incident light: $10^6$ photons per second thanks to highly concentrated chlorophylls in proteins.

2. A photosynthetic excitation can be transferred over 1000s of chlorophylls without getting lost thanks to superposition states and coherence.

3. Reaction centers separate charges by electron tunneling on a picosecond timescale.

4. Plants extract electrons from $H_2O$ with a ‘hole efficiency’ of 1 using an ingenious complex management of electrons and protons.

5. Maximum energy efficiency solar->fuel is 30%, over the complete solar spectrum 12%, to biomass 2-3 % or less.
Plant photosynthesis is not efficient

Solution: Artificial Photosynthesis

1. The artificial leaf
2. The bio-hybrid device
3. The photosynthetic ‘solar fuel cow’
4. Improving natural photosynthesis
Solution: Artificial Photosynthesis

1. The artificial leaf
2. The bio-hybrid device
3. The photosynthetic ‘solar fuel cow’
4. Improving natural photosynthesis
Artificial Photosystem II

The long lifetime of the highly oxidizing relay provides a good match for the slow kinetics of the OEC or metal oxide catalysts.

Artificial Photosynthesis

1. The artificial leaf
2. The bio-hybrid device
3. The photosynthetic ‘solar fuel cow’
4. Improving natural photosynthesis
Wiring photosynthetic enzymes to electrodes†
Adrian Badura, Tim Kothe, Wolfgang Schuhmann and Matthias Rögner
DOI: 10.1039/c1ee01285a
Artificial Photosynthesis
Linking technological with biological solar energy conversion
Hybrid systems and the biological electrical interface

Photovoltaic emf
wire distribution

- Fuels
+ Electricity
electrical work: mechanical, chemical, thermal, & informational

Redox \rightarrow \text{pmf}

+ Fuels
- Electricity

Water oxidation

Halophillic Archaea

Microbial Electrosynthesis: Converting Carbon Dioxide and Water to Fuels and Other Chemicals with Electrical Energy

Biofilm of Clostridium Capable of Using Electrons Derived from Electrodes to Reduce Carbon Dioxide to Butanol
Artificial Photosynthesis

1. The artificial leaf
2. The bio-hybrid device
3. The photosynthetic ‘solar fuel cow’
4. Improving natural photosynthesis
Algae and cyanobacteria for biofuel production

Advantages:
- easy to grow
- Use of salt water

No competition for land with food

Semi-productive levels (high value products, optimization of fuel productions, …)

Synthetic biology (new metabolic pathways leading to fuel)
MIX Photosynthesis with Fermentation

PHOTO

$\text{CO}_2$

$\text{GAP}$

$\text{Sugar-P}$

FERMENTATION

Sugar-P

$\text{GAP}$

ethanol butanol propanediol lactic acid
OPLOSSING:

ALGEN – CYANO’S
Photanol®, concept (2007)

Fermenting bacteria

DNA coding for fermentation

Photosynthetic bacteria

Gentransfer to

Cyano bacteria (Blue green algae)

Photofermenting bacteria
Artificial Photosynthesis

1. The artificial leaf
2. The bio-hybrid device
3. The photosynthetic ‘solar fuel cow’
4. Improving natural photosynthesis
Directing the flow of energy in a reengineered photosynthetic membrane with true tandem cell performance

$\text{O}_2 + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}$

PSII water oxidizing photosystem from *Acaryochloris*

**Solar spectrum**

- **NDH-1**
- **QH$_2$**
- **Q’H$_2$**
- **Cyt $bc_1$ type coupling site**
- **H+ pump**

**pmf**

- **200 mV**
Acknowledgements

Huub de Groot (Leiden)
Roberta Croce (VU Amsterdam)
Eli Romero (VU Amsterdam)

Klaas Hellingwerf (Un. Van Amsterdam)
Wilmar van Grondelle (Photanol)

Tom Moore (ASU)
Greg Scholes (U. Toronto)