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Technology Assessment of Artificial Photosynthesis

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Introduction

Where we are now

Where we came from

Components became smaller while devices became larger on purpose

Introduction

Where we are now

Where we came from

Size and price have continuously dropped.

Introduction

Where we are now

Where we came from

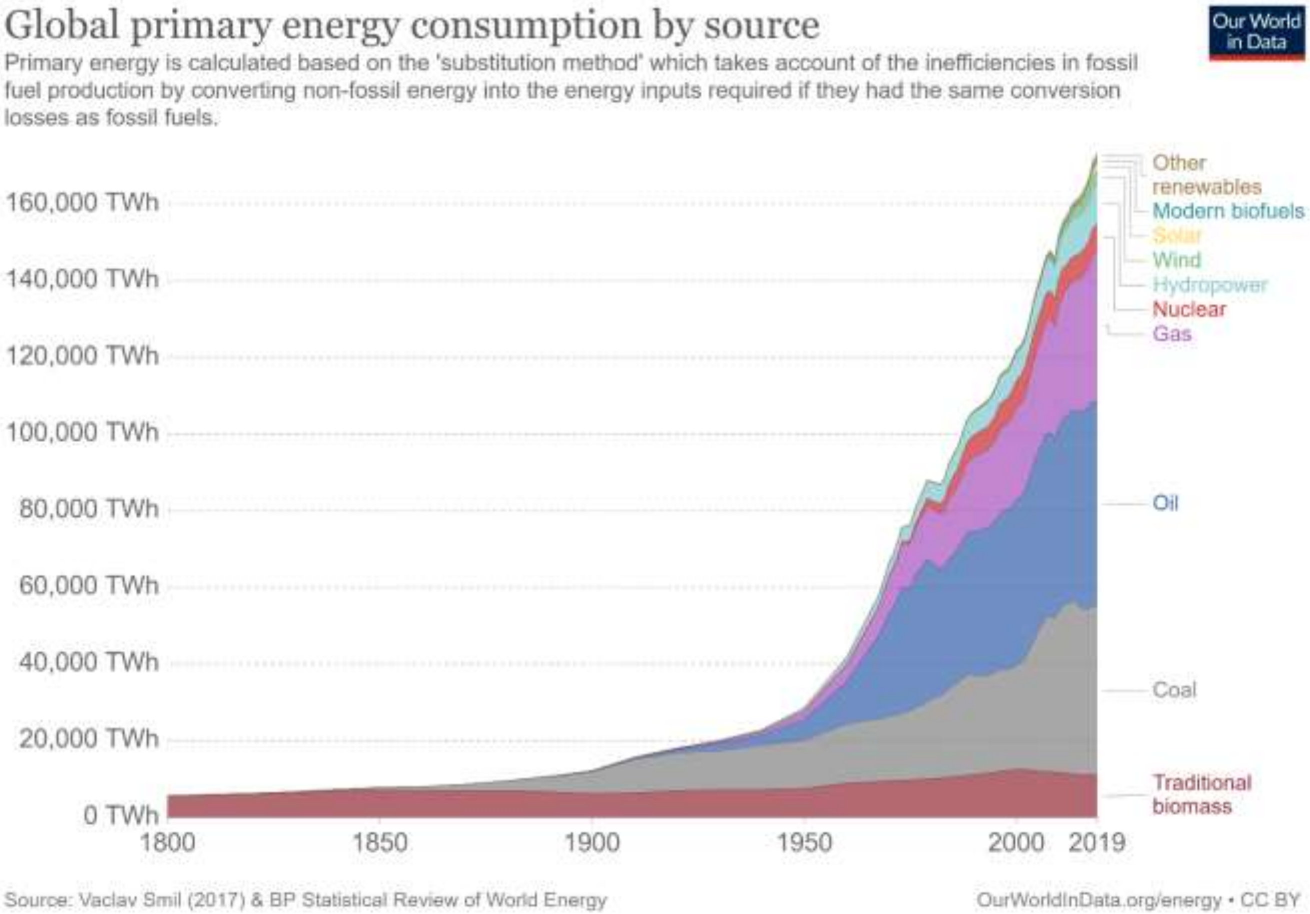
Introduction

Where we are now

Where we came from

Digitalization – miniaturization – integration.
If it is conceivable, it is achievable.
Constant improvement and disruptive innovation will be equally necessary.

Humanity’s energy demand vs. sunlight irradiation



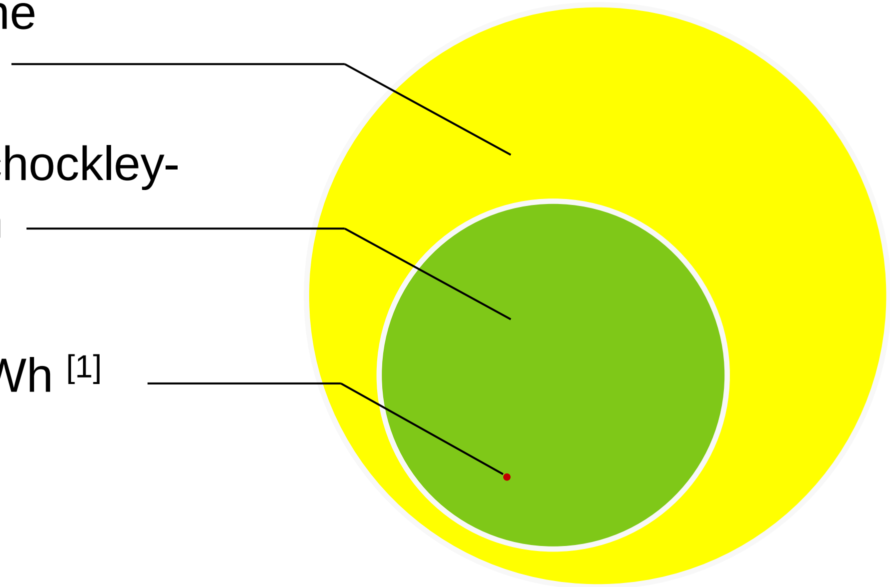
Source: Vaclav Smil (2017) & BP Statistical Review of World Energy

OurWorldInData.org/energy • CC BY

[1] https://ourworldindata.org/energy-production-consumption
[2] https://www.sciencedirect.com/topics/engineering/solar-energy
[3] „Power Generation Technologies“ (Chapter 13 – Solar Power), 2019, P. Breeze, https://www.sciencedirect.com/science/article/pii/B9780081026311000134
[4] „Detailed Balance Limit of Efficiency of p-n Junction Solar Cells”, J. Appl. Phys. 32, 510, 1961, W. Schockley & H. J. Queisser, https://aip.scitation.org/doi/10.1063/1.1736034
[5] „Künstliche Photosynthese Besser als die Natur?“, 2019, H. Dau, P. Kurz, M.-D. Weitze (ISBN: 978-3-662-55718-1)

Humanity’s energy demand vs. sunlight irradiation

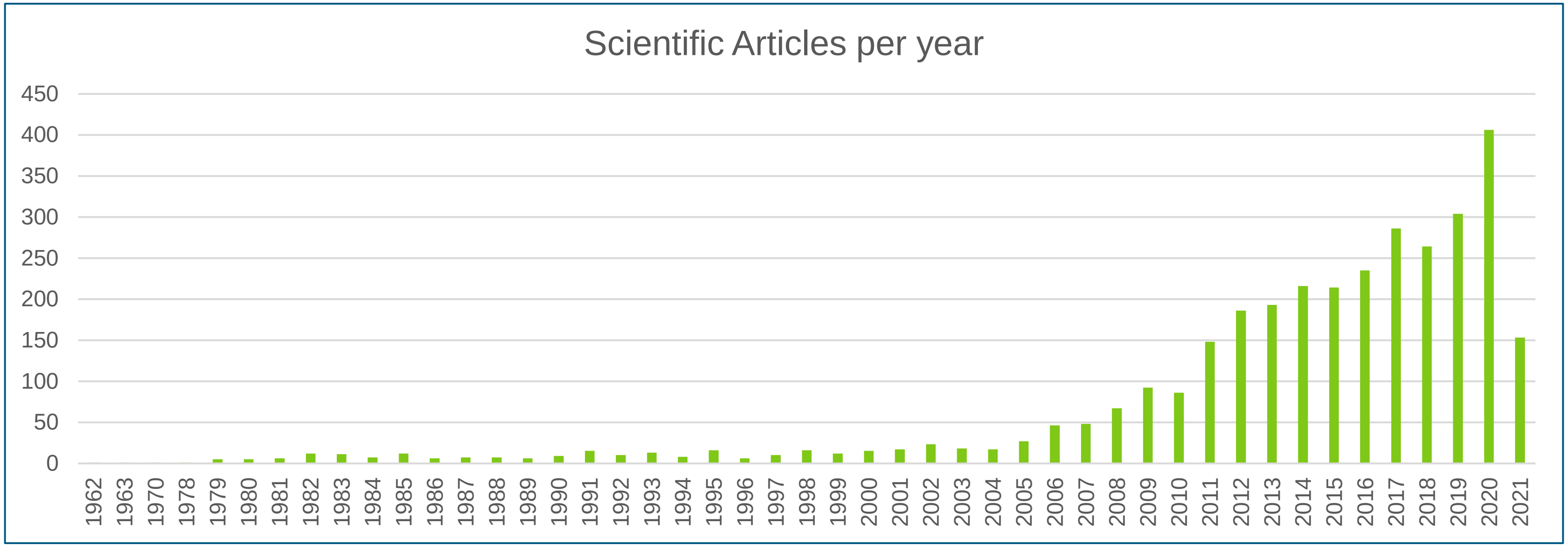
- Sun energy reaching the surface of the earth per year: 944,444,400 TWh [2,3]
- Maximum usable sun energy after Schockley-Queisser-Limit [4,5]: 331,000,000 TWh
- Energy demand per year: 160,000 TWh [1]

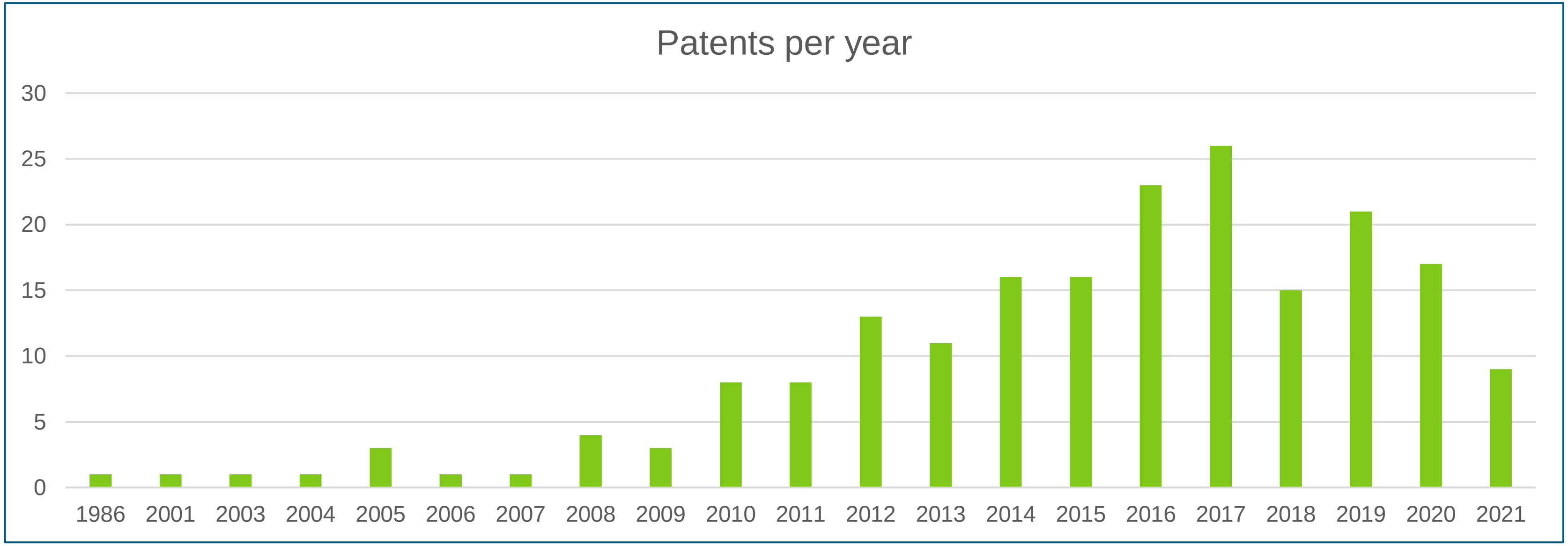


- Even considering Shockley-Queisser efficiency limit of ≈ 35%, the usable sun energy is 20.000 times higher than our yearly energy demand.
- Hence, 0.34% of land area and 17.5% efficiency would suffice to cover our energy demand.

[1] https://ourworldindata.org/energy-production-consumption
[2] https://www.sciencedirect.com/topics/engineering/solar-energy
[3] „Power Generation Technologies“ (Chapter 13 – Solar Power), P. Breeze, 2019, https://www.sciencedirect.com/science/article/pii/B9780081026311000134
[4] „Detailed Balance Limit of Efficiency of p-n Junction Solar Cells”, W. Schockley & H. J. QueisserJ. Appl. Phys. 32, 510, 1961,, https://aip.scitation.org/doi/10.1063/1.1736034
[5] „Künstliche Photosynthese Besser als die Natur?“, H. Dau, P. Kurz, M.-D. Weitze, 2019 (ISBN: 978-3-662-55718-1)

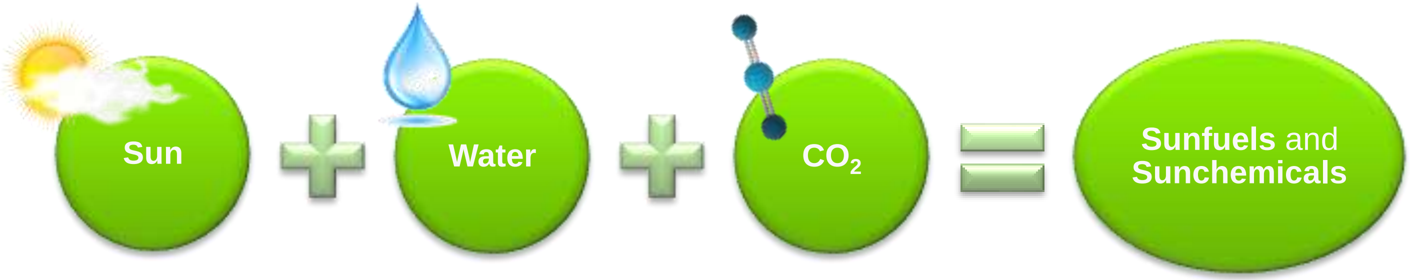
Patents Charts





Reference: SciFinder query for the phrase „artificial photosynthesis“ – analysis by type = „patent“, May 30, 2021

Concepts of Artificial Photosynthesis



Sun + Water + CO_2 = Sunfuels and Sunchemicals

Artificial Photosynthesis Routes

Technologic

- Photoelectrochemical
- Photochemical

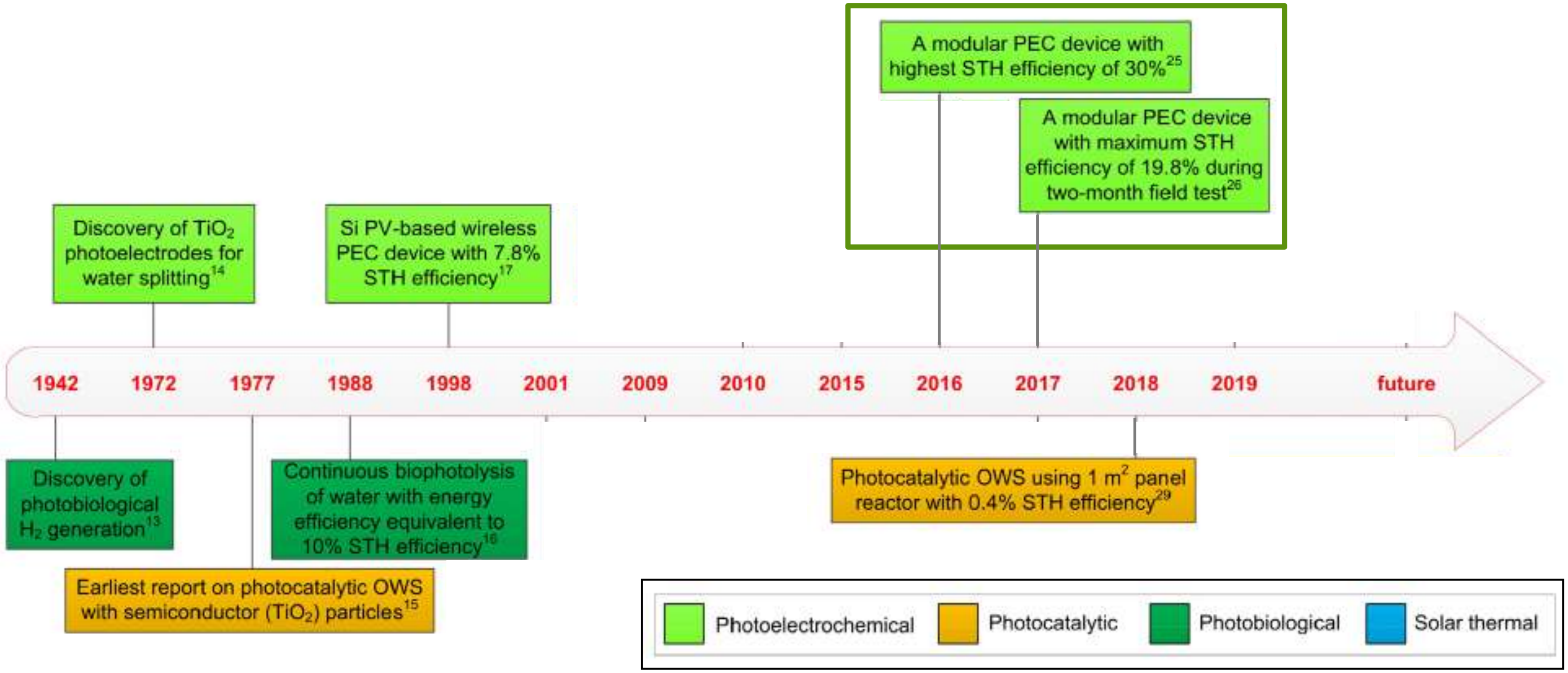
Hybrid

- Photobioelectrochemical

Biologic (mod.)

- Enzymatic (cell-free)
- Full Cell Catalysis

Achievements toward solar Hydrogen production



1942 1972 1977 1988 1998 2001 2009 2010 2015 2016 2017 2018 2019 future

1942: Discovery of photobiological H_2 generation[13]

1972: Discovery of TiO_2 photoelectrodes for water splitting[14]

1977: Earliest report on photocatalytic OWS with semiconductor (TiO_2) particles[15]

1988: Continuous biophotolysis of water with energy efficiency equivalent to 10% STH efficiency[16]

1998: Si PV-based wireless PEC device with 7.8% STH efficiency[17]

2016: A modular PEC device with highest STH efficiency of 30%[25]

2017: A modular PEC device with maximum STH efficiency of 19.8% during two-month field test[26]

2018: Photocatalytic OWS using 1 m^2 panel reactor with 0.4% STH efficiency[29]

🟩 Photoelectrochemical 🟧 Photocatalytic 🟩 Photobiological 🟦 Solar thermal

Image adapted from: „Research advances towards large-scale solar hydrogen production from water", G. Liu, Y. Sheng, J. W. Ager, M. Kraft, R. Xu, EnergyChem 1(2), 2019, 100014, https://doi.org/10.1016/j.enchem.2019.100014

Solar Hydrogen production benchmarks – PV plus electrolysis

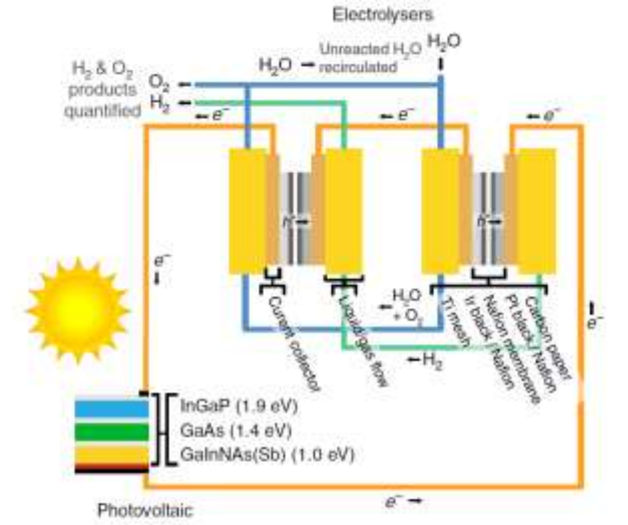


Figure 1 | PV-electrolysis device schematic. The PV-electrolysis system consists of a triple-junction solar cell and two PEM electrolysers connected in series.

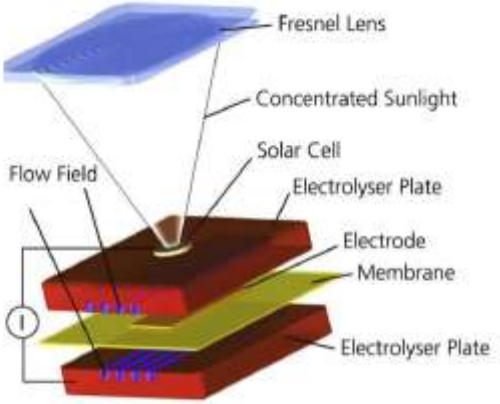


Fig. 1 – **Schematic view of the HyCon concept** [13]. **A**

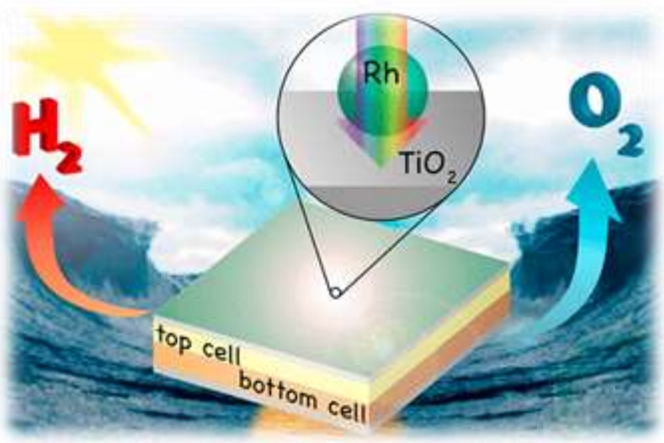
Product	H_2 $(+O_2)$ (separated)
STH	**30%**
Materials	- 3J solar cell (InGaP, GaAs, GaInNAs(Sb)) - Two PEM electrolysers
Lifetime	> 2 d

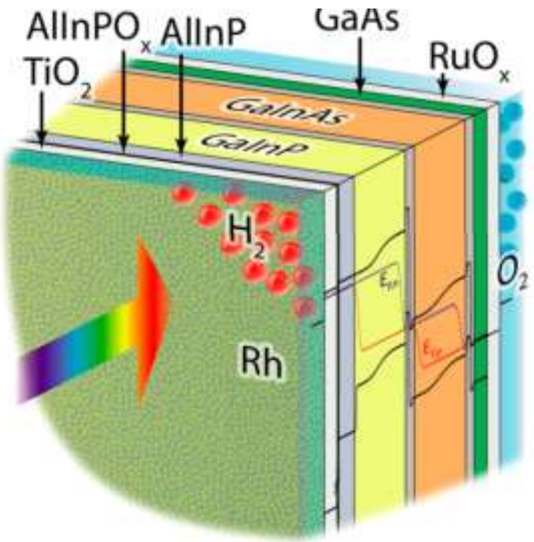
Product	H_2 $(+O_2)$ (separated)
STH	20%
Materials	- Solar cell not specified. - Electrolyzer not specified.
Lifetime	**> 60 d**

Left: „Solar water splitting by photovoltaic-electrolysis with a solar-to-hydrogen efficiency over 30%“, J. Jia, L. C. Seitz, J. D. Benck, Y. Chen, J. W. D. Ng, T. Bilir, J. S. Harris, Th. F. Jaramillo, Nature Communications 7, 2016, https://doi.org/10.1038/ncomms13237

Right: “Hydrogen concentrator demonstrator module with 19.8% solar-to-hydrogen conversion efficiency according to the higher heating value”, A. Fallisch, L. Schellhase, J. Fresko, M. Zedda, J. Ohlmann, M. Steiner, A. Bösch, L. Zielke, S. Thiele, F. Dimroth, T. Smolinka, Int. J. Hydrogen Energy 43(4), 2017, 26804, https://doi.org/10.1016/j.ijhydene.2017.07.069

Solar Hydrogen production – Artificial Leaf – integrated system





Product	H_2 $(+O_2)$ (separated)
STH	**18-19% (at AM 1.5G)**
Materials	• RuO_2 (for OER-Electrode) • GaInP/GaInAs on GaAs substrate (Photoelectrode) TiO_2 (anatase) layer (by ALD) • Rh (Nanoparticles)
Lifetime	≈ 1 d („stability remains an issue“)

Image Source: „Monolithic Photoelectrochemical Device for Direct Water Splitting with 19% Efficiency”, W.-H. Cheng, M. H. Richter, M. M. May, J. Ohlmann, D. Lackner, F. Dimroth, Th. Hannappel, H. A. Atwater, H.-J. Lewerenz, ACS Energy Lett. 3(8), 2018, 1795-1800, https://doi.org/10.1021/acsenergylett.8b00920

C-compounds production from solar energy

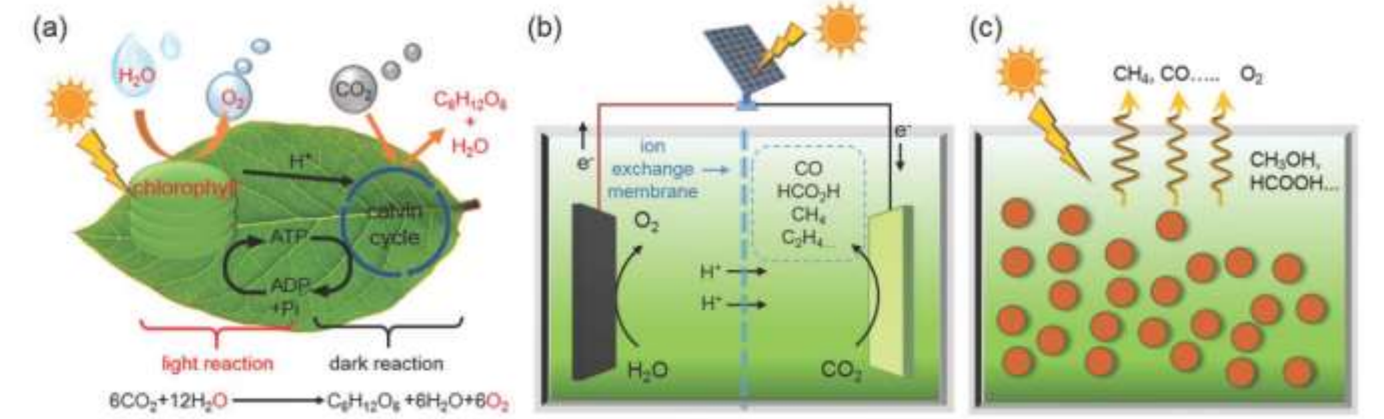


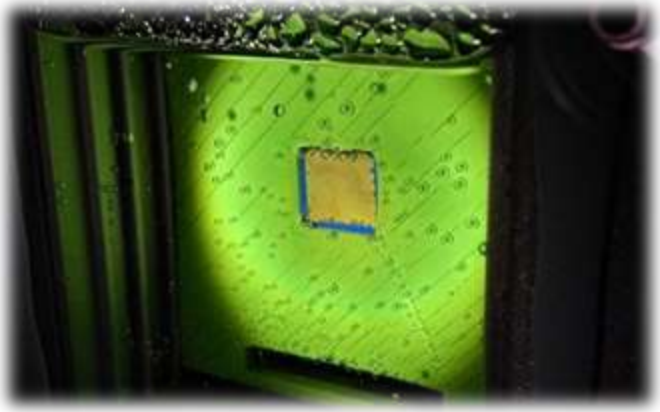
Figure 2. Analogy among a) natural photosynthesis, b) electrochemical synthesis on electrocatalysts powered by a photovoltaic cell, and c) photochemical synthesis on powdery photocatalysts.

- Very different reaction conditions (catalysts, co-catalyst, light sources, …) to produce different compounds.
- Achievable products: CO, Methane, Methanol, Formic Acid, Ethane, Ethanol

Image Source: „CO_2 Reduction: From the Electrochemical to Photochemical Approach", J. Wu, Y. Huang, W. Ye, Y. Li, Adv. Sci. 4(11), 2017, https://doi.org/10.1002/advs.201700194

Recent publications toward photocatalytic C-compounds production

Product	HCOOH (+O_2)
STP	**0.08% (at 98% selectivity)**
Materials	• SrTiO3:La,Rh|Au • RuO2-BiVO4:Mo|Au • CotpyP (immobilized Cobalt-phosphoryl complex)
Lifetime	50% of initial reaction rate after **24 h**. (recovered to 80% after reloading CotpyP)



Product	H_2 + CO (= syngas)
STH **ST-CO**	**0.06 %** **0.02 %**
Materials	• Catalyst: Cobalt porphyrin catalyst immobilized on carbon nanotubes • Photoabsorbers: Triple-cation mixed halide perovskite and $BiVO_4$
Lifetime	**≈ 3 d**

Left: „Molecularly engineered photocatalyst sheet for scalable solar formate production from carbon dioxide and water", Q. Wang, J. Warnan, S. Rodriguez-Jimenwz, J. L. Leung, S. Kalathil, V. Andrei, K. Domen, E. Reisner, Nature Energy 5, 2020, 703-710, https://doi.org/10.1038/s41560-020-0678-6

Right: "Bias-free solar syngas production by integrating a molecular cobalt catalyst with perovskite–$BiVO_4$ tandems", V. Andrei, B. Reuillard, E. Reisner, Nature Materials 19, 2020, https://doi.org/10.1038/s41563-019-0501-6

Advantages & Challenges of different routes

Route	Advantages	Challenges
Photo-electro-chemical	• High efficiencies.	• Increase system integration and decrease interfacial losses. • Increase lifetime. • Decrease costs.
Photo-catalytic	• Inexpensive. • Robust. • Simple.	• Increase efficiencies.
Biologic	• General concepts are well-developed.	• Sensitive to reaction conditions and environment.

TRL assessment

TRL 3: Experimental proof of concept

- ☑ First laboratory scale prototype (proof-of-concept) or numerical model realized
- ☑ Testing at laboratory level of the innovative technological element (being material, sub-component, software tool, …), but not the whole integrated system
- ☑ Key parameters characterizing the technology (or the fuel) are identified
- ☐ Verification of experimental application through simulation tools and cross-validation with literature data (if applicable).

TRL 4: Technology validated in lab

- ◔ (Reduced scale) prototype developed and integrated with complementing sub-systems at laboratory level
- ☐ Validation of the new technology through enhanced numerical analysis (if applicable).
- ☑ Key Performance Indicators are measurable
- ◔ The prototype shows repeatable/stable performance (either TRL4 or TRL5, depending on the technology)

Based on the TRL definitions from: „Technology Readiness Level: Guidance Principles for Renewable Energy technologies“ (Annexes), European Commission (DG RTD), 2017, https://op.europa.eu/de/publication-detail/-/publication/d5d8e9c8-e6d3-11e7-9749-01aa75ed71a1

Economic Assessment – A look into the future

From lab…

…to something that looks likes this…

…to a business case.

What do we know?

- ☑ Possible products that can be produced by APS
- ☑ Market size, production costs and price of the products for today

Where we need assumptions

- ? Materials used for a market ready technology ➔ CapEx
- ? Market situation in the future (20 - 30 years) ➔ OpEx, serviceable market and selling price

Economic Assessment – Example Hydrogen

Hydrogen is expected to cover almost one fifth of global demand for final energy in 2050.

Today	Production volume	Production costs per ton
Steam reforming	117 Mt, Global, 2019	≈ 1.400 €
Electrolysis	Negligible	3.000 – 5.500 €

Future needs for APS	Lifetime	Solar to Hydrogen efficiency	Area
Artificial Photosynthesis	10 years	10%	*≈ 58.500 km²*

Current and future needs

- To speak a common language, i.e., develop a common understanding of knowledge and challenges.
  - Open research data, e.g., the materials genome.
  - Artificial intelligence and computational methods.
- An intense and multidisciplinary collaboration to make fast and big steps at the same time.
  - National research centers & think tanks
  - International infrastructures and user facilities
- To demonstrate scalable systems with medium (short-term) and high (mid-term) efficiencies and lifetimes.
- To develop standards to ease market penetration.