ENERGY earthshots
U.S. DEPARTMENT OF ENERGY

Hydrogen

Advanced Pathways – Photoelectrochemistry

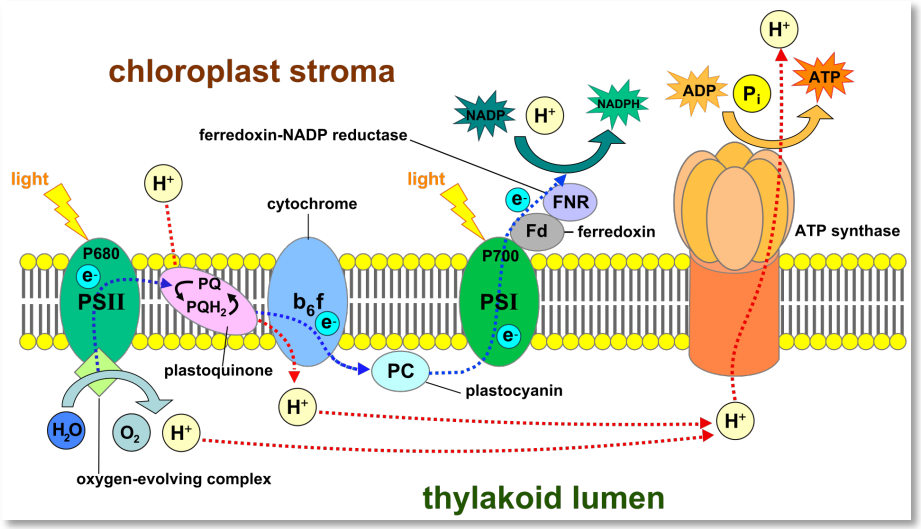
Tom Jaramillo, Stanford/SLAC, and Frances Houle, LBNL

Hydrogen Shot Summit

Artificial photosynthesis by photoelectrochemistry

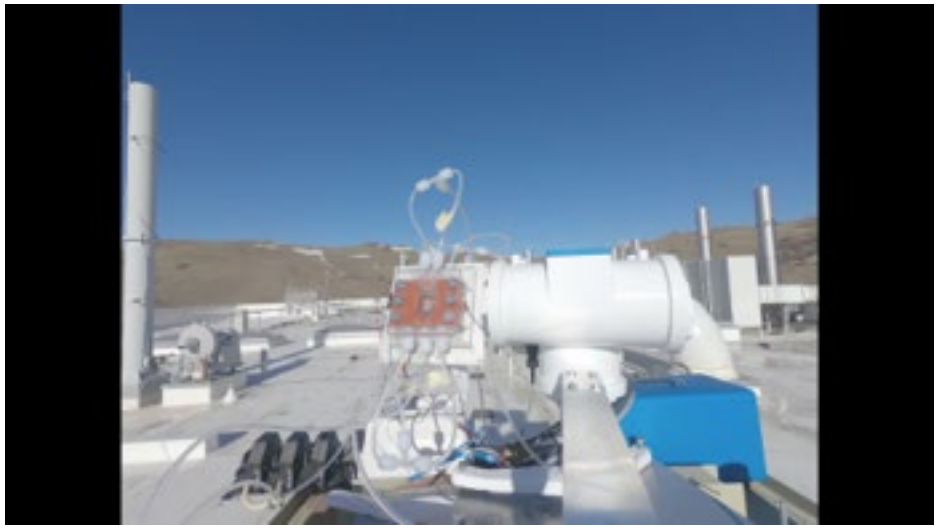
$$2H_2O + \text{sunlight} \rightarrow 2H_2 + O_2$$

Natural photosynthesis



https://en.wikipedia.org/wiki/Light-dependent_reactions

Artificial photosynthesis

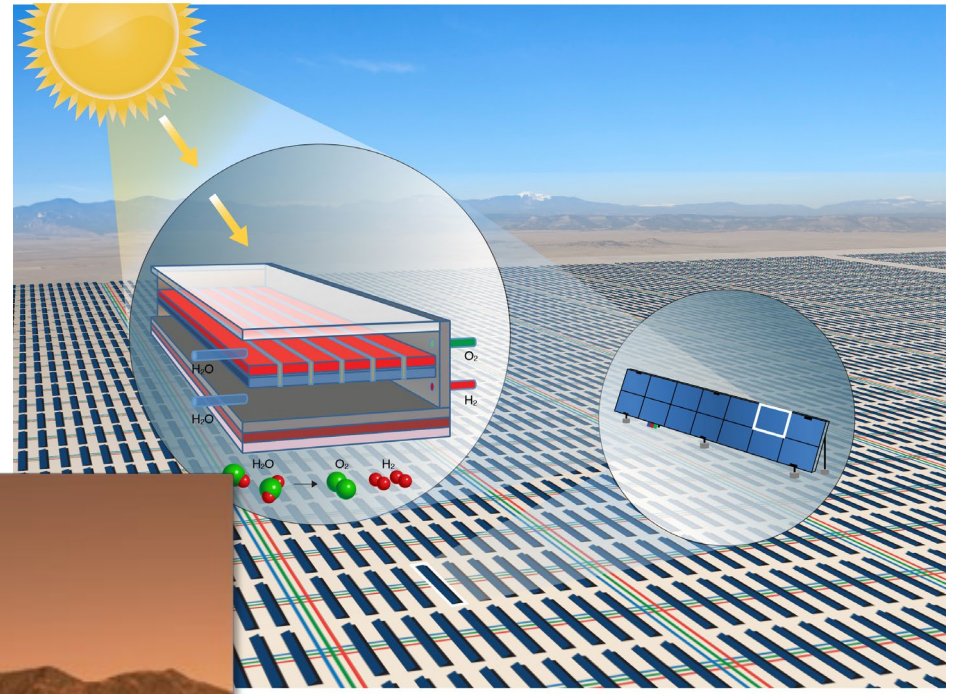


NREL

Micha Ben-Naim, Chase W. Aldridge, Myles A. Stenier, Adam C. Neilander, Todd G. Deustch, James L. Young, and Thomas F. Jaramillo, *submitted*, 2021

Deployment and uses

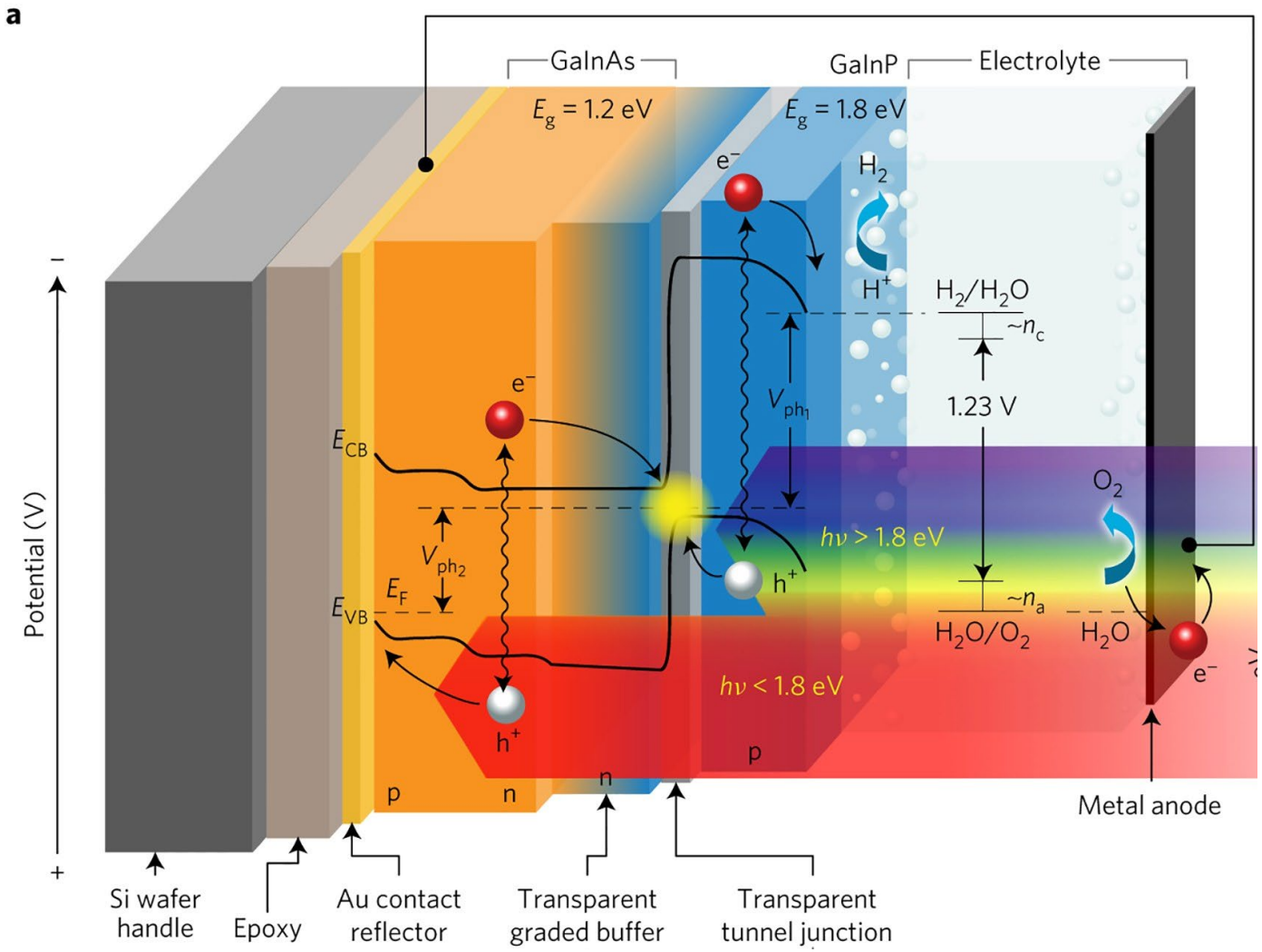
1. Small to large scale
2. H_2 fuel and feedstock generation
3. dispatchable chemical storage of intermittent renewable energy (wind, solar etc),
4. In-situ resource utilization for personnel support, eg personal fuel cells vs batteries



Sathre et al, EES 7 (2014) 3264

The Mars ISRU Challenge
kiss.caltech.edu/new_website/programs.html#isru

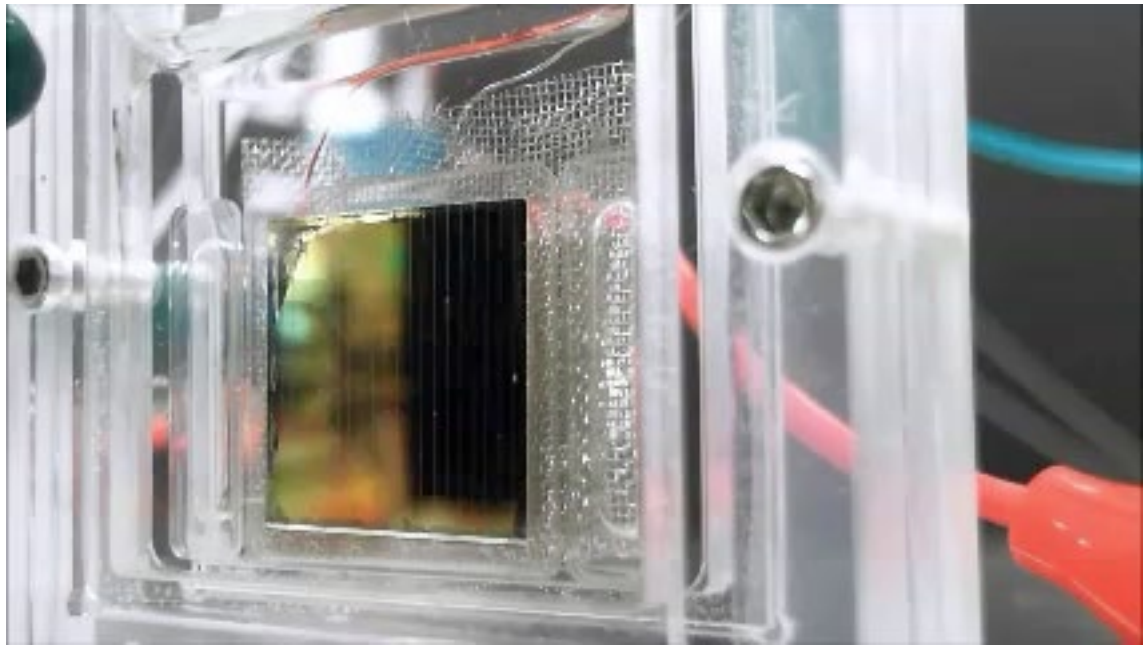
How photoelectrochemical H_2 production works



J.L. Young, M.A. Steiner, H. Döscher, R.M. France, J.A. Turner, T.G. Deutsch. *Nature Energy*. 2, 17028 (2017).

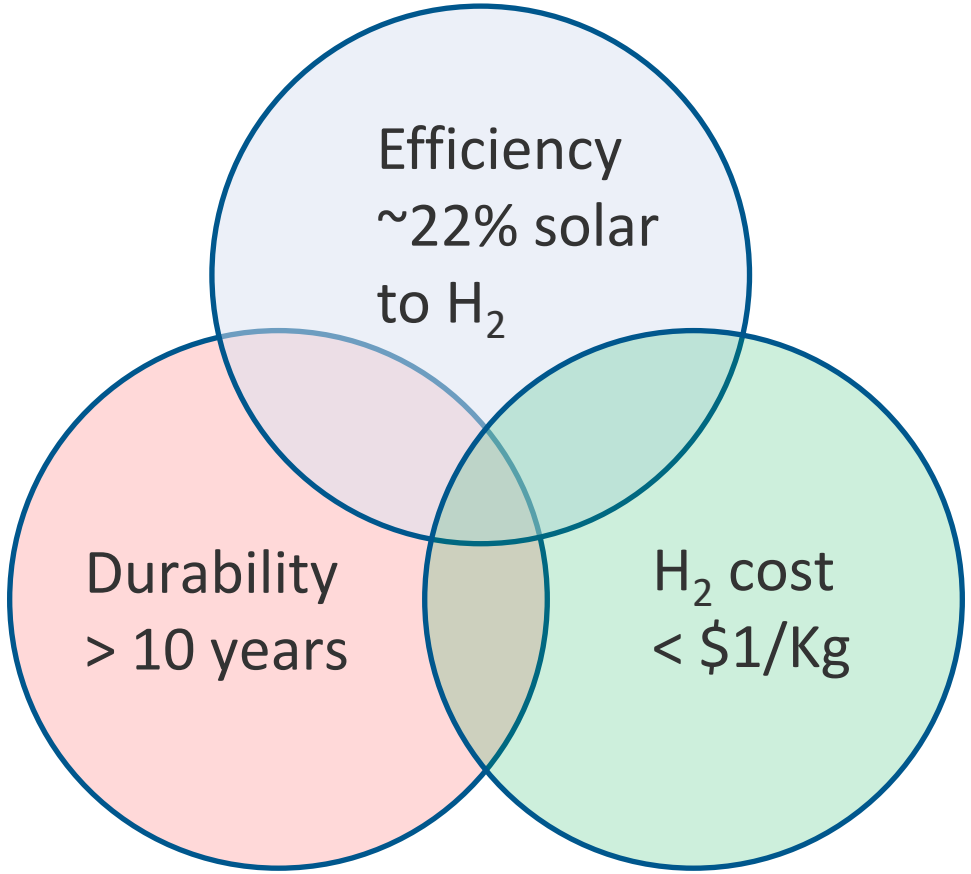
Benefits of the technology

- Instant-on and -off
- Follows sunlight fluctuations, diurnal and seasonal cycles
- Stand-alone (no electrical grid required)
- Ultra-pure H_2 and O_2 generation
- Water in liquid or vapor phases

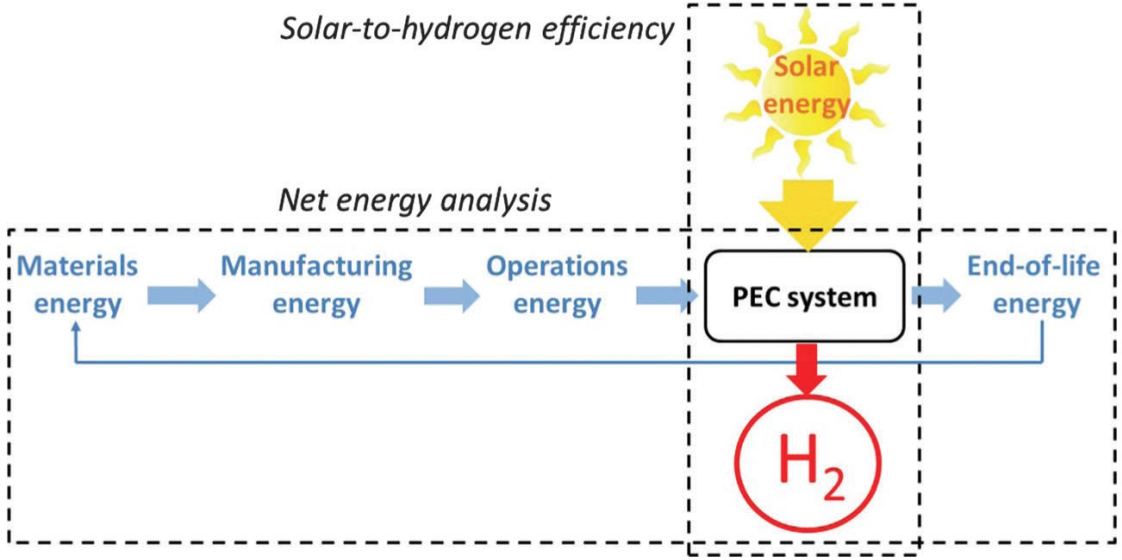


Video credit: K. Walczak, LBNL

Requirements for a viable technology



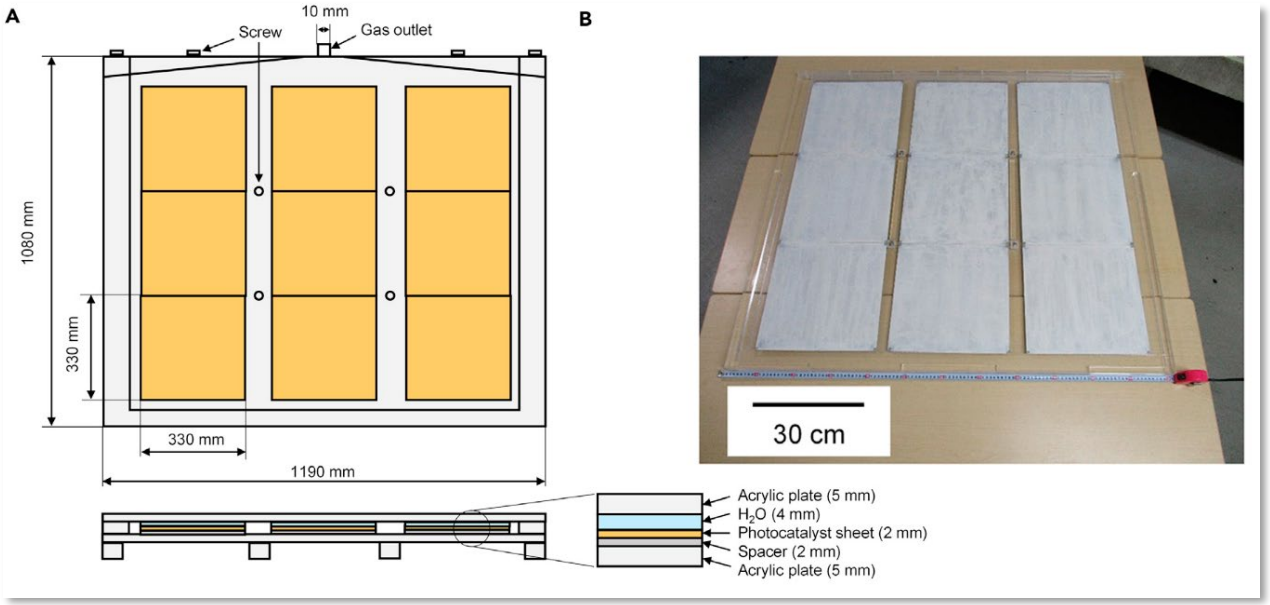
The challenge: all 3 at once *sustainably*



Sathre et al, EES 7 (2014) 3264

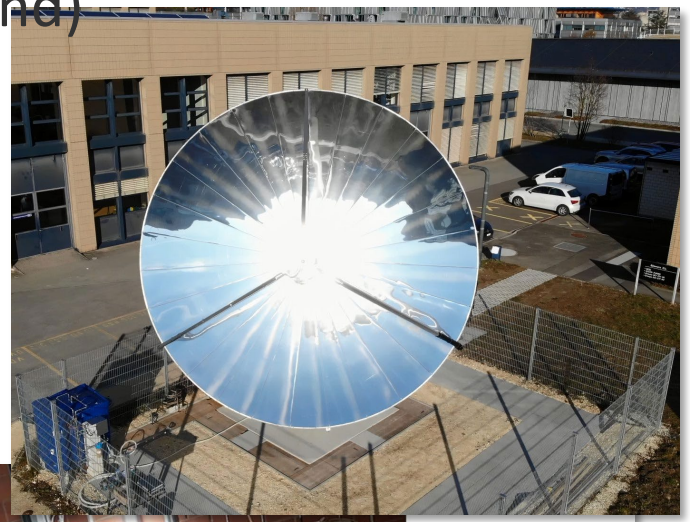
International progress to reduce system costs

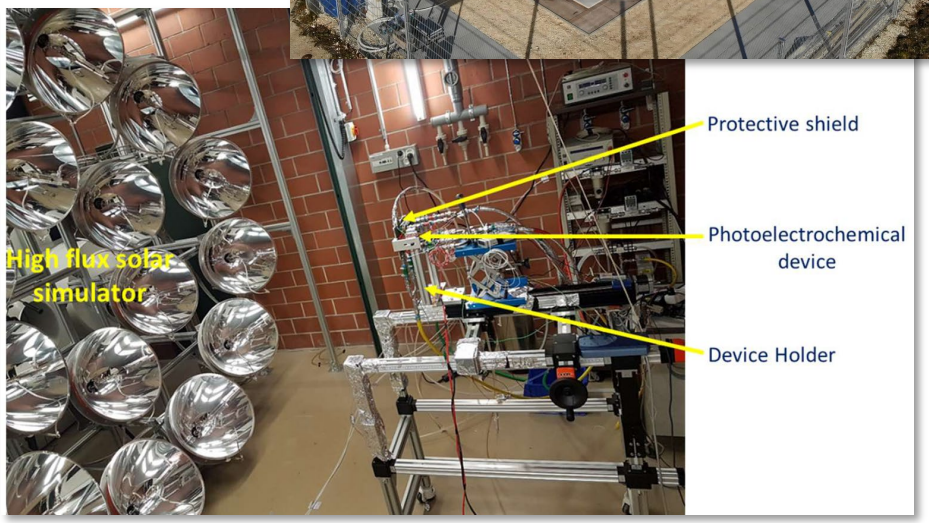
Photocatalytic bed reactors using low-cost materials (Japan)



Yamada and Domen, chemeng. 2 (2018) 36
Goto et al, Joule 3 (2018) 509

Concentrated light to reduce III-V use (Switzerland)



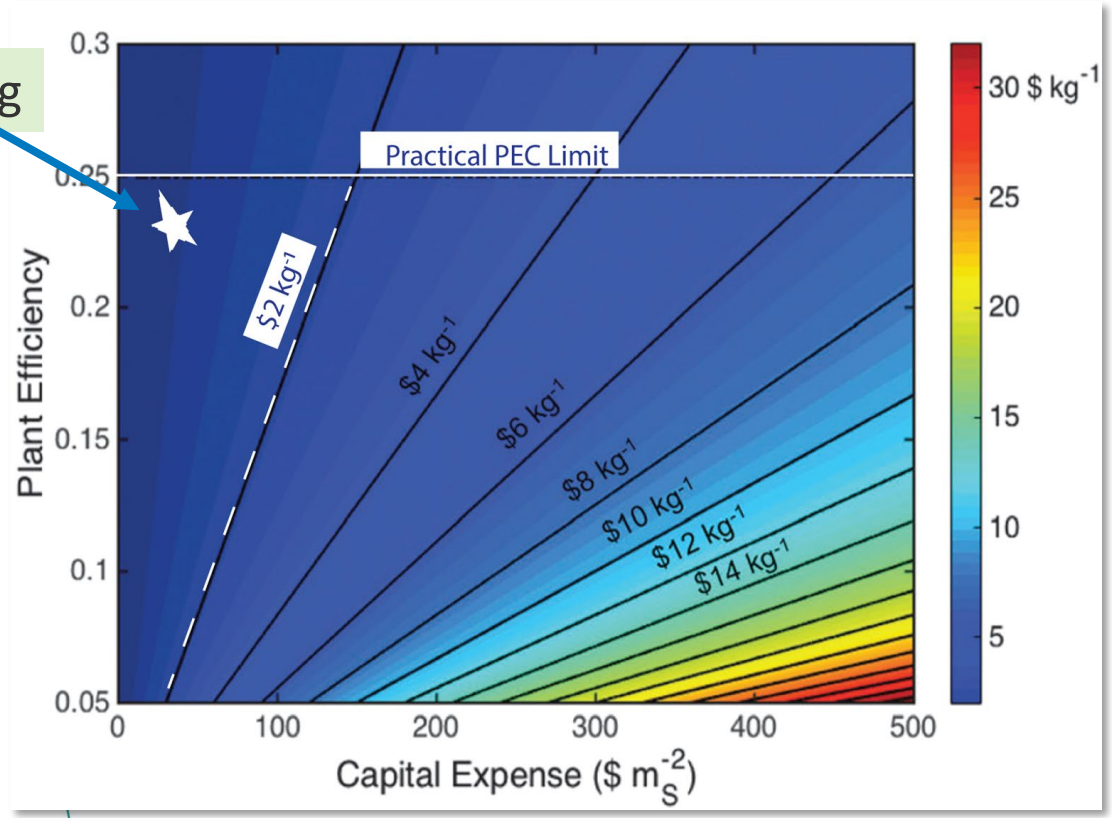


Tembhurne et al, Nat. Energy 4 (2019) 399
http://solardish.epfl.ch

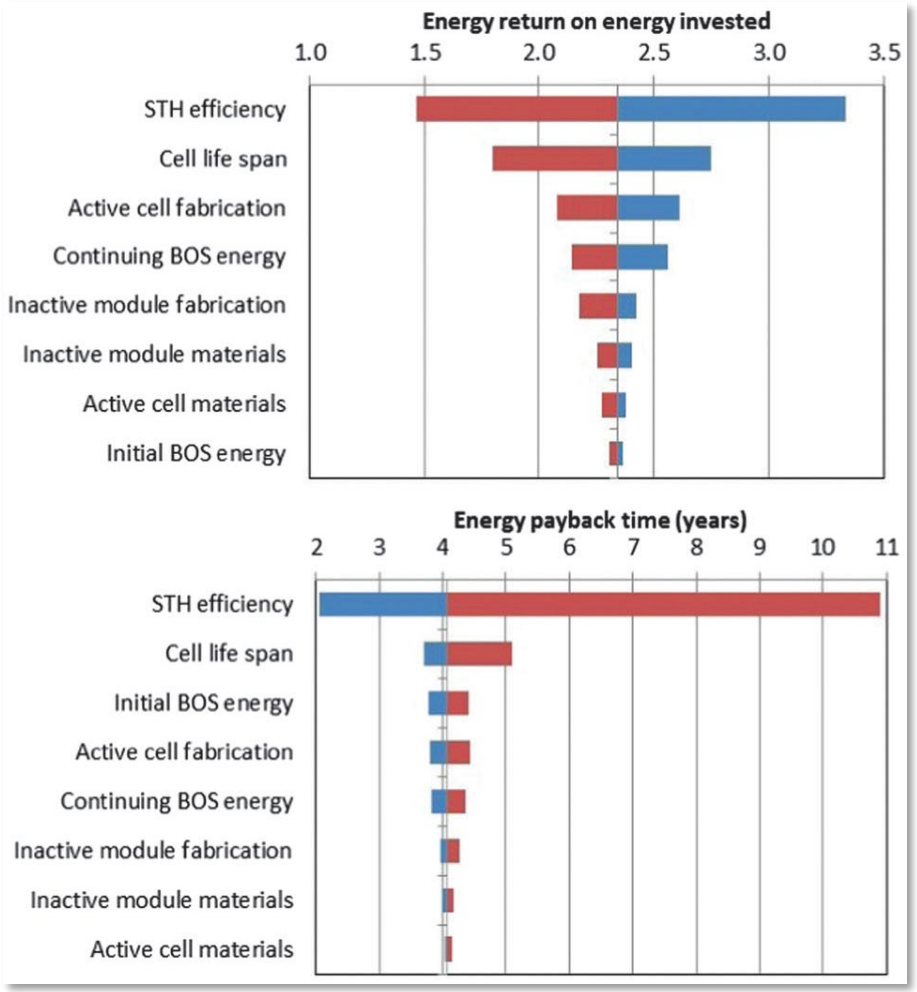
Broader strategy to address challenges

1. Improve PEC durability
2. Reduce manufacturing and maintenance costs
3. Minimize balance of plant

Target: $1/Kg



Adapted from Shaner et al, EES 9 (2016) 2354



Sathre et al, EES 7 (2014) 3264

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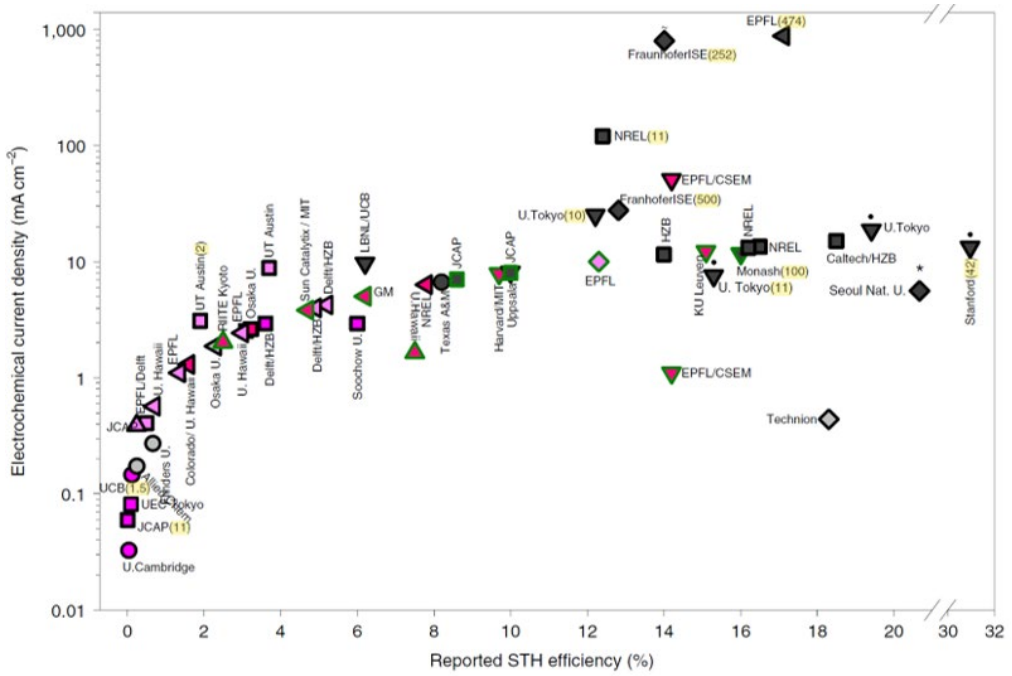
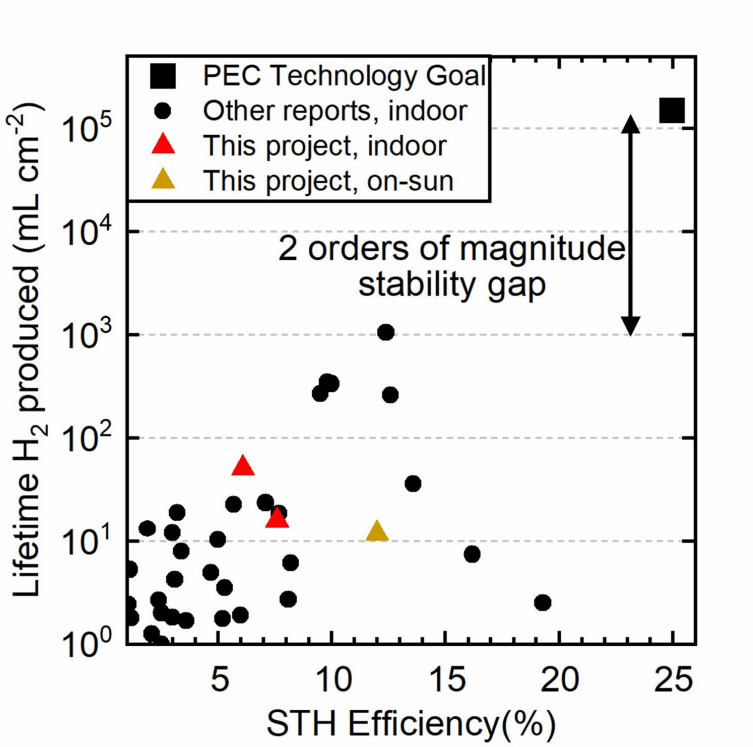
Scientific progress

- *Improving efficiency and reaction rates*
  - optical designs to fully utilize solar spectrum
  - high photovoltage and photocurrent materials assemblies



S. Tembhurne, F. Nandjou, S. Haussener. *Nature Energy* **2019**, *4*, 399-407

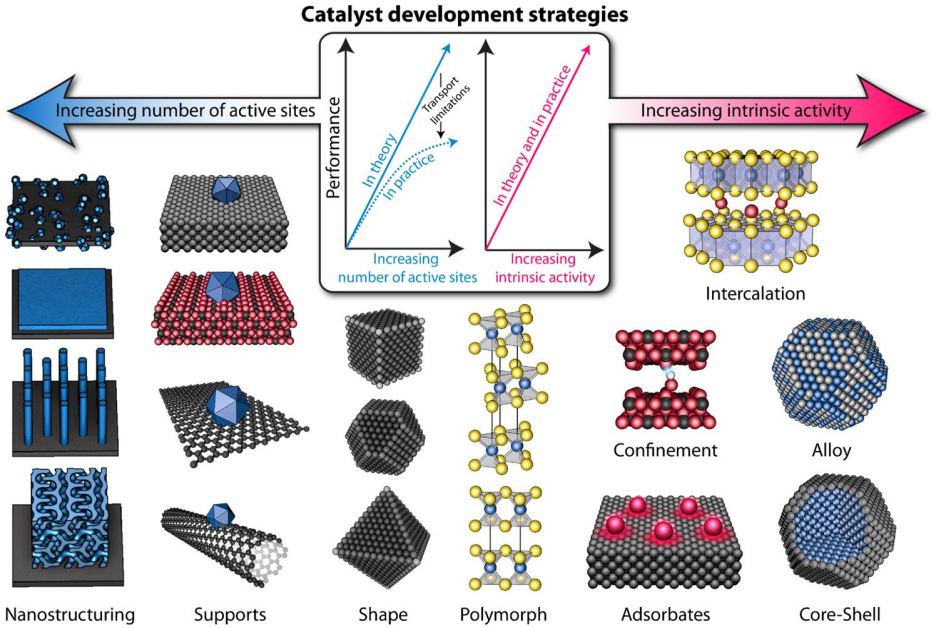
- *Improving durability*
  - from liquid-electrolyte to vapor-fed and MEAs
  - effective corrosion protections
  - discovery of more stable materials



M Ben-Naim et al. *ACS Energy Lett* **2020**, *5*, 2631-2640

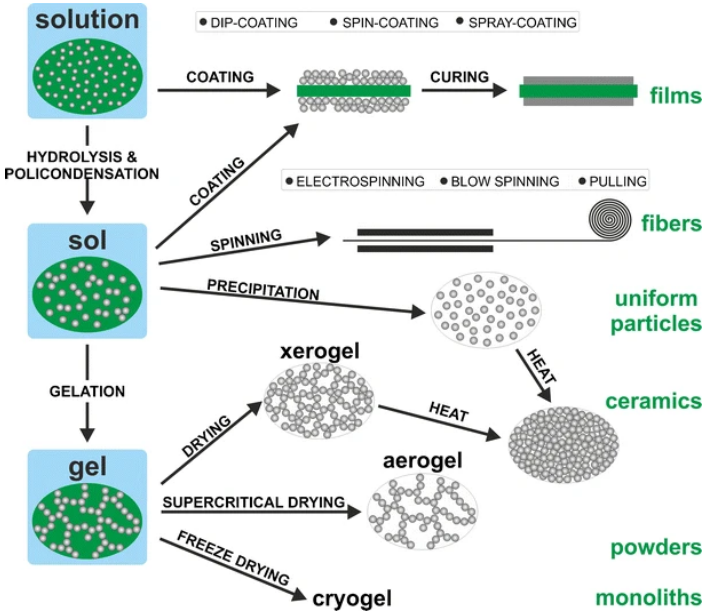
Science opportunities

- improved systems to minimize land use
- improved component designs (electrodes and membranes)
- improve energy return on energy invested and climate impacts (carbon costs, water costs)
- better catalysts



Z. She et al, *Science*, **355** 6321 (2017)

- reaching theoretical efficiency with more stable materials
- low-cost materials synthesis, e.g. spray coating, sol-gel, etc.



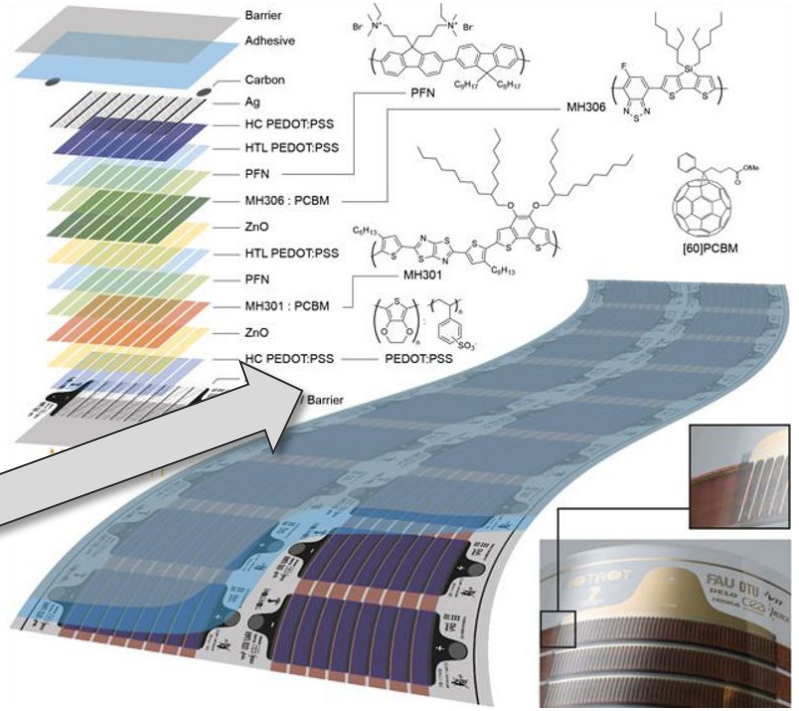
Barczak et al *Microchim Acta* **183,** 2085–2109 (2016)

Engineering opportunities

- from cm^2 scale to m^2 scale and beyond
- innovations in materials processing and manufacturing, roll-to-roll, or continuous tunnel.
- certification process, akin to PVs

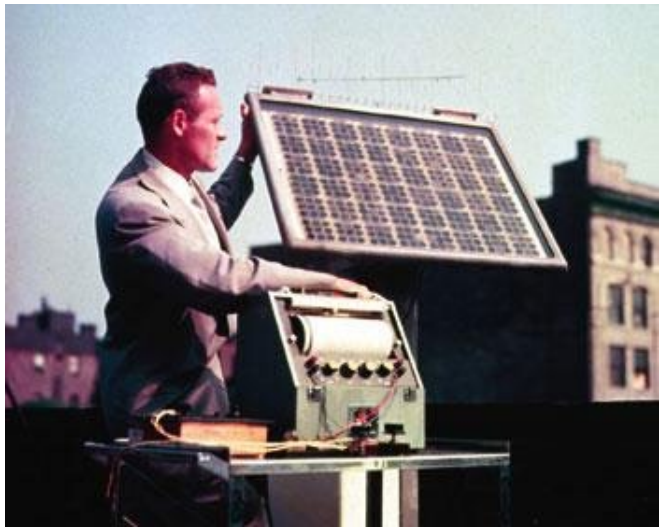
Asyst Technologies, inc,
http://www.ilocis.org/documents/chpt83e.htm

https://qnewshub.com/business/globalfoundries-in-malta-new-york-unexpected-link-in-global-supply-chains/ Sept 2020 image credit GlobalFoundries



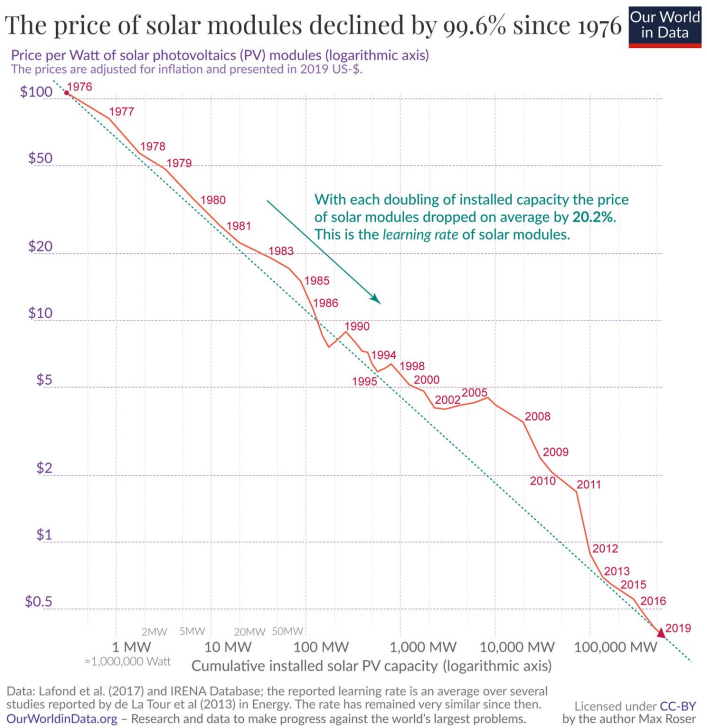
Andersen et al, EES 7 (2014) 2925

The PV industry, from scientific discovery to 1 TW_p



Bell Labs, 1954

Photo credit: Bell Labs
solartribune.com/history-of-photovoltaics/



Our World In Data - Max Roser - https://ourworldindata.org/cheap-renewables-growth

us.sunpower.com/sites/default/files/cs-solar-star-projects-fact-sheet_0.pdf

In 2022

- Total installed PV worldwide > 1 TW_p
- Large-scale utility solar < 3 ¢/kWh
- In well-suited locations: ~ 1 ¢/kWh
- 40-year lifetime
- $60/$m^2$ panels
- Installed costs of PV cheaper than installed windows

The opportunity: leverage PV advances for direct solar PEC H_2 production

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