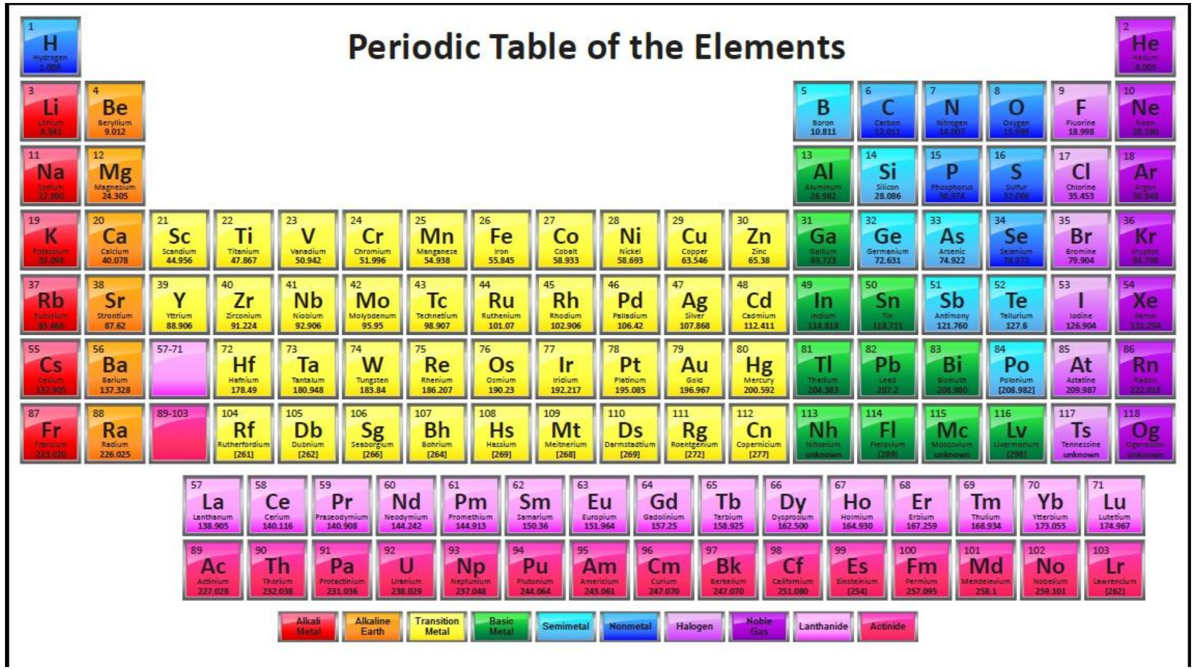

Green Hydrogen

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The World Hydrogen Energy Summit 2021 (16-17 November 2021)

Hydrogen as an Energy Vector

Currently Hydrogen meets 4 % of Global Energy Demand.
Used in oil refining, ammonia production, steel manufacturing, chemical and fertilizer production, food processing, metallurgy…

Hydrogen production in 2020 = 73 Million Metric Tons

- **23 % derived from Coal**
- **75 % derived from Natural Gas (Steam methane reforming)**
- **2 % produced by Electrolysis**

Today's Hydrogen- Environmental Impact

The Hydrogen produced today has negative impact on environment

- Results in 830 million metric tons of CO_2 emissions each year.
- Carbon intensity of hydrogen production:
  ~ 12 -20 kg of carbon dioxide per kg of Hydrogen

Brown Hydrogen
Through gasification of coal or lignite

Grey Hydrogen
Through reformation of Natural Gas or fossil fuels.

Blue Hydrogen
Through reformation of Natural Gas utilizing CCS (carbon Capture and Storage)

Green Hydrogen
Through electrolysis using electricity generated from renewable sources

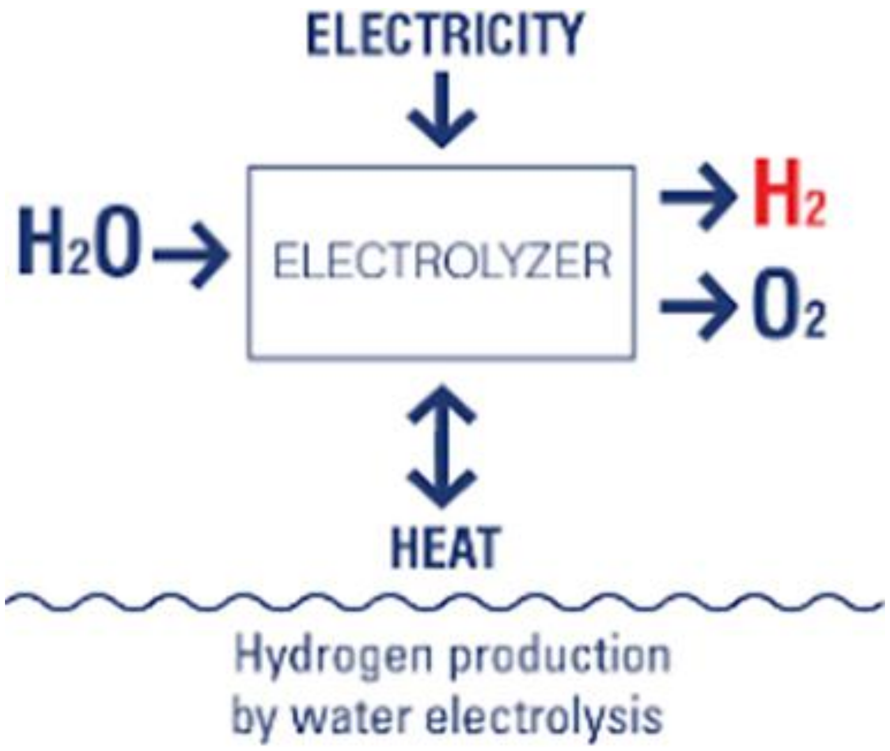
The rapidly declining cost of renewable energy is one reason for the growing interest in green hydrogen.

Green Hydrogen contributes to achieve:

- Energy security
- Reduction of carbon emissions

It also provides provision of storage that helps solving the problem of Intermittency of Renewable Energy

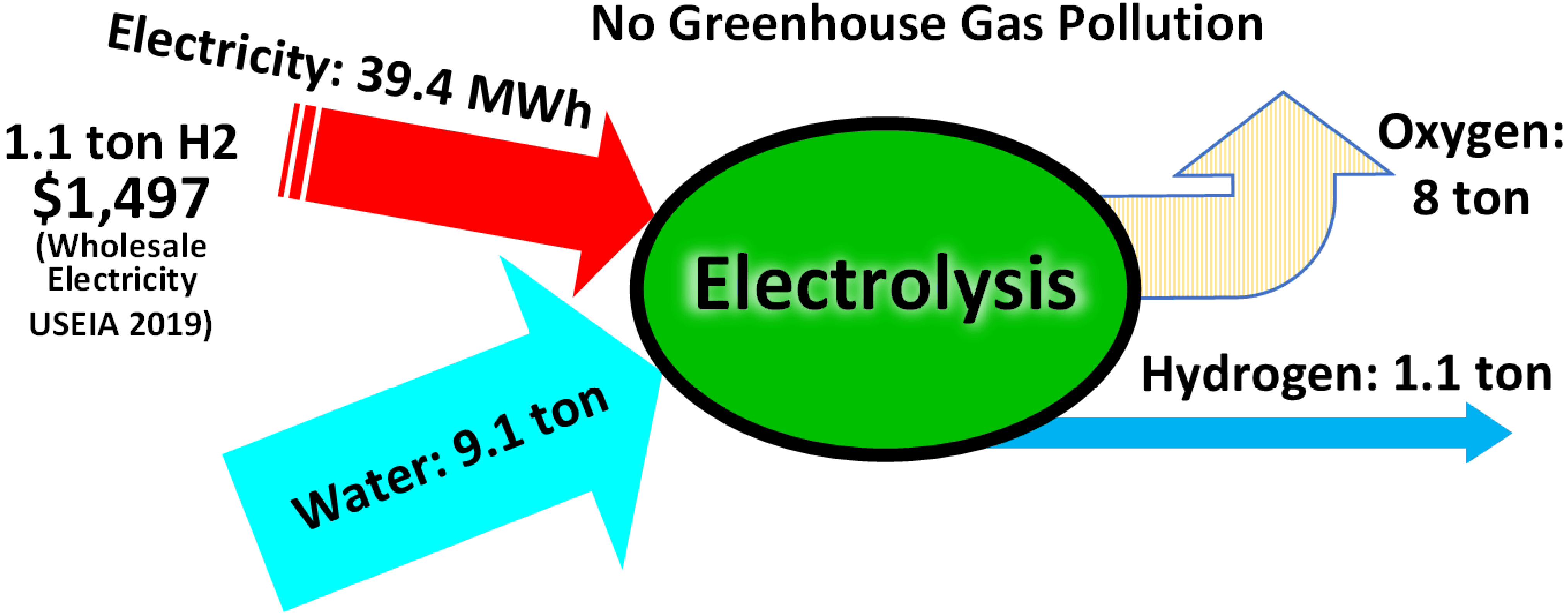
Electrolysis



- Electrolyzers use electricity to break water into hydrogen and oxygen
- Contains an electrolyte that has free ions for carrying electric current.
- Requires Direct Current (DC) supply
- Electrolysis produces very pure hydrogen

- In 1800, Direct Current Electrolysis was discovered by William Nicholson and Anthony Carlisle
- Since the advent of commercial power at the beginning of the 20th century, Electrolysis was the dominant technology for industrial production of hydrogen
- Afterwards because of increasing availability of Natural Gas, more cost effective Steam Reforming replaces electrolysis

Newer Hydrogen Production Method
No Greenhouse Gas Pollution



1 kg of Hydrogen → 36 kWh electricity (HTSE)

1 kg of Hydrogen → 50-65 kWh electricity (LTE) Efficiency= 55 %

Determining Carbon Intensity of Hydrogen

$$\text{Carbon Intensity of Hydrogen production through Electrolysis} = \frac{\text{Carbon intensity of the electricity used for hydrogen}}{\text{Efficiency of the Electrolyzer}}$$

(expressed in its energy content gm CO2/kWh)

1 kg of Hydrogen = 33..33 kWh

Life cycle electricity emissions by electricity source

Technology	Description	gm CO2/ unit electricity
Coal	Without scrubbing	1001
Hydroelectric	Reservoir	4
Natural gas	CC turbines without scrubbing	469
Nuclear	Various reactors (Average)	16
Solar PV	Polycrystalline Silicon	46
Solar Thermal	Parabolic trough	22
Wind	Onshore	12

Electricity to hydrogen efficiency of Electrolyzers

Electrolyzer Technology	Efficiency	Notes
Bi-polar Alkaline	43-69 %	
Bi-polar Alkaline system (High pressure)	~ 78 %	Because of high pressure, electricity requirement is less
Polymer Electrolyte Membrane (PEM)	~ 80 % (Target 82-86 % by 2030)	more advantageous due to ecological cleanness, easy maintenance, compactness.
Solid Oxide	More than 90 %	Operates at 500-600 C. Electricity requirement is less.

Electrolyzer efficiency is critical both technically and economically for electrochemical hydrogen production

Costs of electrolyzer that produces one standard cubic meter of hydrogen in one hour

PEM Electrolyzer	USD 4900 -6000	Low maintenance More suitable for intermittent RE
Alkaline Electrolyzer	USD 3000-4000	High BOS High maintenance
Solid Oxide Electrolyzer	No market ready product still now	Ceramic membranes that conduct ions at very high temperatures separate superheated steam at 600 to 800 degrees Celsius into oxygen and hydrogen.

Power electronics used in large electrolyzers are currently not yet a mass product

Cost of Green Hydrogen keeps falling

Approximate cost of Hydrogen		
Hydrogen without CCS (Grey Hydrogen)	USD 1.8 per kg.	
Hydrogen with CCS (Blue Hydrogen)	USD 2.4 per kg.	
Green hydrogen	USD 4-6 per kg.	Target: USD 2 per kg. (2025) USD 1 per kg. (2030)

Factors that lead to cost reduction of Green Hydrogen

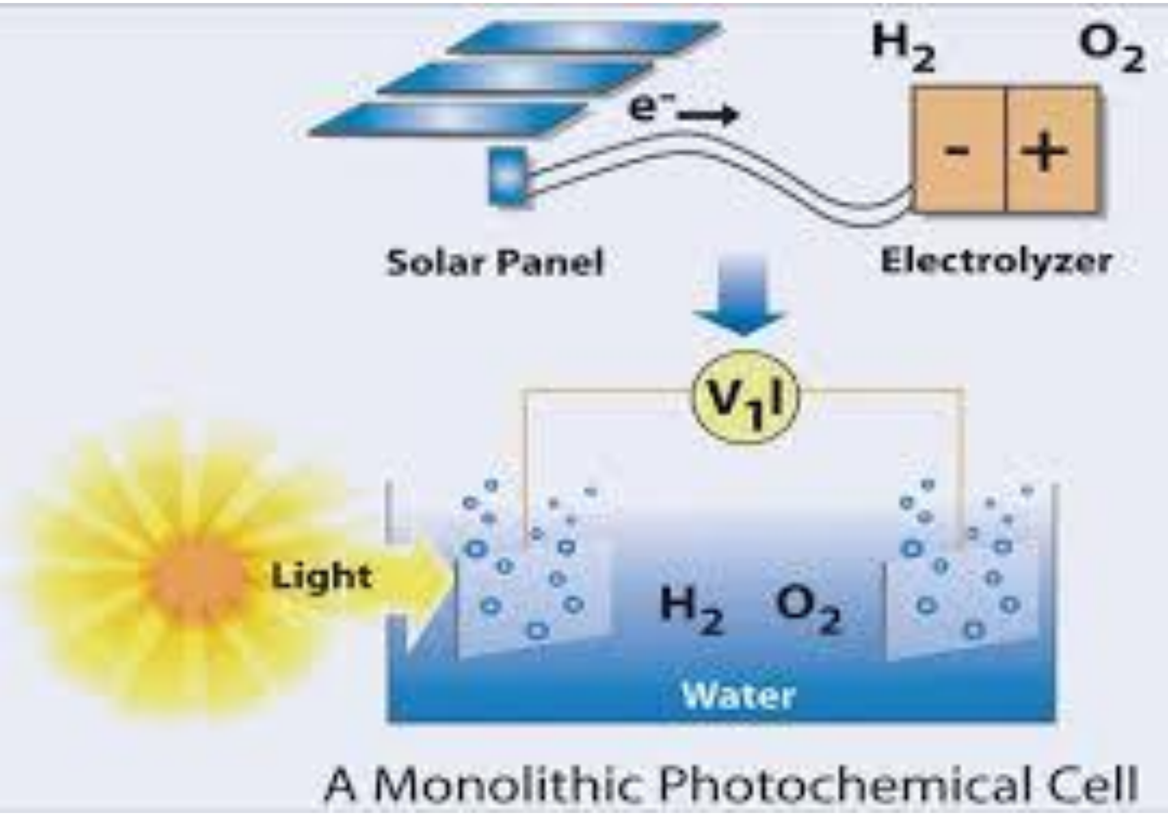
- Access to low cost renewable electricity
- Improved Electrolyzer design leads to more efficient use of materials and better efficiency
- Scaling up to larger capacity plants
- Mass manufacturing of electrolyzers
- Reducing the capital cost of electrolyzers and balance of the system.
- Innovative designs (high-temperature electrolysis systems present a value proposition in reducing electrical energy requirements)
- Increasing Operational life

Photoelectrolysis
Water + Sunlight = $H_2 + O_2$

Indirect photoelectrolysis
Solar cell + Electrolyzer

Direct Photoelectrolysis
Water splitting by photogenerated electrons

Combines a Light Harvesting system and a Water Splitting system in a single monolithic device



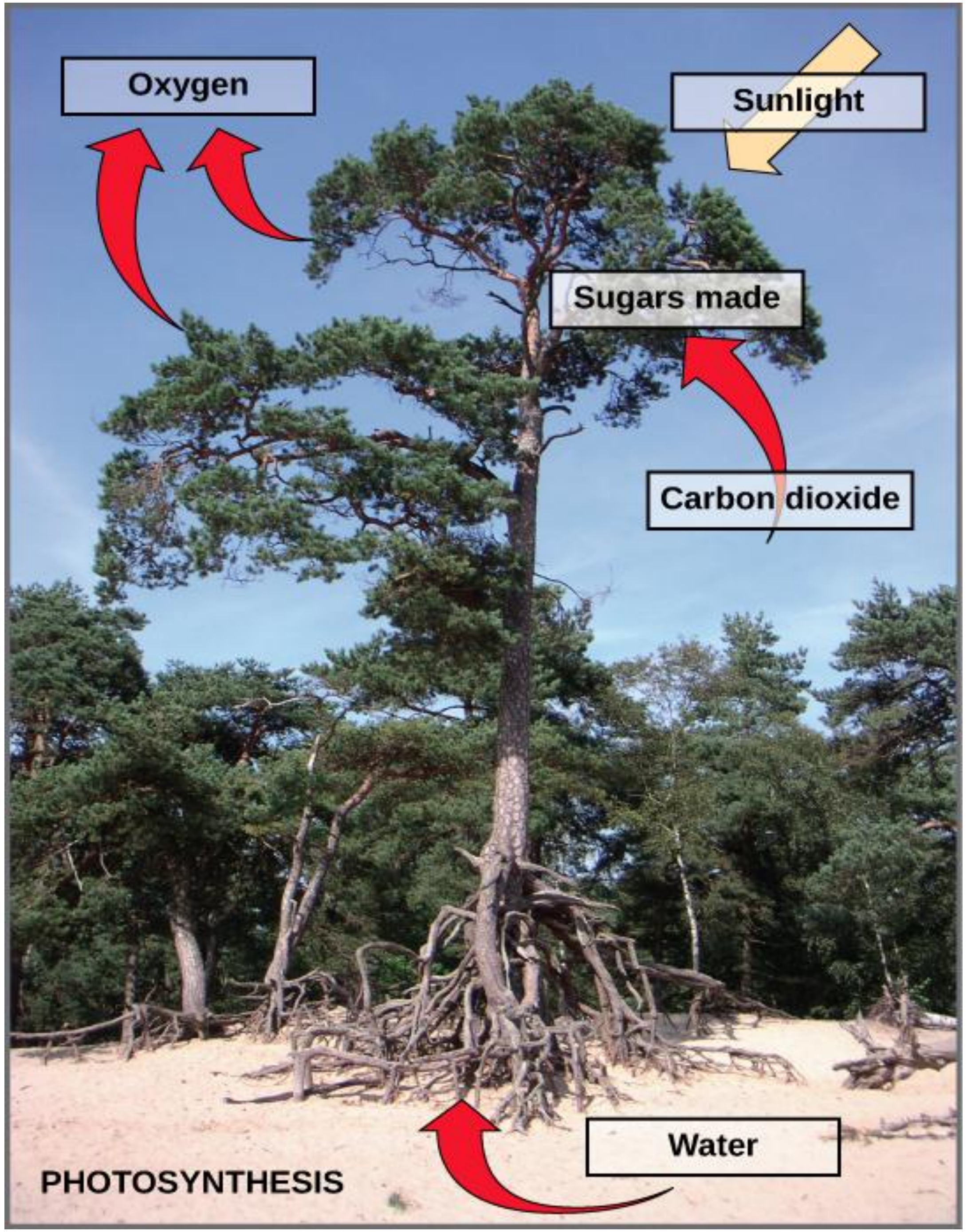
Ref: Sustainable Energy Science and Engineering Centre: Florida University

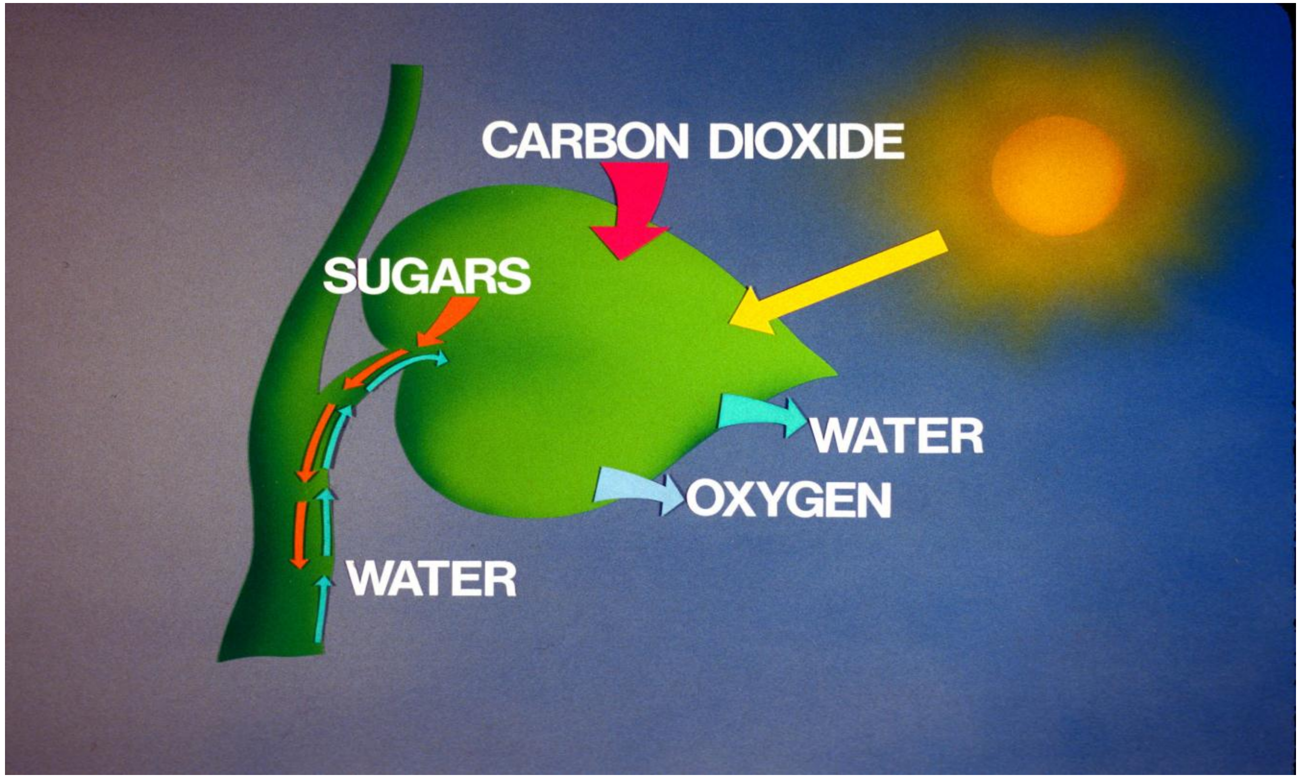
Nature has been doing it for millions of year

In photosynthesis

- solar photons are captured by chlorophylls
- and the exitonic energy is quickly transferred to the Reaction Centres
- ultimately to make Glucose by capturing Carbon Dioxide from the atmosphere and Water from the soil.

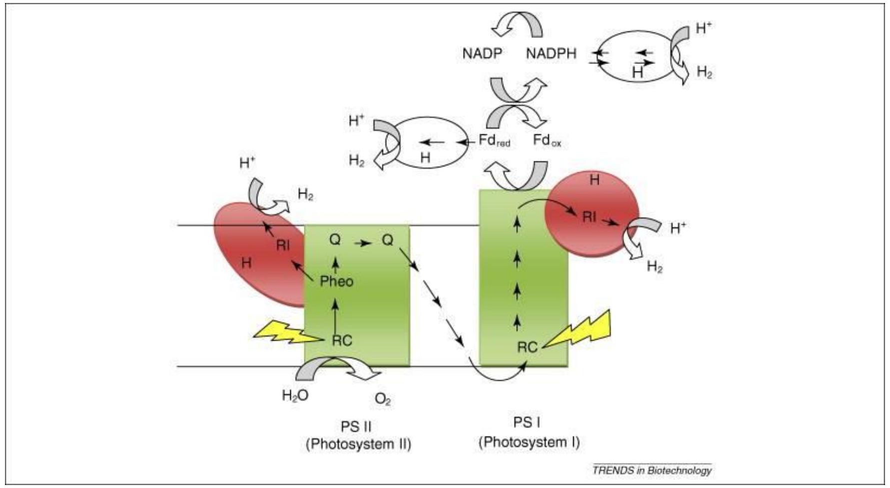
$$6\ CO_2 + 6\ H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$$





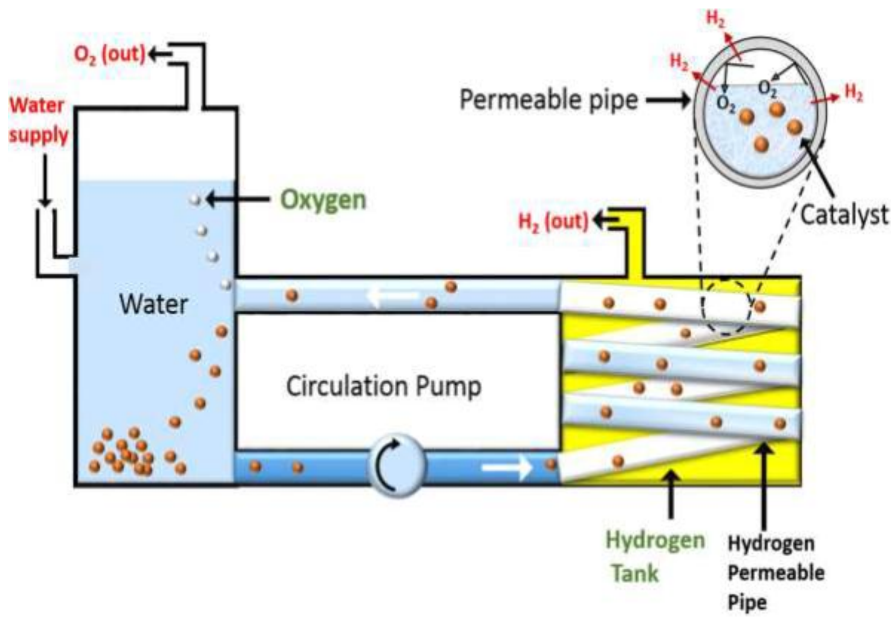
Photosynthesis is a two stage process:

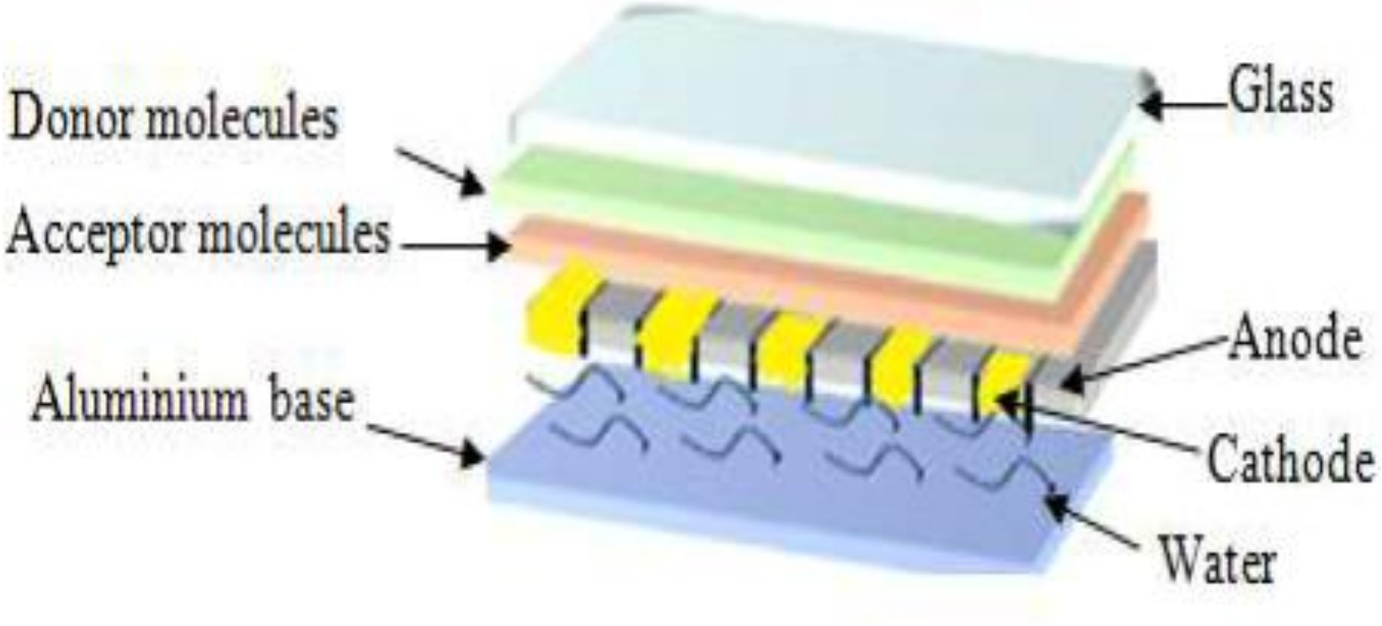
- Photosystem II (PSII) uses the energy of the absorbed photon to split water into Oxygen and Hydrogen ions (electrons/protons from water)
- Photosystem I (PSI) uses photons to provide additional energy to the 'PSII-energized' electrons/protons so as to drive the CO2-fixation process.



Proposed Structure of the solar cell for water splitting

- Donor and acceptor materials to interact with sunlight and release sufficient electrons at both short and long Wavelength
- The electrons interact with the two photocatalysts
- The anode photocatalyst, interacts with water and splits it into protons and oxygen gas.
- The cathode photocatalyst interacts with protons to evolve hydrogen gas

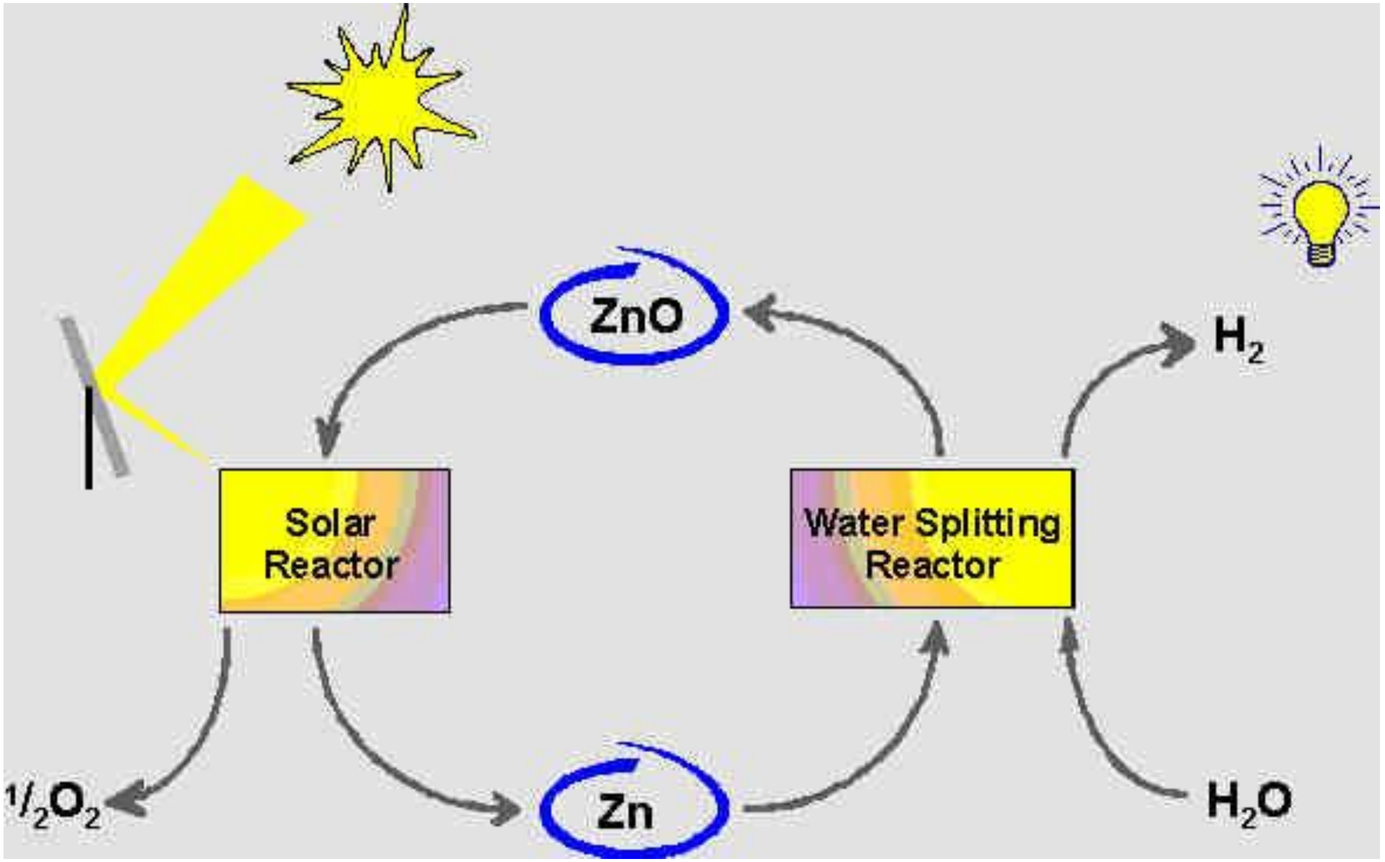




Reference: Artificial Photosynthesis for Production of Hydrogen Gas for Fuel: Research Gate 2020 (Given Kalonga etal.)

Solar Thermal Hydrogen Production

A set of heliostats collect the solar thermal energy. The temperature level is realized by using a solar power tower



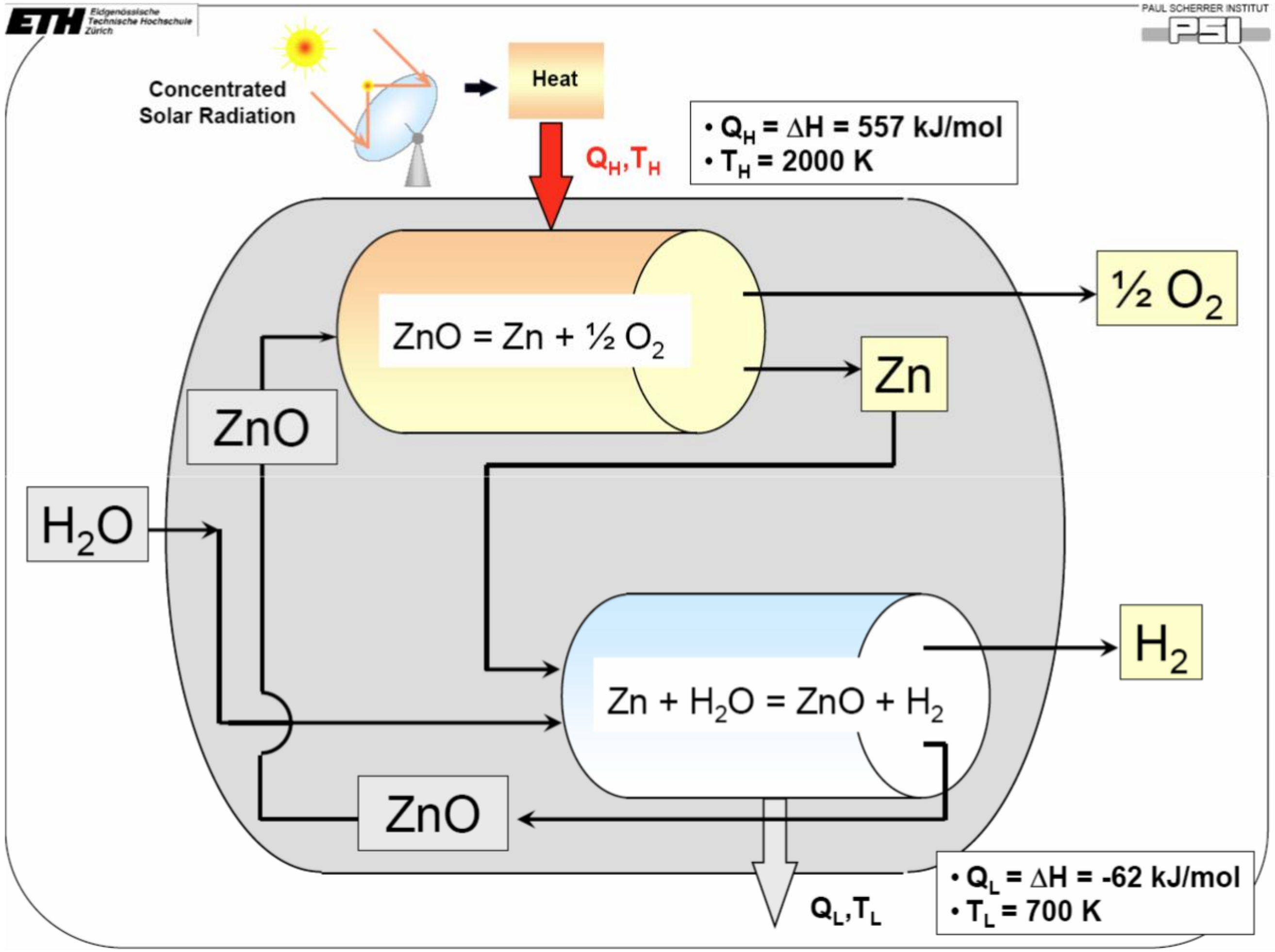
Ref: Swiss Federal Office of Energy: Aldo Steinfeld et al.

ZnO serves the functions of radiant absorber, thermal insulator, and chemical reactant.

The thermochemical two-step water splitting process uses redox systems:

- Dissociation: $ZnO \rightarrow Zn + 1/2\ O_2$
- Hydrolysis: $Zn + H_2O \rightarrow ZnO + H_2$

For the first endothermic step concentrating solar power is used in which zinc oxide is thermally dissociated at 1,900 °C (3,450 °F) into zinc and oxygen.
In the second non-solar exothermic step zinc reacts at 427 °C (801 °F) with water and produces hydrogen and zinc oxide.


Eidgenössische Technische Hochschule Zürich
PAUL SCHERRER INSTITUT
Concentrated Solar Radiation
Heat
Q_H, T_H
• $Q_H = \Delta H$ = 557 kJ/mol
• T_H = 2000 K
$ZnO = Zn + ½ O_2$
½ O_2
Zn
ZnO
H_2O
$Zn + H_2O = ZnO + H_2$
H_2
ZnO
Q_L, T_L
• $Q_L = \Delta H$ = -62 kJ/mol
• T_L = 700 K

The Reactor

Thank you for your attention