Hydrogen Pathways Course

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Hydrogen Production
Lecture 2

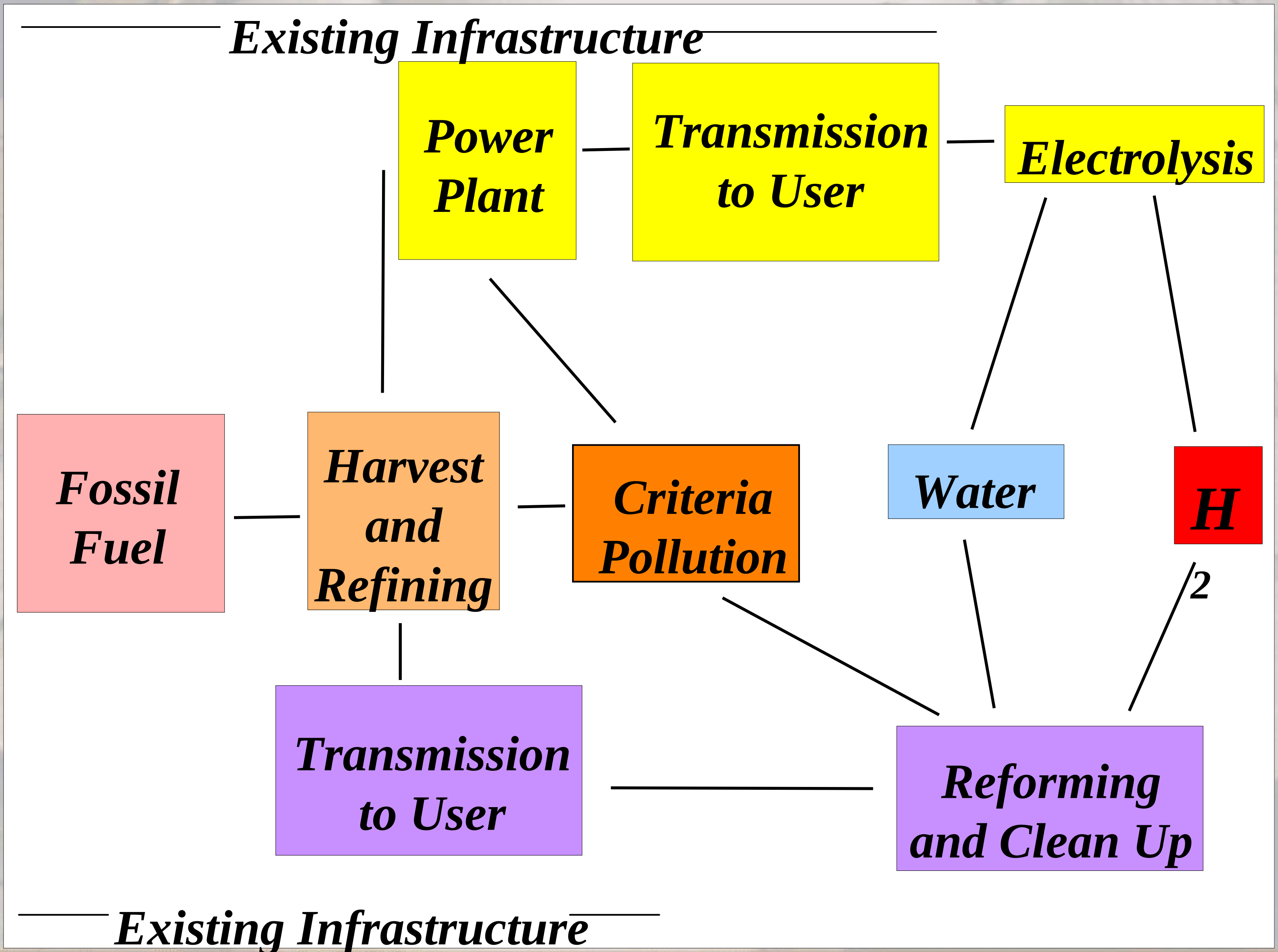
Todays Lecture

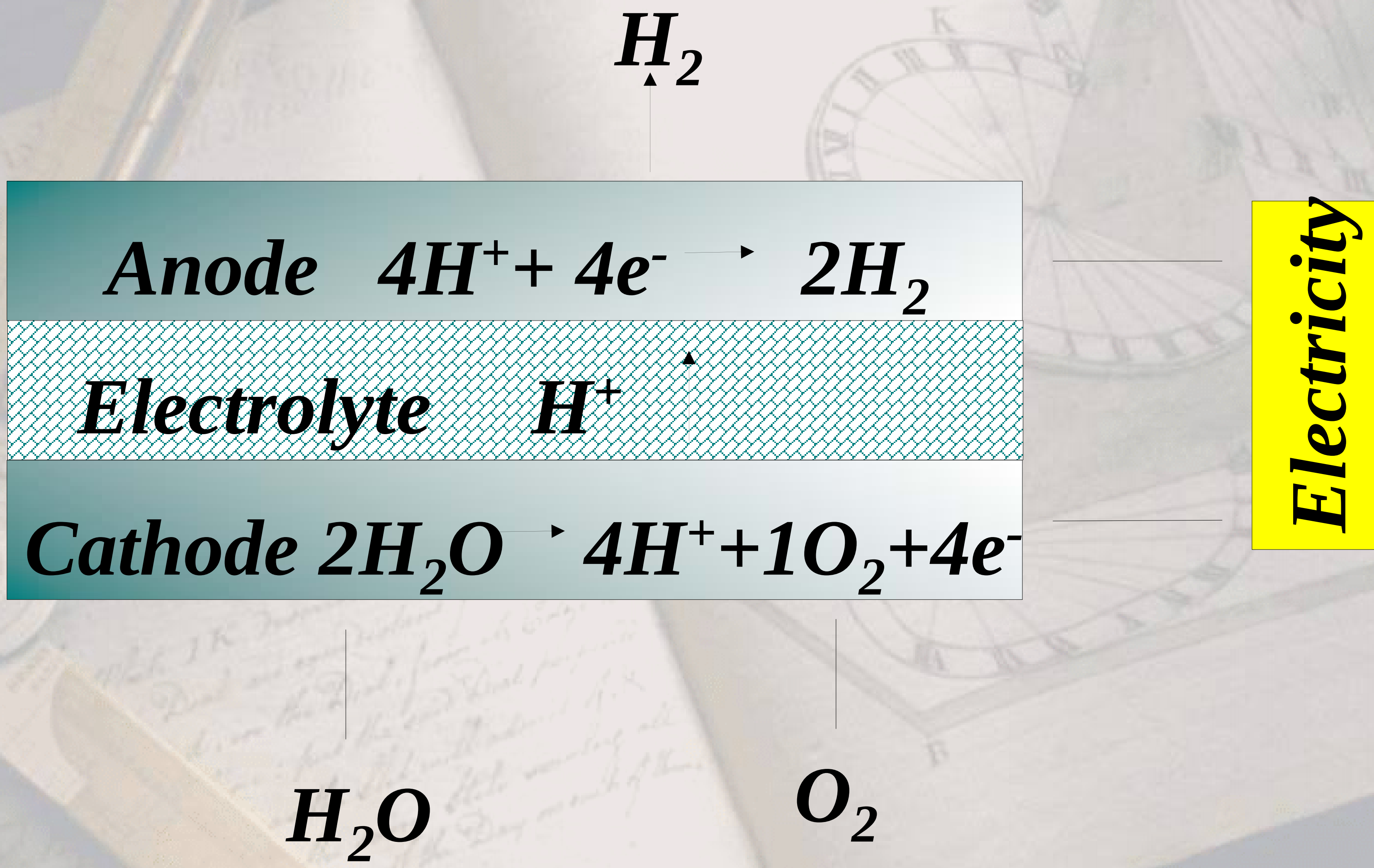
Hydrogen Production

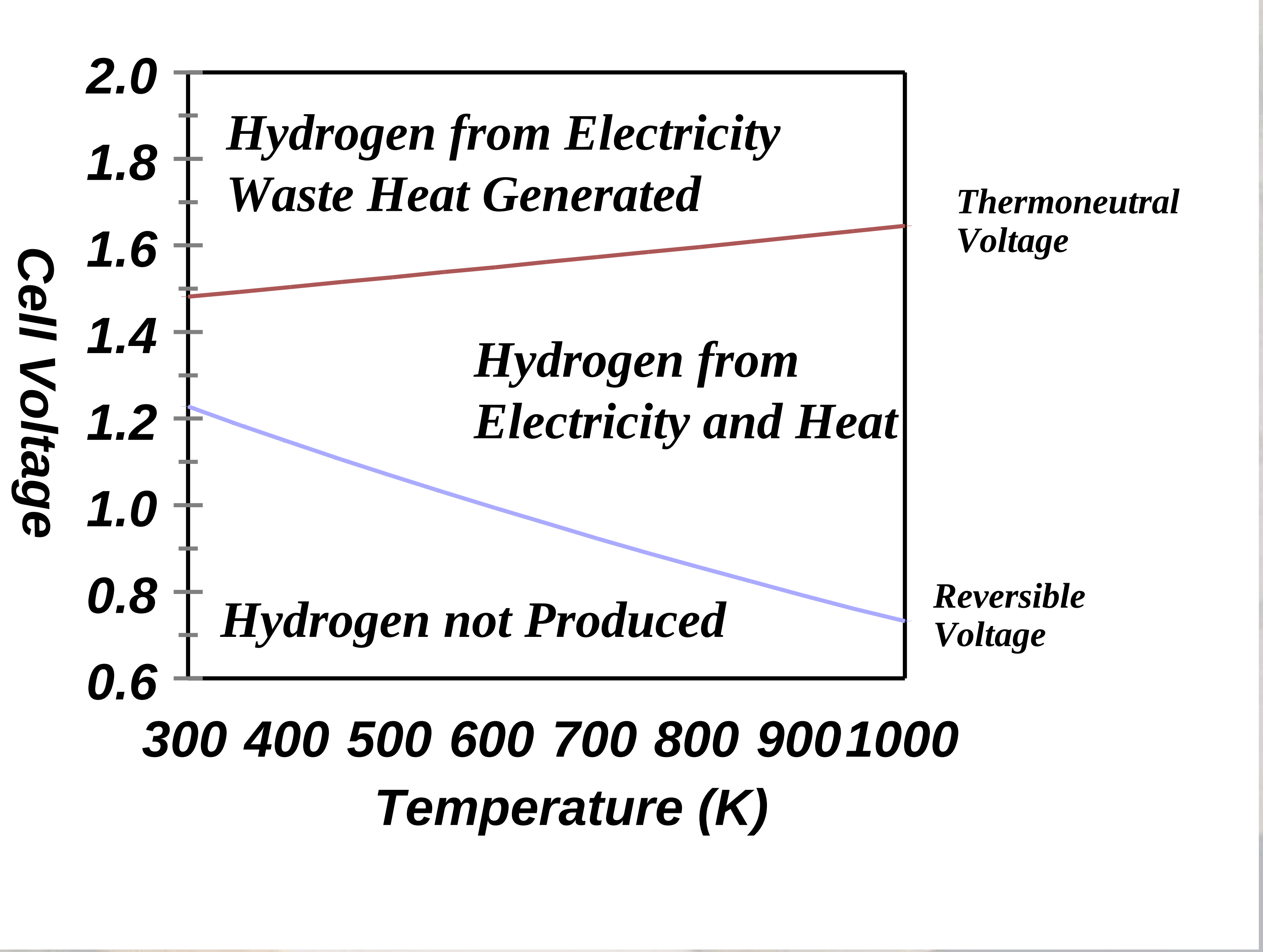
$Direct Methods of Solar to Hydrogen Production via Water-splitting

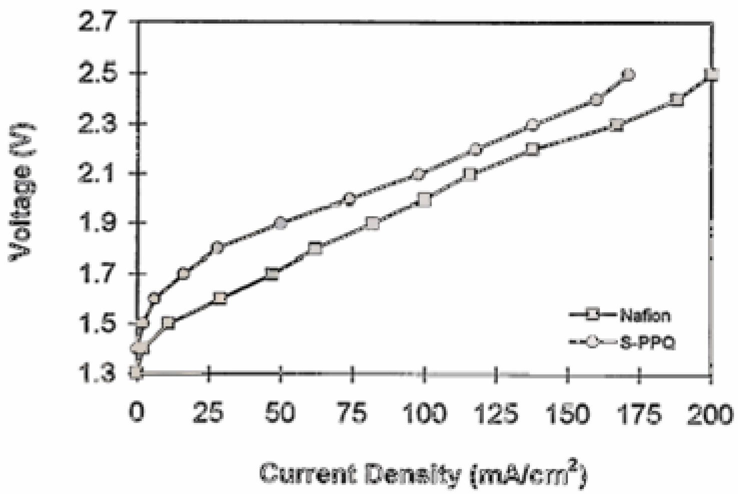
- ②Photoelectrical
- ②Photochemical
- ②Thermochemical
- ②Thermal decomposition

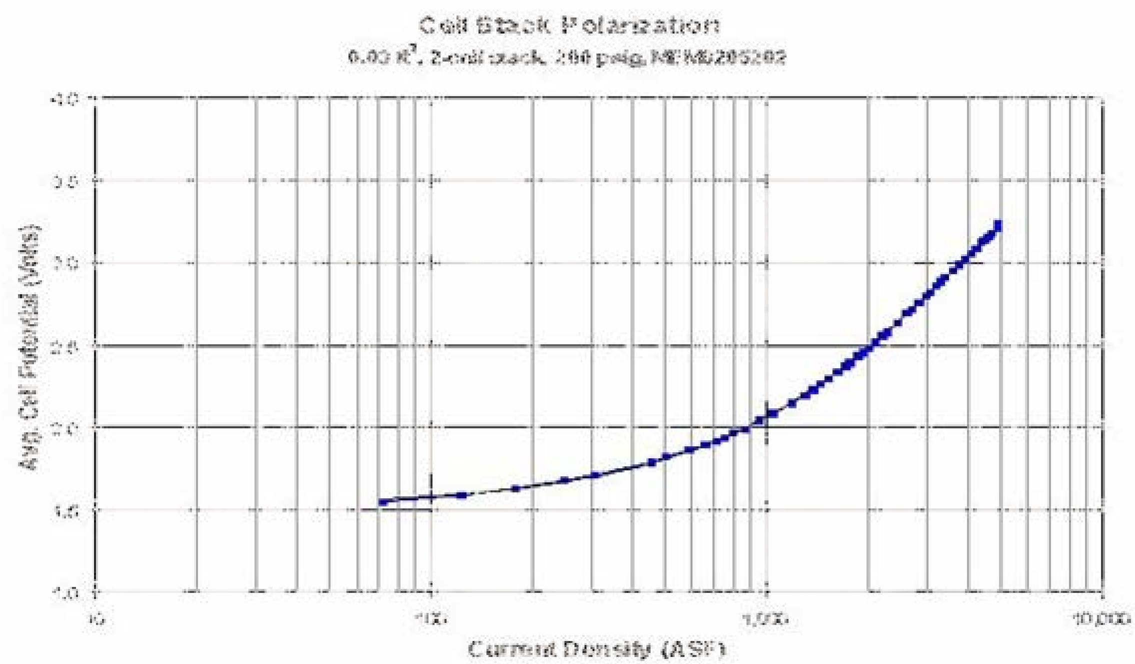
Current Production of Hydrogen



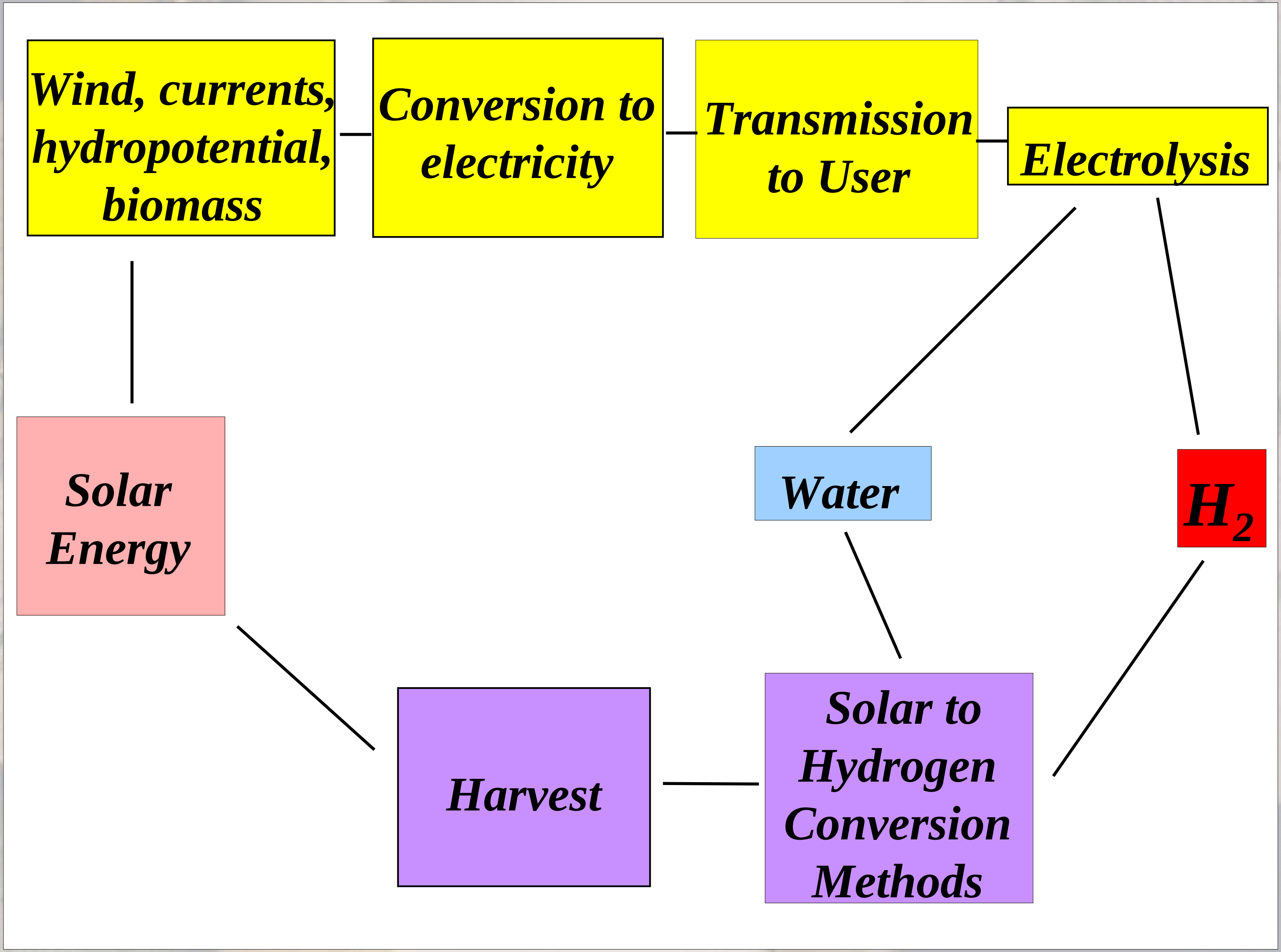

H_2
Anode $4H^+ + 4e^- \rightarrow 2H_2$
Electrolyte H^+
Cathode $2H_2O \rightarrow 4H^+ + 1O_2 + 4e^-$
Electricity
H_2O
O_2


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Cell Voltage
Hydrogen from Electricity
Waste Heat Generated
Thermoneutral Voltage
Hydrogen from Electricity and Heat
Reversible Voltage
Hydrogen not Produced
300 400 500 600 700 800 900 1000
Temperature (K)


Voltage (V)
2.7
2.5
2.3
2.1
1.9
1.7
1.5
1.3
0
25
50
75
100
125
150
175
200
Current Density (mA/cm²)
Nafion
S-PPQ


Cell Stack Polarization
Avg. Cell Potential (Volts)
10
100
1,000
10,000
Current Density (ASF)

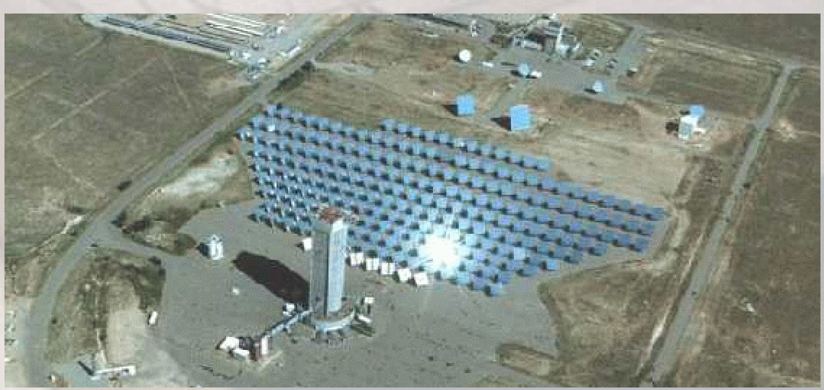
Renewable Hydrogen Production



Methods of Hydrogen Production with Solar Energy Conversion

- **Photoconversion**
  - Photovoltaics with Electrolysis
  - Photoelectrochemical
  - Biological
- **Thermal Conversion**
  - Solar Heat Engines with Electrolysis
  - Thermal Decomposition
  - Thermochemical Cycles
- **Hybrid cycles**

Schatz Energy Center



Sandia National Lab

Photovoltaics with Electrolysis

Sunlight-Photovoltaics-Electrolysis-H_2

- $Conceptually elegant (low voltage DC)
- $Demonstrated and commercial

- $Low conversion efficiency due to photovoltaic conversion
  - ②Multijunction PV can boost efficiency
- $Cost

Schatz Hydrogen Generating Station

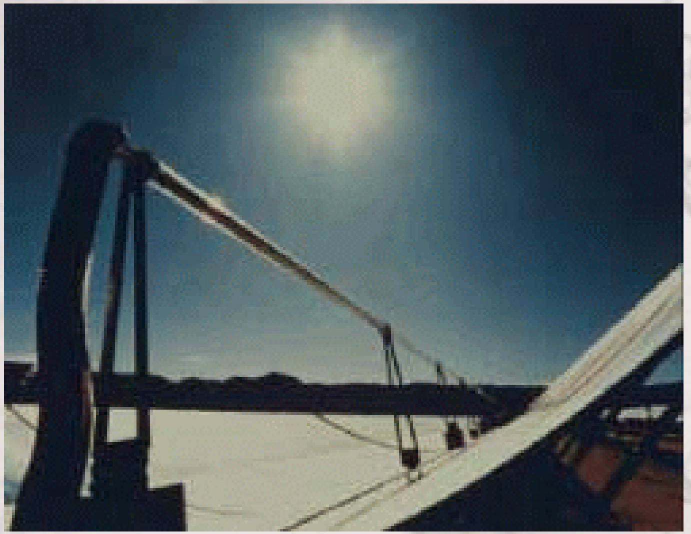
Solar Heat Engines with Electrolysis

Sunlight-Concentrator-Heat Engine-Generator-Electrolysis-H_2

- $*Can use well known cycles such as Rankine, Brayton, or Stirling*
- $*High conversion efficiency*
- $*Requires high concentration ratios for high temperatures (Carnot limited thermal cycles)*
- $*Additional conversion step (kinetic to electrical)*
- $*Intermittent nature of sunlight can complicate heat engine (numerous start-ups and shutdowns)*

Solar Heat Power Systems for Hydrogen Production

Parabolic Concentrator SEGS Power plants



Dish Stirling

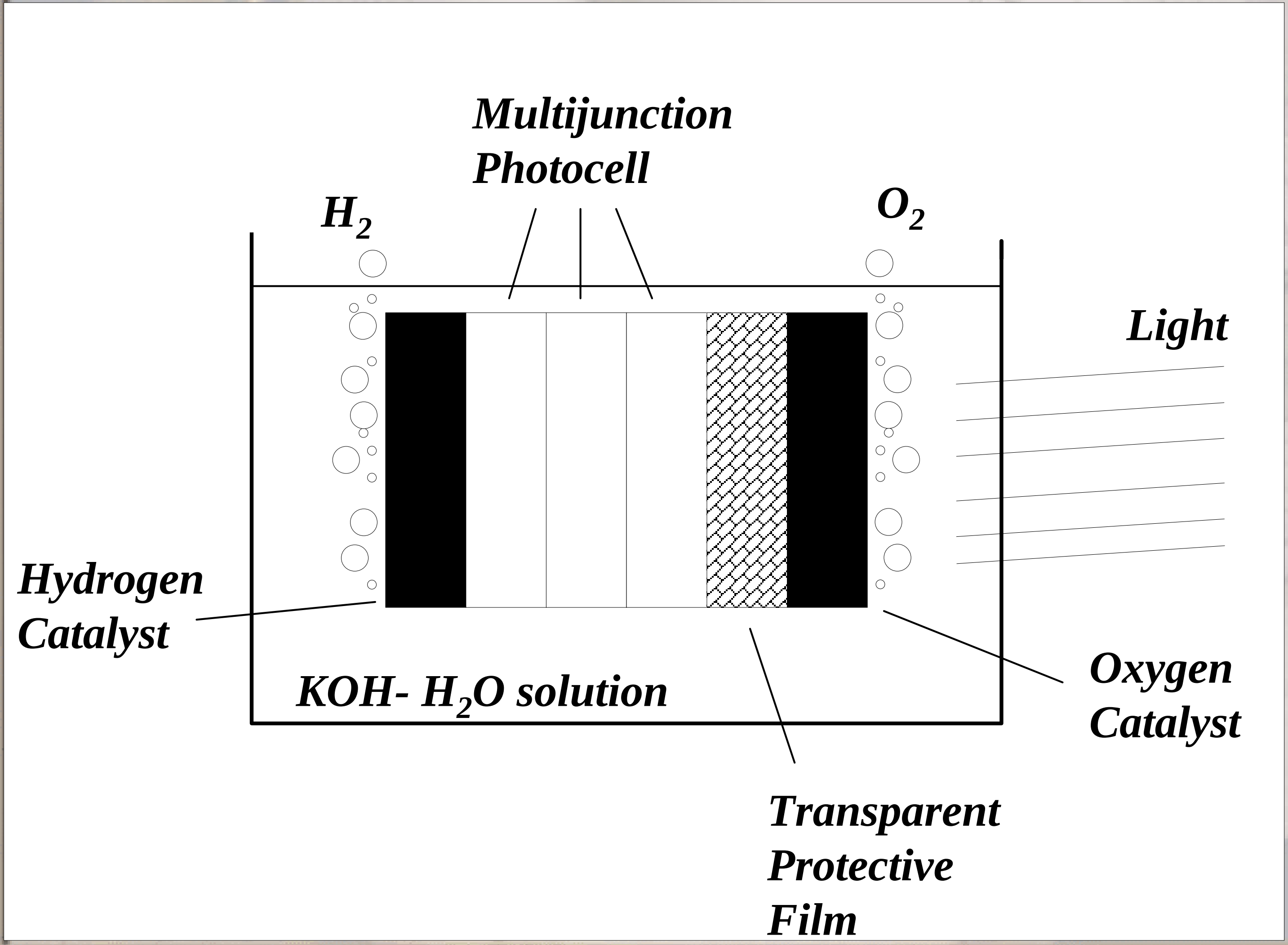
Heliostats Power Tower Solar 1

Hydrogen generating system by Proton Energy Systems

Photoelectrochemical

Sunlight-Photoelectrochemical Cell-H_2

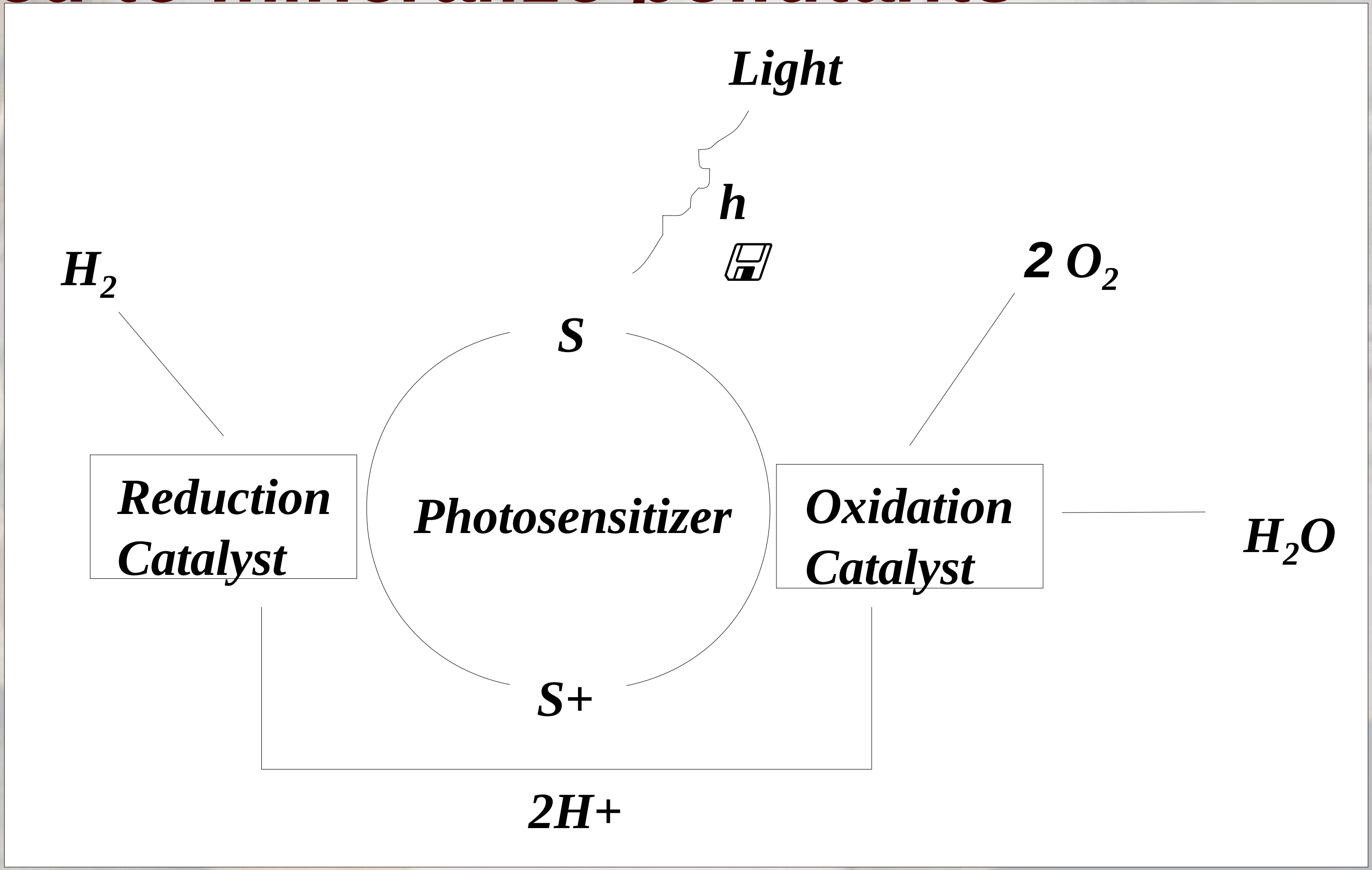
- Miniaturization and marriage of PV-



Photochemical

Sunlight-Chemical Solution-H_2/O_2-Separator-H_2

$Photochemical systems can also be used to mineralize pollutants



Thermal Decomposition

Sunlight-Concentrator-High Temperature Reactor-Separator-H_2

- $Separation of High Temperature Mixture
- $Reactor Materials

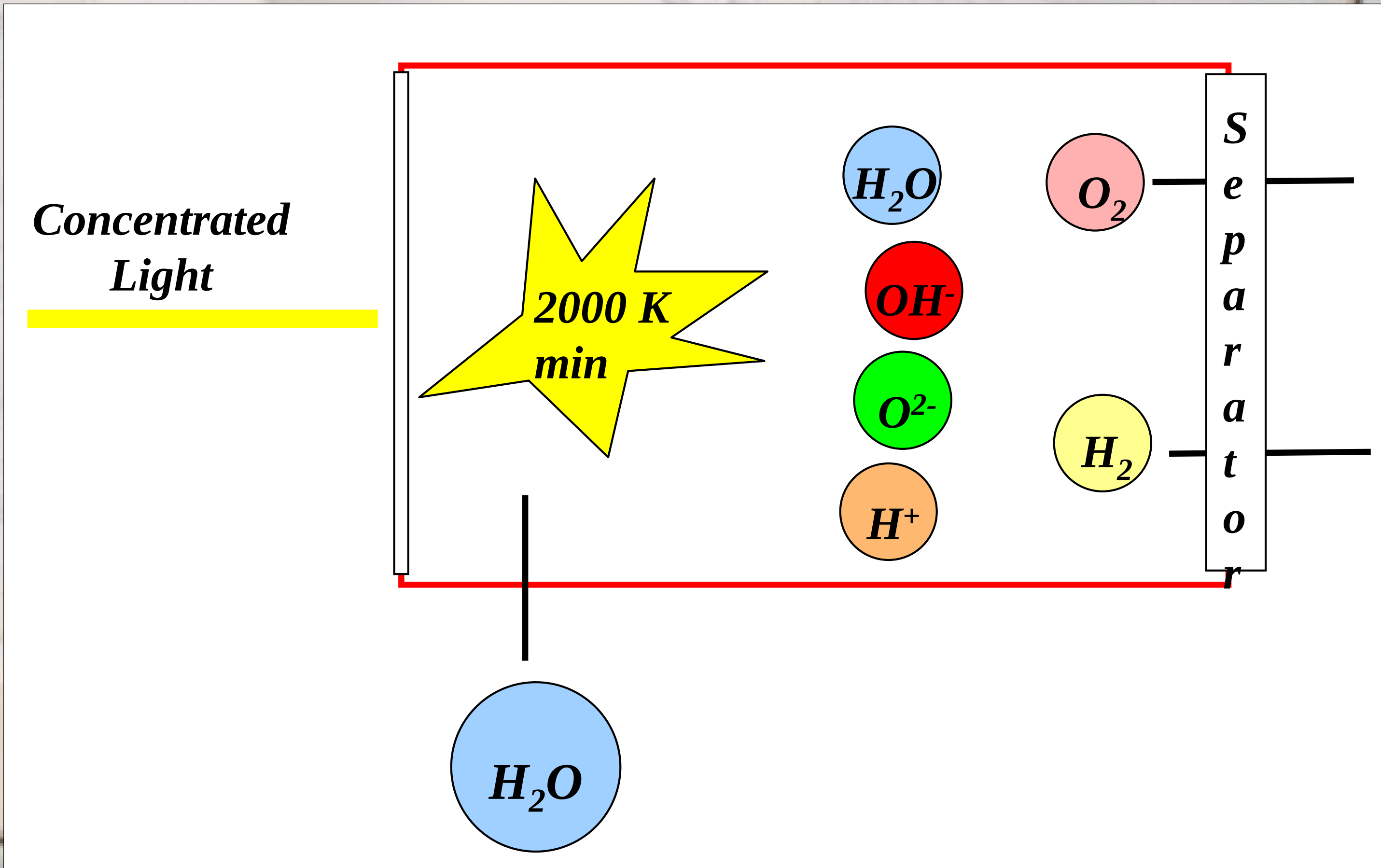


Table 2 Equilibrium Mole Fractions of a Water Mixture at Different Pressures and Temperatures

Temperature	2000 K		
Pressure	1 atm	0.1 atm	0.02 atm
H	0.0001	0.0006	0.0016
H_2	0.0058	0.0124	0.0209
H_2O	0.9896	0.9773	0.9607
O	0.0000	0.0002	0.0004
OH	0.0021	0.0042	0.0075
O_2	0.0024	0.0052	0.0088
Temperature	2500 K		
Pressure	1 atm	0.1 atm	0.02 atm
H	0.0052	0.0230	0.0627
H_2	0.0428	0.0843	0.1259
H_2O	0.9110	0.8059	0.6685
O	0.0018	0.0081	0.0226
OH	0.0233	0.0464	0.0705
O_2	0.0160	0.0322	0.0497
Temperature	3000 K		
Pressure	1 atm	0.1 atm	0.02 atm
H	0.0578	0.2114	0.4153
H_2	0.1352	0.1811	0.1398
H_2O	0.6440	0.3239	0.1021
O	0.0244	0.0914	0.1866
OH	0.0914	0.1260	0.1010
O_2	0.0470	0.0062	0.0552

General Thermochemical Cyclical Process

AB + H_2O ✂ Heat ⌛ AH_2 + BO Water Consumption

2BO ✂ Heat ⌛ O_2 + 2B Oxygen Production

AH_2 ✂ Heat ⌛ A + H_2 Hydrogen Production

A + B ✂ Heat ⌛ AB Material Regeneration

3000+ cycles

Materials

Build-up or depletion of intermediate compounds

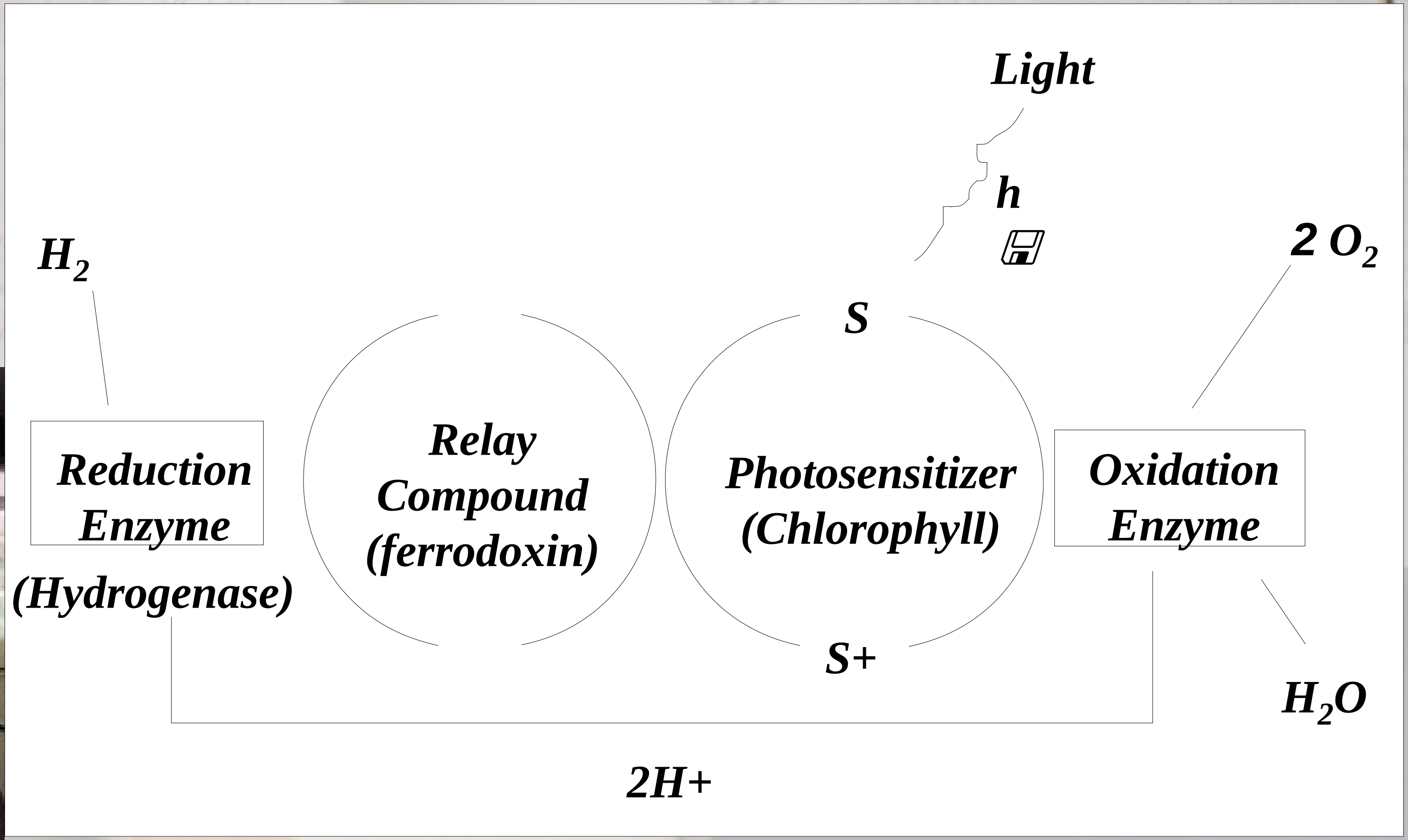
Toxicity of intermediate compounds

Biological Methods

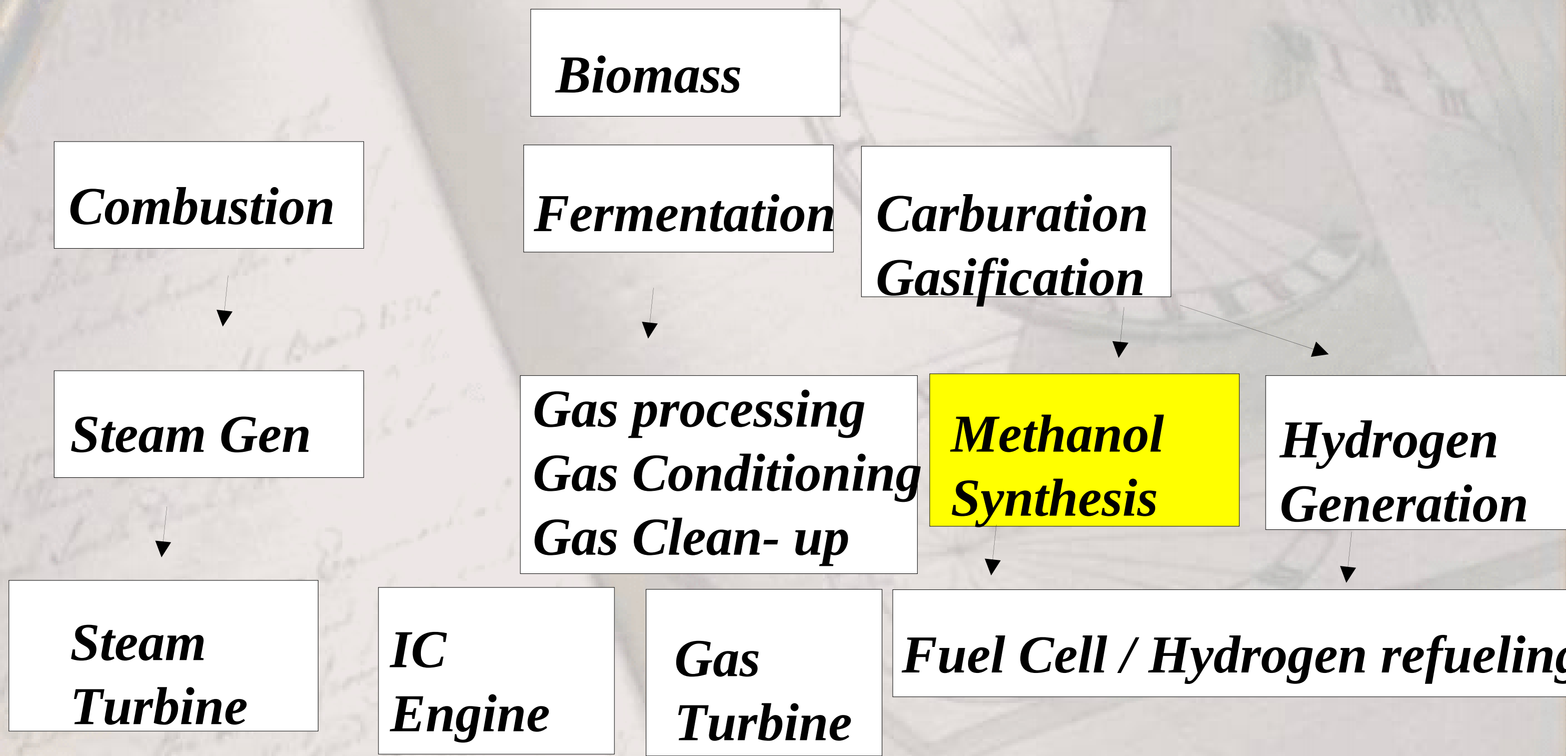
Sunlight-Bioreactor-Separator-H_2

\$Saturation at about 0.3 suns

\$Oxygen sensitivity



Energy Production Via Biomass Sources



Biogas Pathway

Fuel cell	Step	Method
	Biogas 60% Methane 37% CO2 1-2% Hydrogen	
	Removal of Sulphur	Absorbtion on Fe-O or Zn-O Absorbtion on Activated Carbon
	Removal of Halogens	Absorbtion on Activated Carbon
	Removal of Siloxanes	Cooling to -2C Absorbtion on Activated Carbon
	Removal of Moisture	Drier
SOFC or MCFC	Removal of Solids	60% Methane 37% Carbon Dioxide
	Convert Biogas to CO and H2	Steam-Reforming Partial Ox Autothermal Reforming
PAFC	CO Conversion	Water-gas Shift
PEMFC	Low Level CO removal	PSA PROX Membrane Purification

Efficiencies and Estimated Costs

Method	Theoretical Efficiency	Achieved Efficiency	Estimated Cost	DOE goal
PV electrolysis	27.8%	13% Calculated for Multi-junction PV	41$/GJ	9-14 $/GJ
Solar heat engine and electrolysis	36%	18.8% Calculated for Dish Stirling	46 $/GJ projected Power Tower	
Photoelectro-chemical	31% Single Photosystem	12.4% Concentrated light	24 $/GJ projected	
Thermal Decomposition	40%	2.1%	??	
Biological	31%	11% Transient only	??	
Thermochemical cycles	~40%	18% From Heat only	??	
Fossil Based Hydrogen Production	N/A	N/A	10$/GJ	6-8 $/GJ