National Renewable Energy Laboratory
Innovation for Our Energy Future

Hydrogen production: Overview

Hydrogen Technical Advisory Committee

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The Sustainable Hydrogen Economy

The production of hydrogen, primarily from water, its distribution and utilization as an **energy carrier and feedstock.**

Note: The energy generation and the feedstock must be sustainable

Energy Generation

- Biomass
- Nuclear
- Geothermal
- Sustainable e^-
  - Solar
  - Wind
  - Hydro
  - Other

Production

- Electrolysis
- Thermolysis
- Conversion

Feedstock

- Water
- Biomass

Distribution

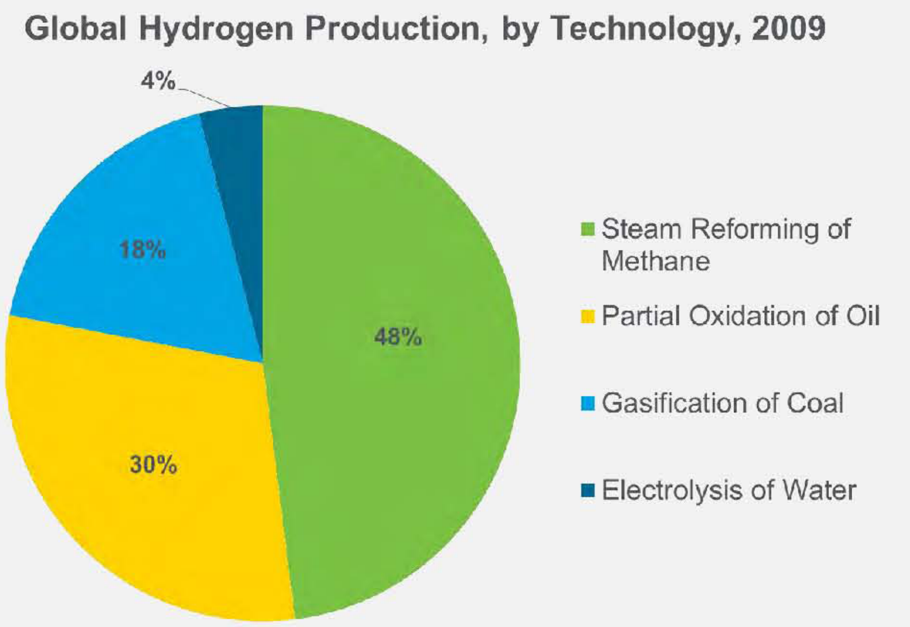
- Used onsite
- Pipelines
- Compressed gas
- Liquid

Utilization

- Fuel cells
- Turbines
- IC Engines
- Synthesis

Transportation fuel Ammonia and Energy Storage.

Hydrogen Production & Applications

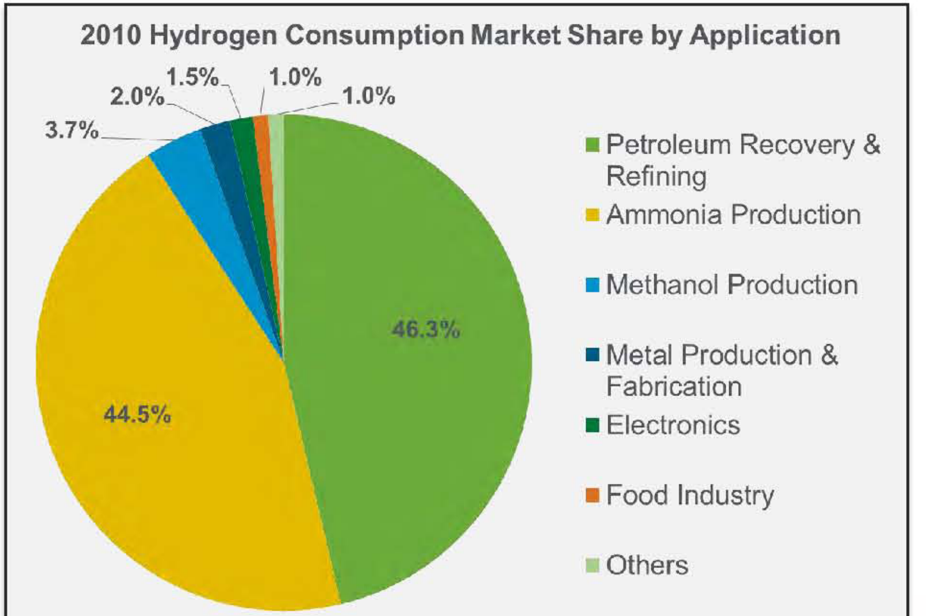


Hydrogen is produced through a variety of technologies, though ~95% of U.S. hydrogen production comes from SMR.

Hydrogen is used in a broad range of applications including electronics and metal production and fabrication in addition to its traditional role in refinery operations and ammonia production.

Major merchant suppliers

- Air Products and Chemicals, Inc.
- Airgas, Inc.
- Air Liquide
- BOC India Limited
- Linde AG
- Praxair Inc.
- Taiyo Nippon Sanso Corp.



The US Energy Carrier Challenge: Hydrogen

For Light Duty Vehicles = 61 million tonnes per year

- 250 M vehicles, 12,200 miles/year, 50 mi/kg

For 1TW-hr of Energy Storage = 61 million tonnes/year

- 50% fuel cell conversion efficiency

For Air Travel = 27 million tonnes/year

- 1:1 energy correspondence

For Ammonia = 23 million tons/year (Global)

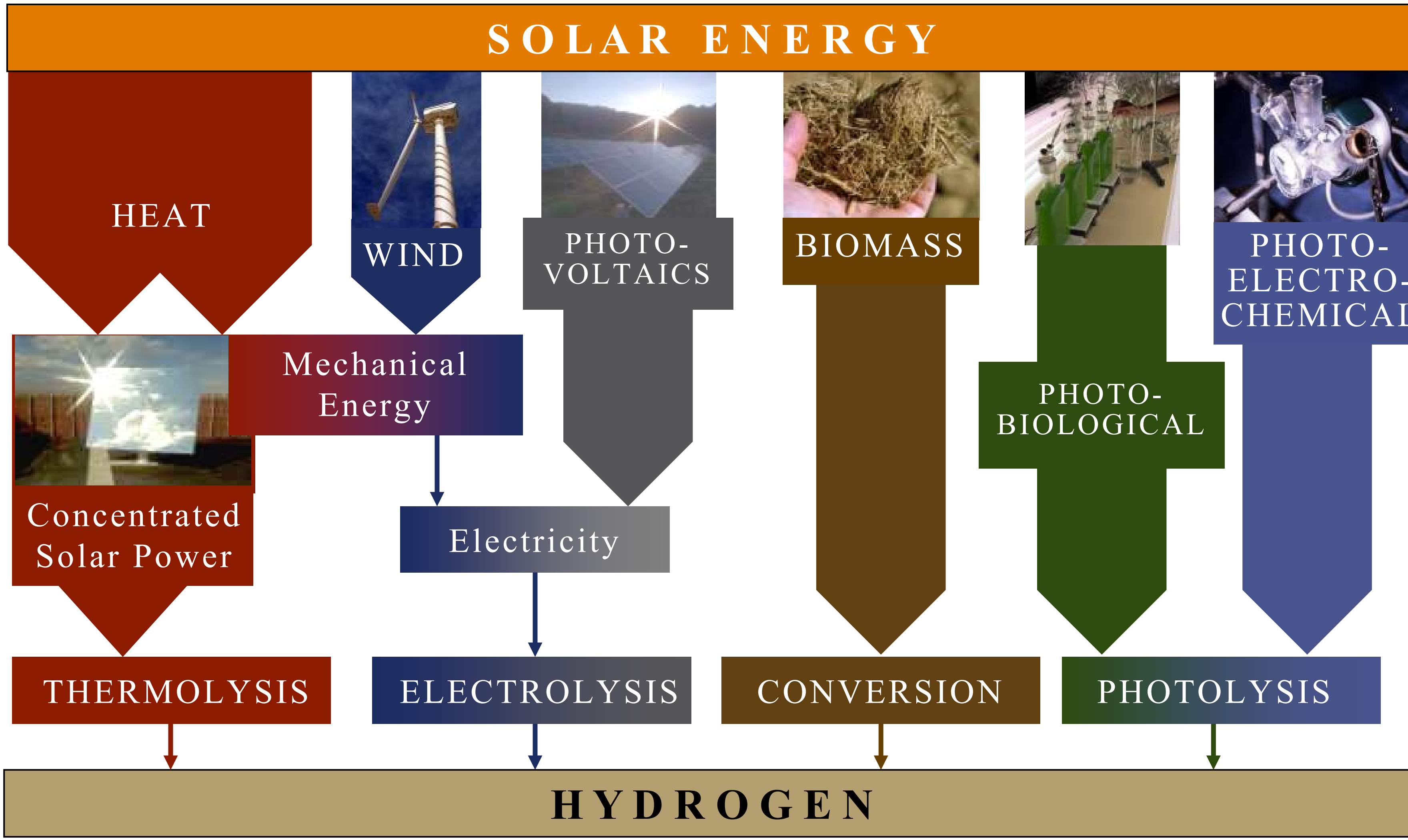
Hydrogen Consumption for Fuels Production

Hydrogen derived from steam methane reforming (SMR)

Standard Refinery Operations	Hydrogen Consumption (kg/BBL)
Hydrotreating (Naphtha to Heavy Oils)[1]	0.12 – 2.9
Hydrocracking (Distillates)[1]	2.4 – 6.0
Renewable Fuel Production	**Hydrogen Consumption (kg/BBL)**
Conversion of fatty acids to diesel[2]	4.3 – 7.2
Catalytic Conversion of Sugars to Gasoline [3] (based on Virent process)	10.1 – 16.8
Upgrading Pyrolysis Oil (Wood, Corn Stover)[2,4,5]	13.2- 15.6

1. Venderbosch et. Al., J. Chem. Technol. Biotechnol. 2010; 85: 674–686.
2. Marker, T., Opportunities for Biorenewables in Oil Refineries, 2005; DOE report # DE-FG36-05GO15085.
3. Blommel, P. G. et. al., Virent Technology Whitepaper, 2008; http://www.virent.com/.
4. Jones, S.B. et. al., 2009; PNNL Report # PNNL-18481.
5. White, M. et. al. Fuels (in press)

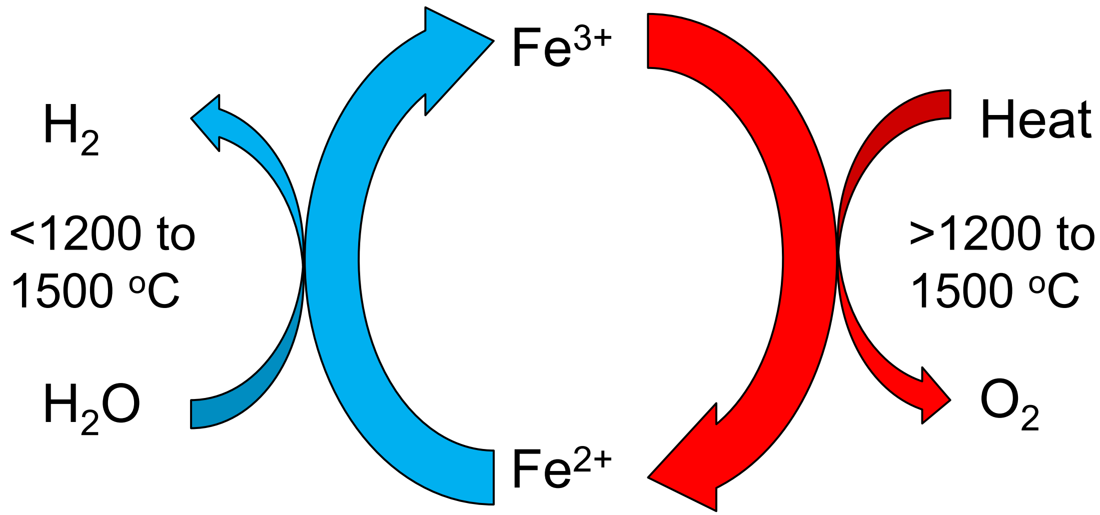
Sustainable Paths to Hydrogen (Sunlight and Water)



The price of the delivered hydrogen will determine the pathway(s) used

Solar-thermal Water-splitting Ferrite Cycles

$M_xFe_{3-x}O_4$: M=Co, Ni



Challenges

- Sintering/Deactivation/Robustness
- Diffusion rate limitations
- Heat transfer through mass
- Cycle times
- Material movement

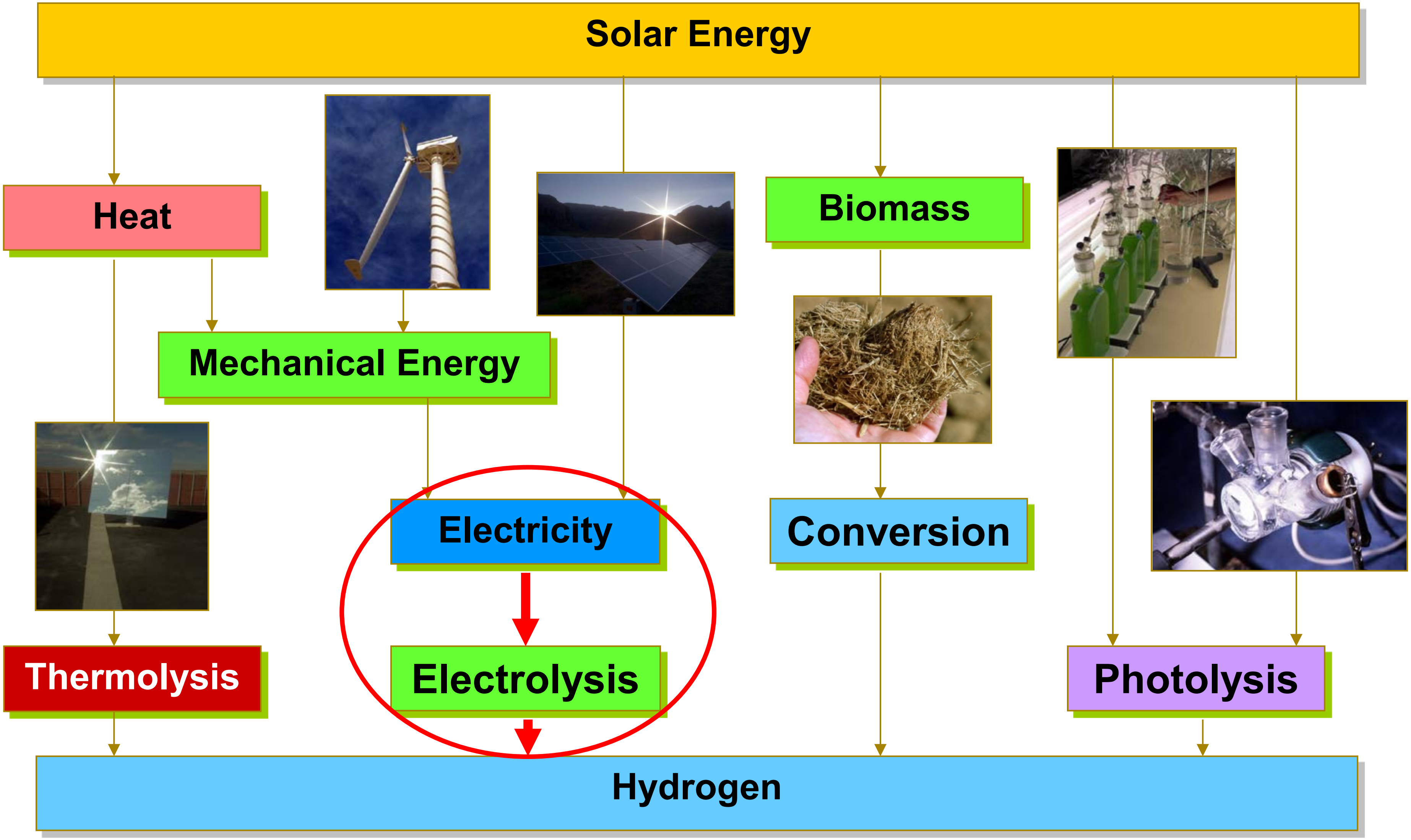
Solar-thermal Water Splitting Vision

Christopher L. Muhich, Brian W. Evanko, Kayla C. Weston, Paul Lichty, Xinhua Liang, Janna Martinek, Charles B. Musgrave, Alan W. Weimer, *"Efficient Generation of H_2 by Splitting Water with an Isothermal Redox Cycle"*, Science, Vol 341, p 540, Aug 2, 2013

Central Production (100,000 kg H_2/day)

Image source http://inhabitat.com/energy-breakthrough-storing-solar-power-with-salt/

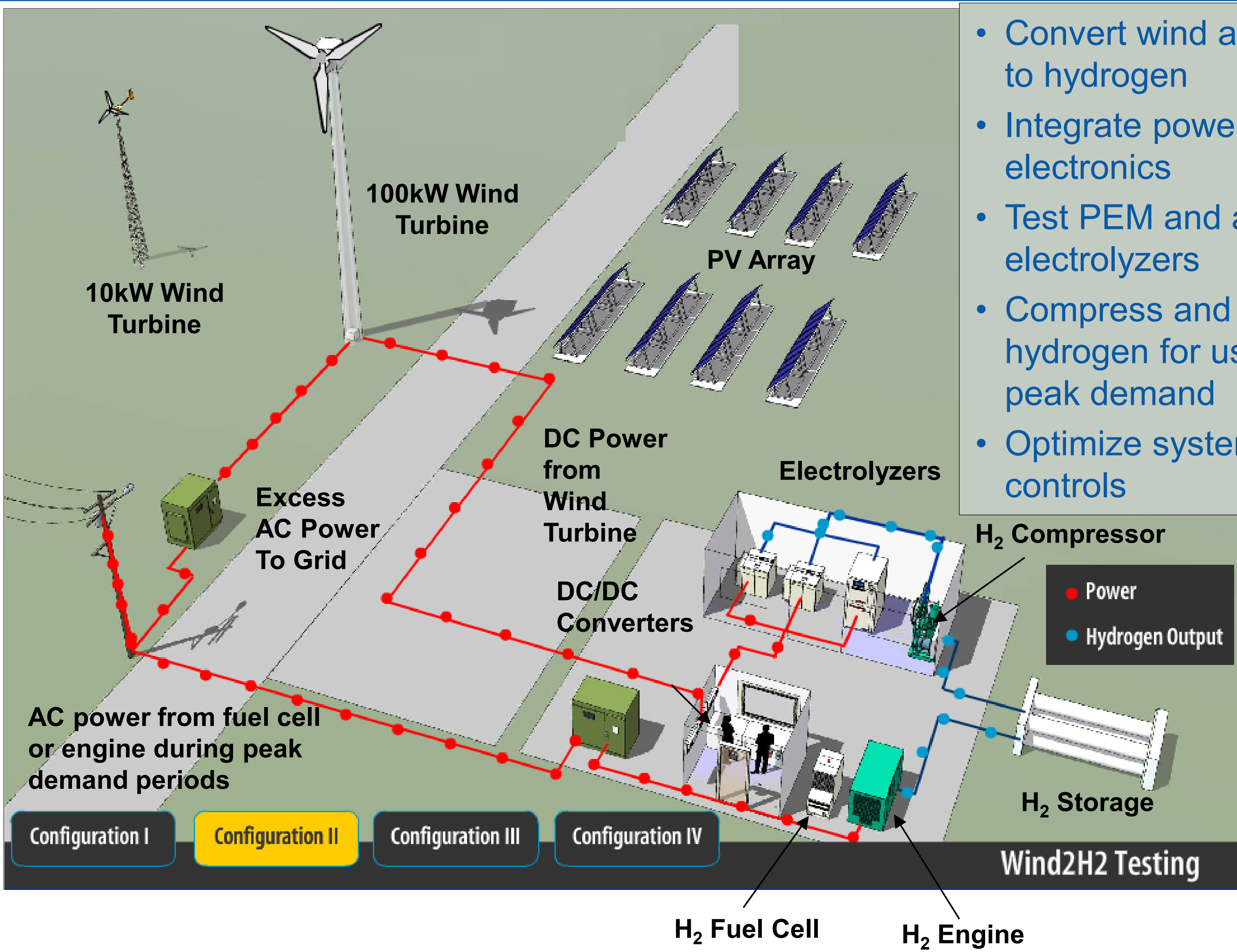
Sustainable Paths to Hydrogen



The final cost of hydrogen will determine the pathway

NREL/Xcel Wind-to-Hydrogen Project

- Convert wind and solar to hydrogen
- Integrate power electronics
- Test PEM and alkaline electrolyzers
- Compress and store hydrogen for use during peak demand
- Optimize system controls



http://www.nrel.gov/hydrogen/proj_wind_hydrogen.html

150 MW: It has been done before!

Image removed from slide due to lack of citation

Norsk Hydro's 30,000 Nm^3/h (~150 MW) Electrolyzer Plant (1948 - 90)

Knut Harg, Hydro Oil & Energy, Hydrogen Technologies
NAS – Hydrogen Resource Committee, April 19, 2007

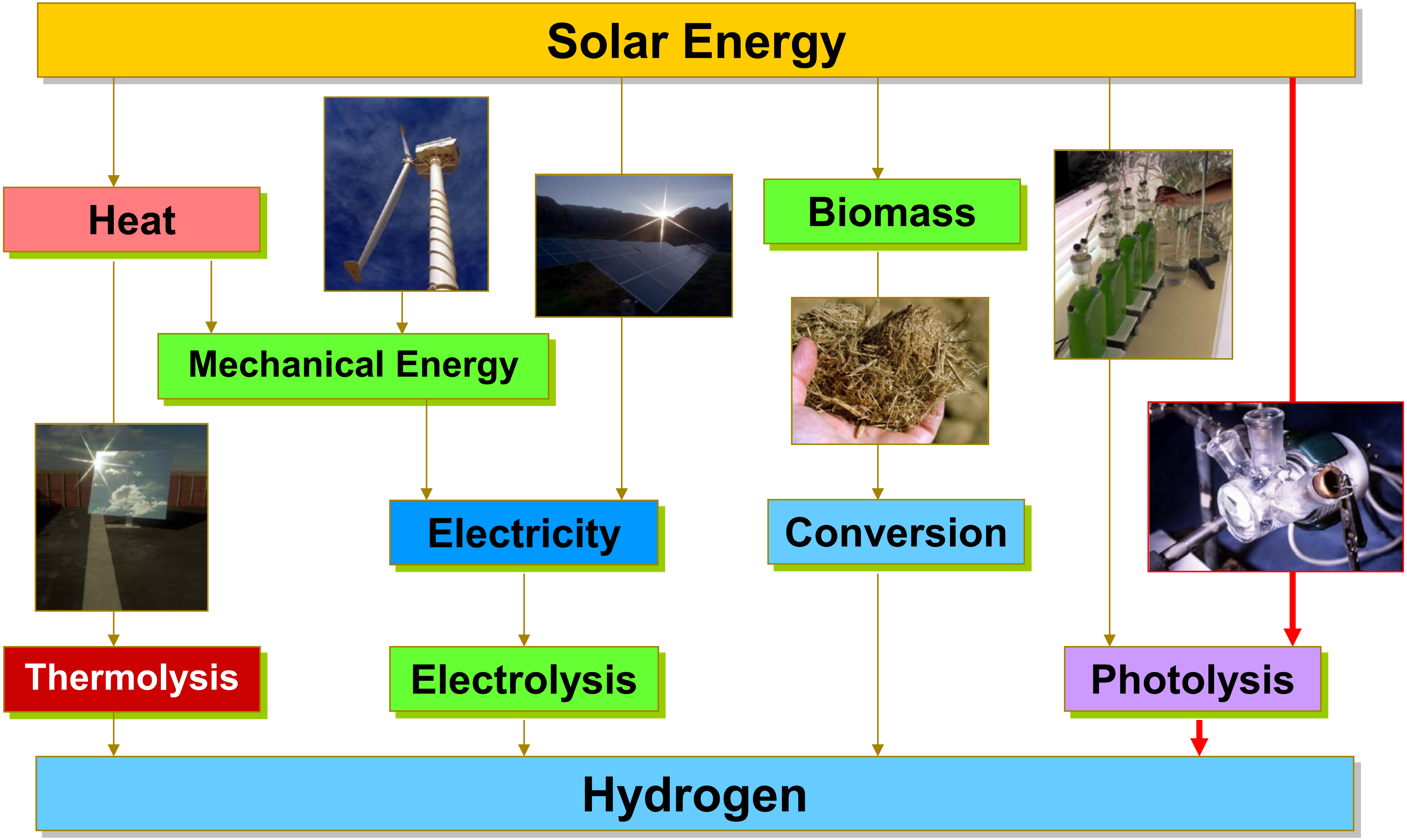
Connected to a hydroelectric plant, generating about 70,000 kg/day, enough for 3,500,000 miles/day for FCVs.

The US would need ~ 3000 of these for 250 million FCVs

H_2 Production: Biomass Conversion – Pyrolysis & Gasification

- Biomass pyrolysis produces bio-oil—which can be shipped and reformed to hydrogen.
- NREL is investigating the low-temperature, partial oxidation, and catalytic autothermal reforming of bio-oil.
- Biomass gasification produces syngas—by applying heat in the presence of steam and oxygen.
- NREL is investigating gasification yields, gas compositions, and contaminant removal for centralized hydrogen production

Sustainable Paths to Hydrogen



The final cost of hydrogen will determine the pathway

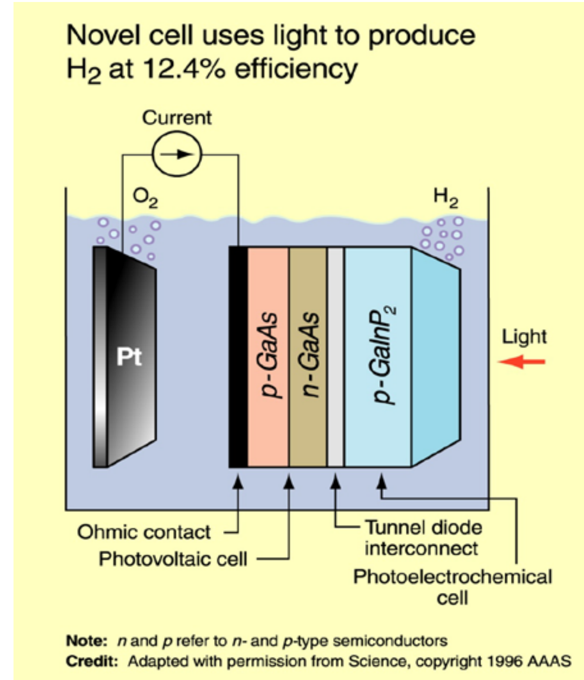
H_2 Production: Photoelectrochemical

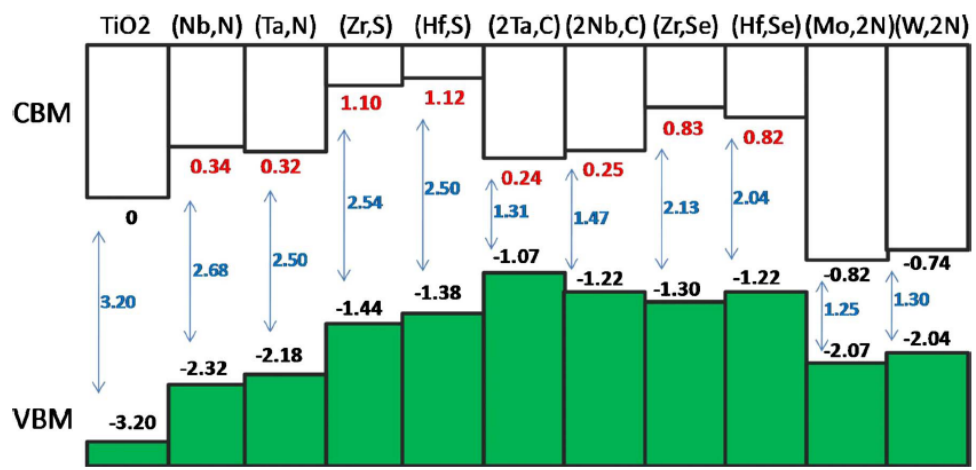
World record in direct water splitting efficiency – 12.4% solar-to-hydrogen

Research focuses on stabilization of high efficiency water splitting devices based on III-V semiconductor systems.

Advanced theory for prediction of new semiconducting alloys for photoelectrochemistry

JCAP works in this area.





- *Khaselev, Turner, Science, April 17, 1998*
- *Wan-Jian Yin, et.al., Phys. Rev. B, 82, 045106 (2010)*

Challenges: Technoeconomic Analysis of the costs for PEC Hydrogen

PEC systems have an innovative approach and offer significant cost reductions for solar hydrogen production.

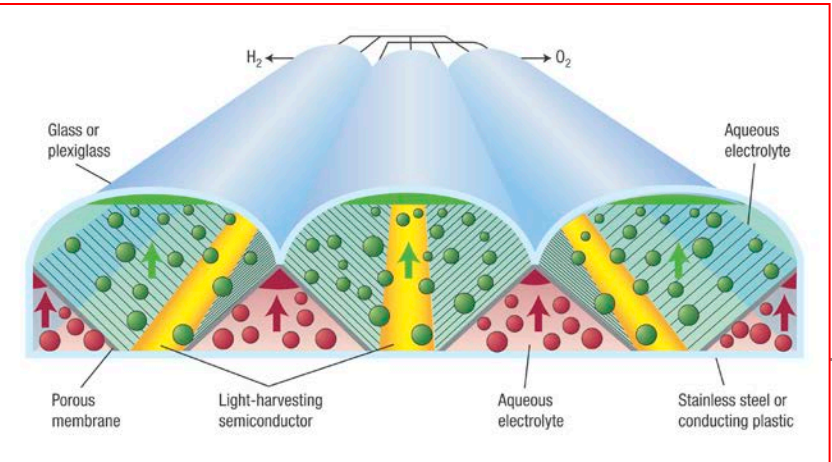
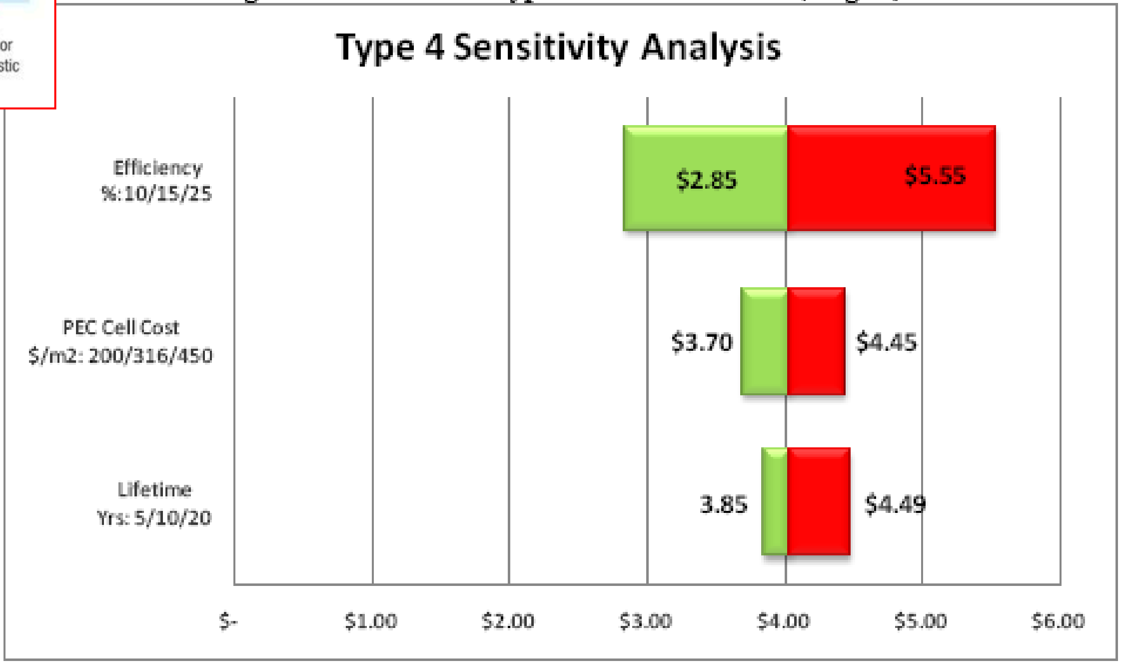


Figure 10-24: Type 4 Sensitivity Analysis Parameters

Type 4 Sensitivity Analysis Parameters		
Efficiency	PEC Cell Cost	PEC Cell Lifetime
10%	$200/m^2	5 year
15%	$316/m^2	10 year
25%	$450/m^2	20 year

Tracking concentrator system

Figure 10-25: Overall Type 4 Cost Sensitivities ($/kgH$_2$)

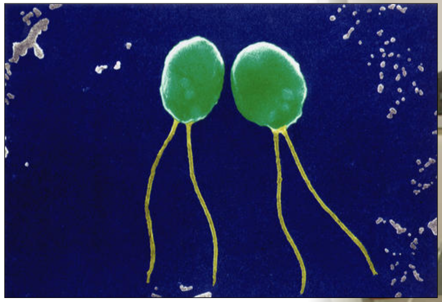


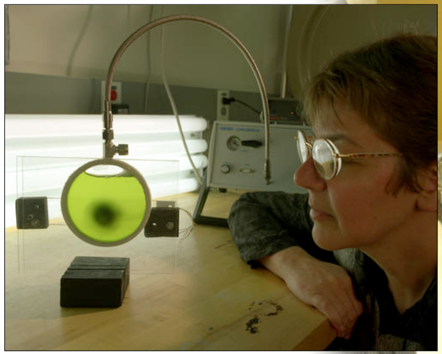
B.D. James, G.N. Baum, J. Perez, K.N. Baum, "Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production", DOE Report (2009) http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pec_technoeconomic_analysis.pdf

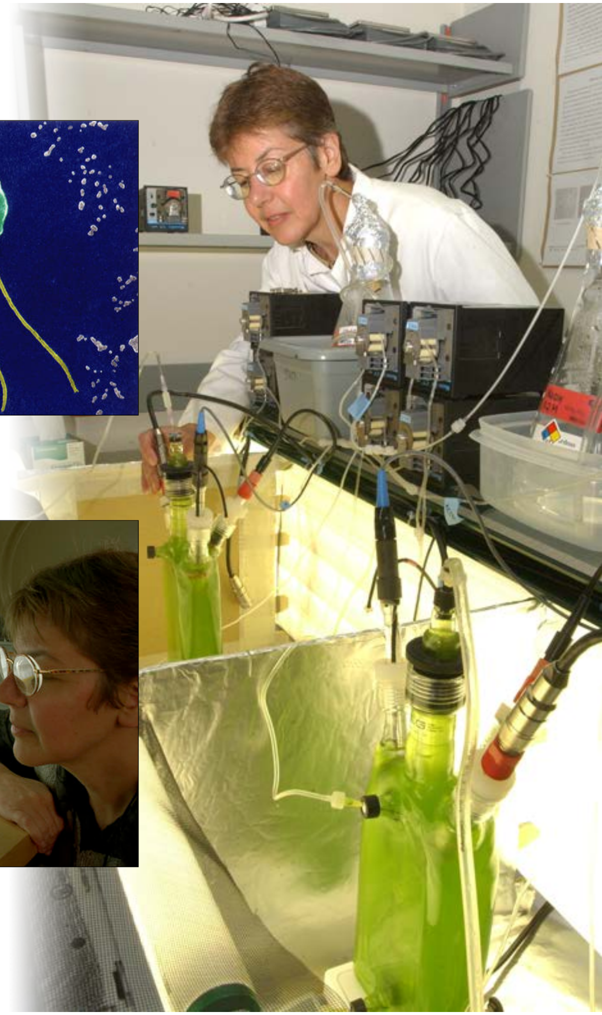
H_2 Production: Photobiological - H_2 from Cyanobacteria

Research focused on developing a robust O_2-tolerant cyanobacterial system (CBS) for light-driven H_2 production from water to surmount O_2 inhibition while increasing system durability and efficiency.

- Genes encoding the CBS O_2-tolerant hydrogenase (half life ~21 h) and its maturation machineries have been cloned.
- Two *Synechocystis* recombinants generated harboring 10 CBS genes.
- Work is underway to boost H_2 production by manipulating promoter strength.



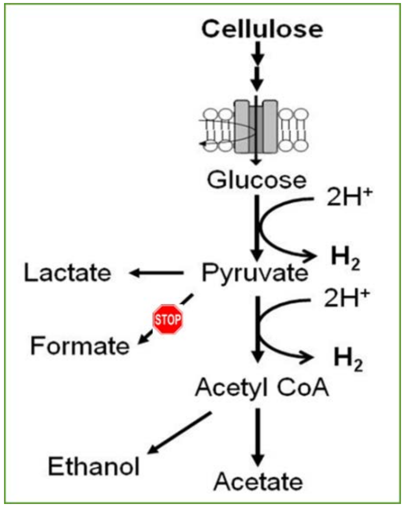




H_2 Production: Fermentation

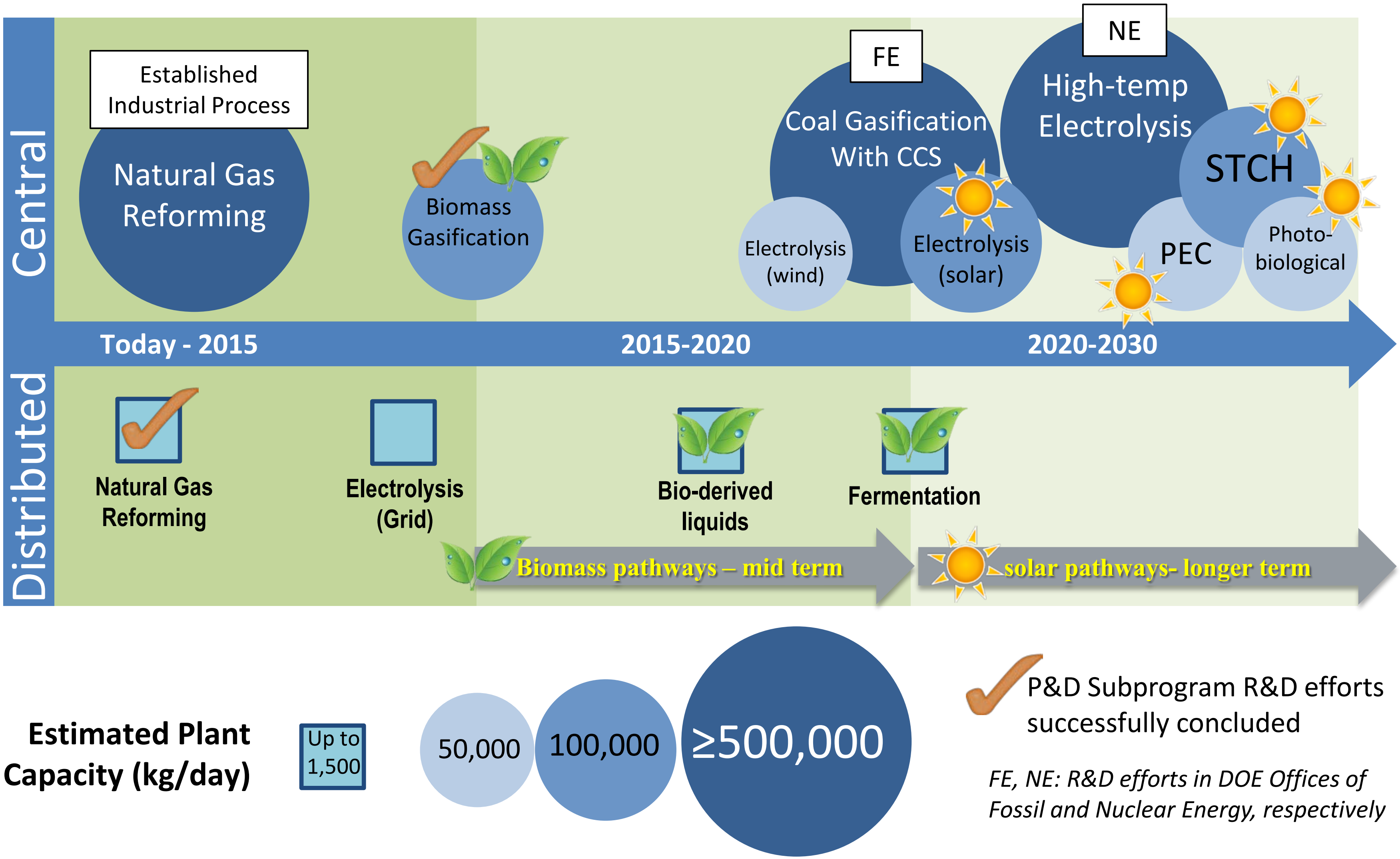
Research focused on developing **direct** fermentation technologies using cellulose-degrading microbes to convert renewable lignocellulosic biomass resources to H_2.

- The goal is to redirect more cellular flux toward H_2 via eliminating competing pathways
- NREL has developed in-house genetic tools to modify *C. thermocellum* (one of two labs in the world with this capability)
- Yielded a *C. thermocellum* mutant lacking the pyruvate-to-formate pathway.
- Work is underway in a bioreactor to determine the effect on H_2 production resulting from redirection of cellular flux.



Hydrogen Production - Strategies

Technology Readiness of DOE Funded Production Pathways



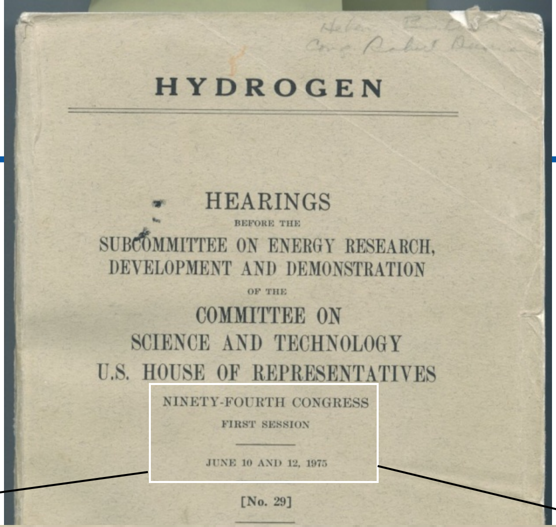
Hydrogen Production Expert Panel

The Panel focused on R&D priorities for H_2 production and opportunities for coordination with other agencies/offices to optimize effectiveness of the H_2 production portfolio

- **A subcommittee of the *Hydrogen and Fuel Cells Technical Advisory Committee (HTAC)***
- **Over two dozen participants from academia, industry, and national laboratories in the field of hydrogen production**
- **Evaluated current status and future prospects for viable hydrogen production technologies for near and long term applications**
- **Recommendations have been provided in a report to DOE through HTAC**

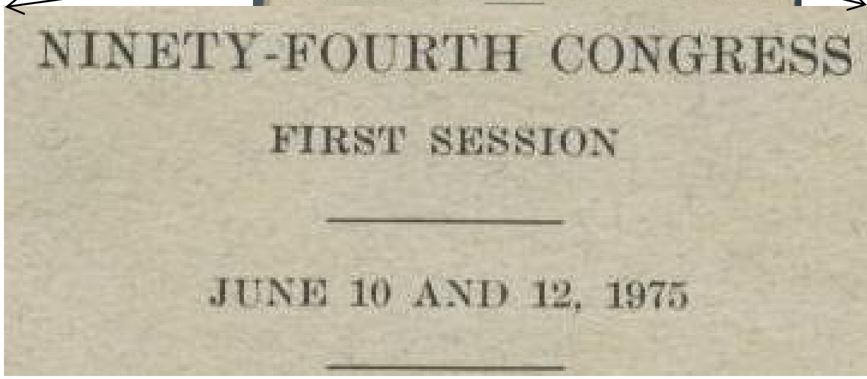
The report and the DOE response can be found at: http://www.hydrogen.energy.gov/advisory_htac.html

Hydrogen Economy *(1975)*



HYDROGEN

HEARINGS
BEFORE THE
SUBCOMMITTEE ON ENERGY RESEARCH, DEVELOPMENT AND DEMONSTRATION
OF THE
COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES
NINETY-FOURTH CONGRESS
FIRST SESSION
JUNE 10 AND 12, 1975
[No. 29]



NINETY-FOURTH CONGRESS
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Conclusions

- Hydrogen is clean burning, the main combustion product is clean water.
- It may be substituted for nearly all fuel uses.
- It can be produced from domestic resources.
- It is available from a renewable and universal resource—water.
- Nearly all primary energy sources, nuclear, solar, etc. can be used in its production.

"In the long term the panel envisions an energy economy based on nonfossil sources, with electricity and hydrogen being the staple forms of energy distributed to cities and industries. *The transition from fossil fuels to synthetic fuels will occur when the total cost of producing and using fuels from nonfossil energy sources intersects the rising costs, including environmental effects, of coal and imported oil and gas*."