# Hydrogen from Renewable Resources

GCEP Hydrogen Conference

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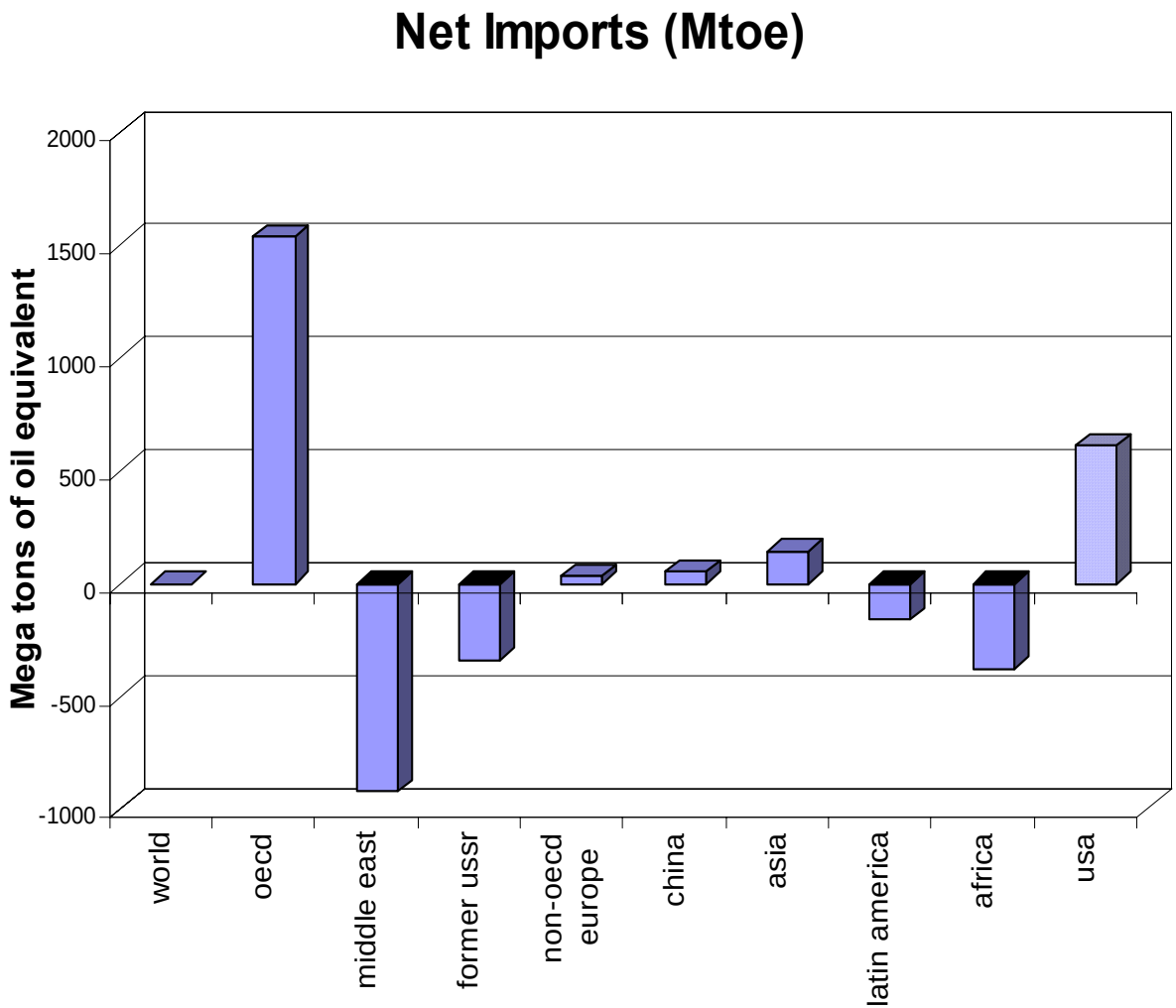
April 14-15, 2003

# Why a Hydrogen Economy?

- **Energy Security**
  - Hydrogen can replace imported petroleum as a transportation fuel

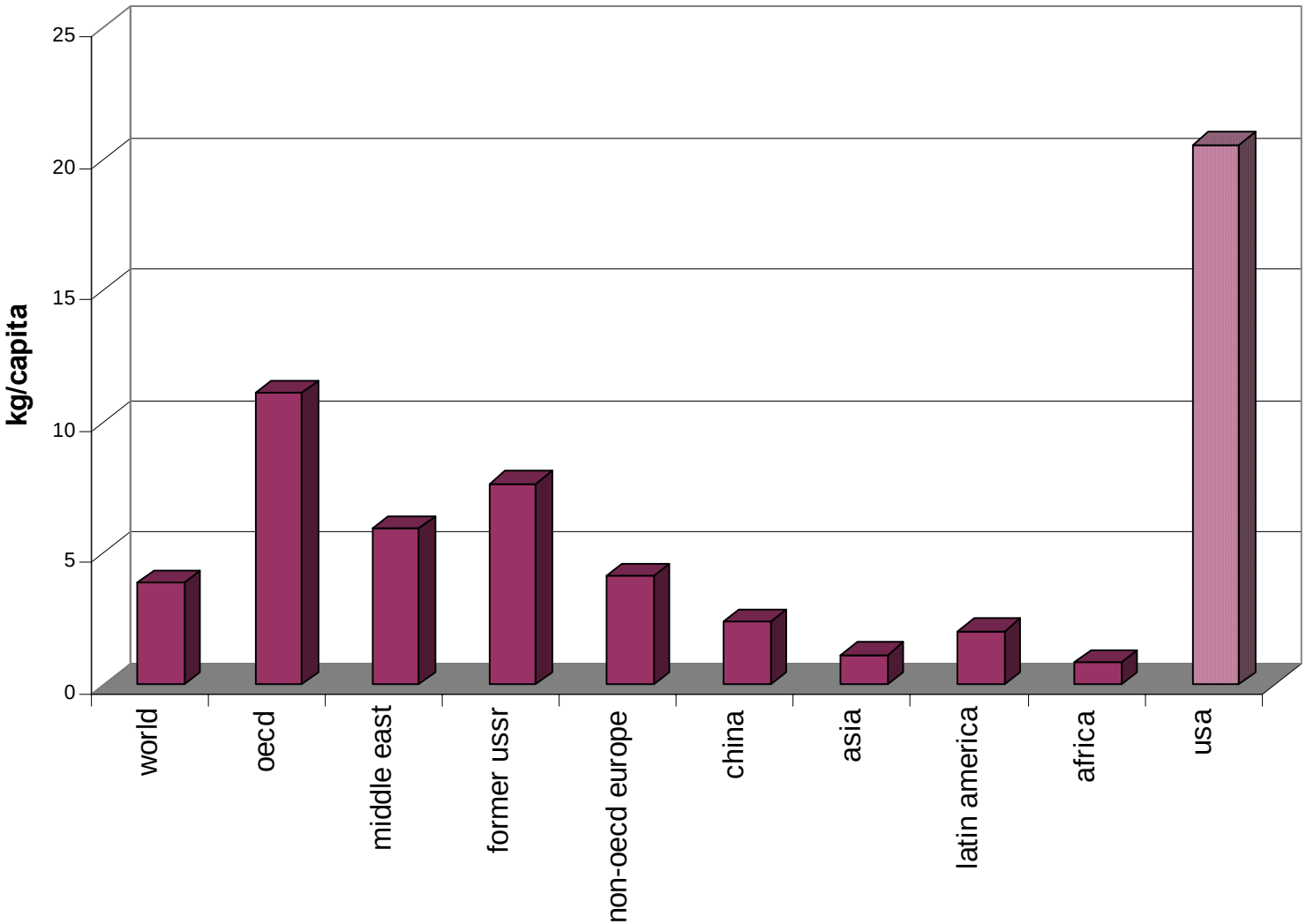



**Note: USA included in OECD – also plotted separately to show contribution**

# Why a Hydrogen Economy?

- **Global Climate Change**
  - Hydrogen can reduce greenhouse gas emissions through sequestration or increased use of renewables
  - $CO_2$ emissions per capita
  - $CO_2$ emissions per $ of GDP

# $CO_2$ Emissions per Capita

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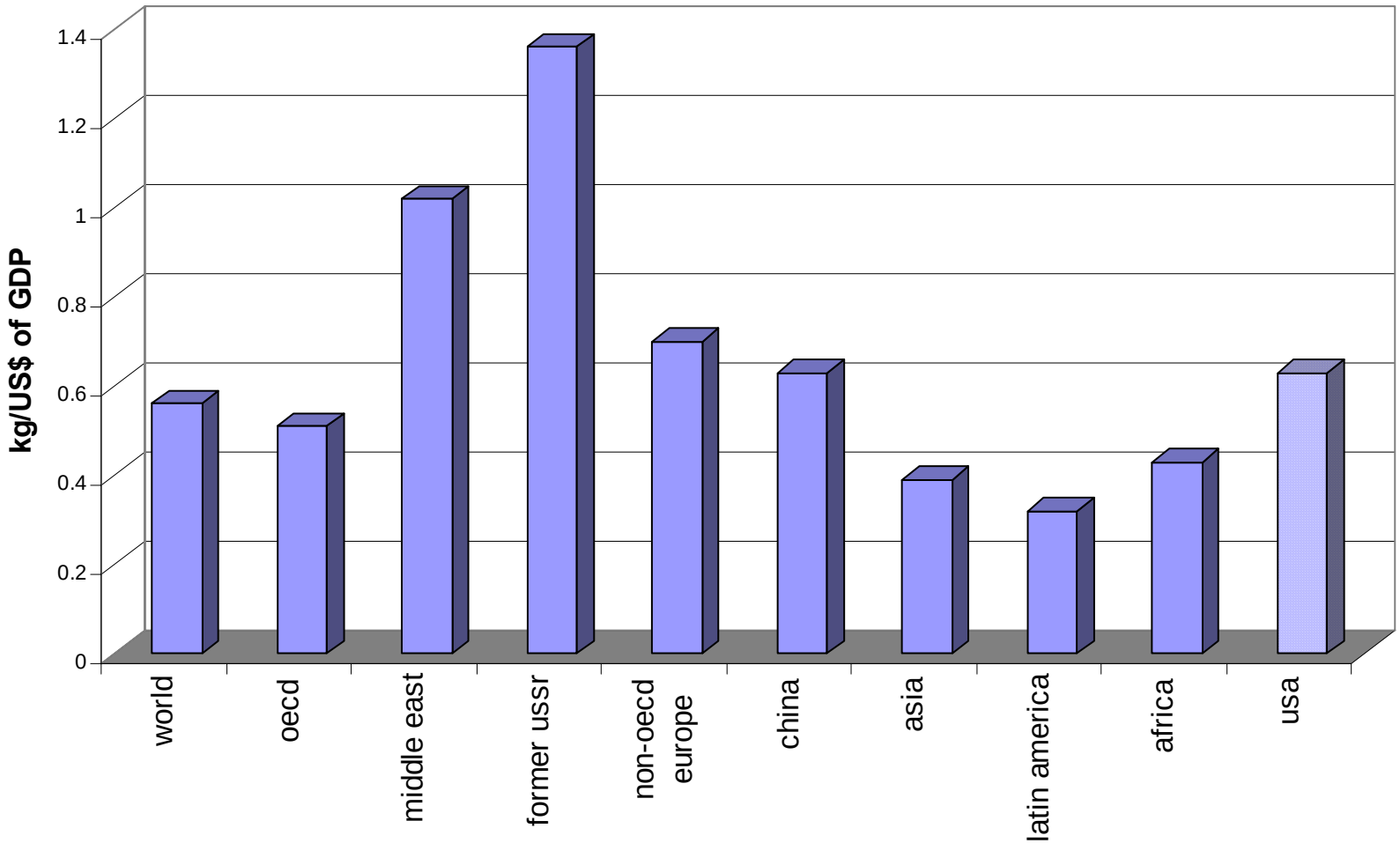
# $CO_2$ Emissions per GDP

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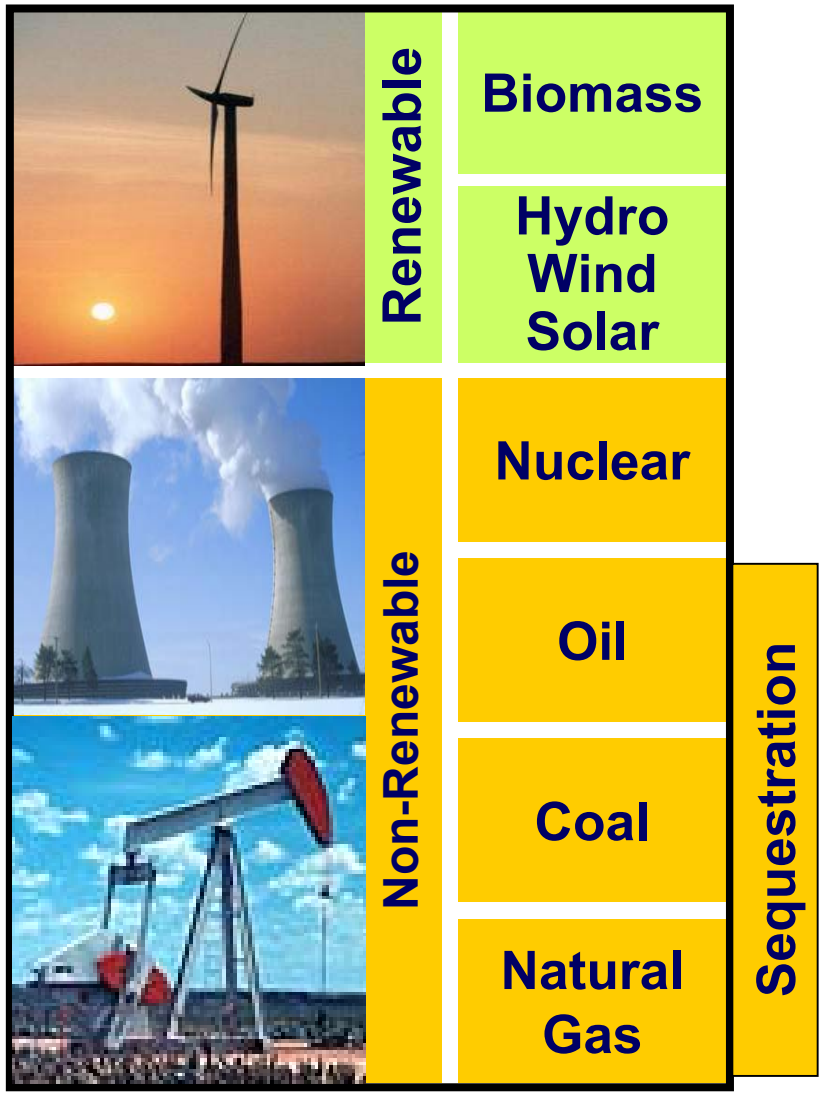
# Why a Hydrogen Economy?


- **Urban Air Quality**
  - Hydrogen produces water and heat as the only products when used in a fuel cell for power and heat generation
  - Hydrogen in combustion systems produces heat, water and small amounts of NOx

# Why a Hydrogen Economy?

- **Flexibility**
  - Hydrogen can be produced from water or from carbon-containing materials (reacting with water)
  - Regional variations in traditional energy resources are no longer an issue (every region in the U.S. has some indigenous fossil or renewable resource that can be used to make hydrogen)



# What is so Different about Hydrogen?

- We won't talk about "energy sectors" – Utility, Transportation, and Industrial Sectors will be so blended that we will be unable to distinguish where one sector ends and another begins
- Our homes and businesses will interact with our vehicles and our vehicles will interact with our homes ("home" refueling and "plug-in" cars)
- There will be a very different "utility" for energy services, with distributed generation the norm and local control common
- We will make much better use of available generating capacity
- Renewables can be integrated effectively without concerns about transmission system instabilities
- Energy independence will be a very personal issue

# A Diverse Portfolio is a Robust Portfolio

- **Hydrogen is hydrogen is hydrogen**
  - Doesn't matter where it comes from (well, sort of)
  - We can improve existing technologies to provide additional benefits
  - We need to develop additional technologies to provide all the energy we will need as our use of hydrogen continues to grow
- **Impacts are far-reaching**
  - Jobs, jobs, and more jobs
  - Environmental quality – global and local
  - Energy independence on a personal level
  - Freedom from price instabilities

# Production Potential from Domestic Resources

- **As an example, how could we fuel half of the current fleet with hydrogen?**
  - Current consumption in the light-duty market is 16 quads of gasoline
  - Assume a 2x increase in efficiency with hydrogen fuel cell vehicles
  - For half of the fleet, we need 4 quads
  - This is about 40 million tons of hydrogen per year (4 times the current domestic hydrogen production)
- **Using only ONE domestic resource, can we make this much hydrogen?**
  - Of course we will use a combination of resources, but this is an eye-opening exercise
  - Humor me…

# Production Potential from Domestic Resources

**For 40 million tons/year of hydrogen, we would need:**

- 95 million tons of natural gas (current consumption is around 475 million tons/year in all energy sectors)

**OR**

- 310 million tons of coal (current consumption is around 1,100 million tons/year)

**OR**

- 400-800 million tons of biomass (availability is 800 million tons/year of residue plus potential of 300 million tons/year of dedicated energy crops – no food, feed or fiber diverted)

**OR**

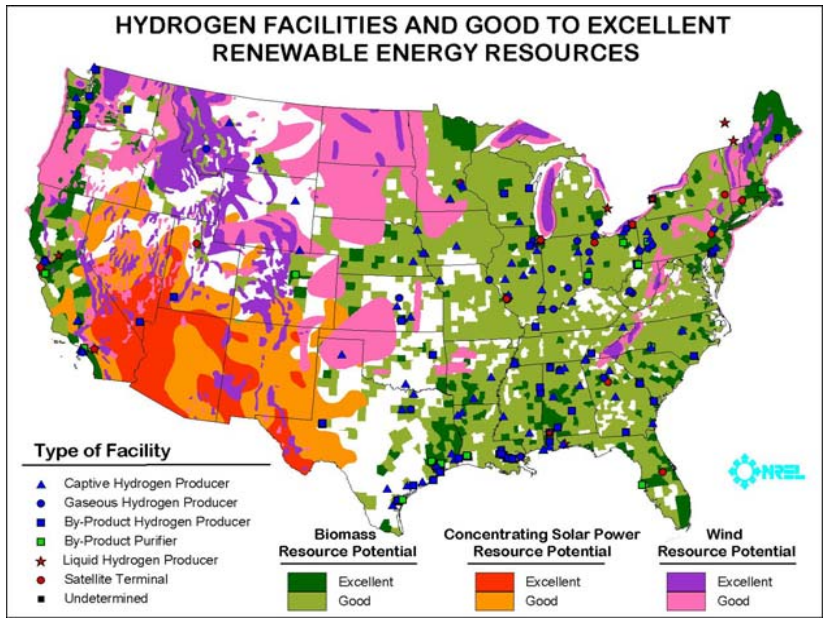
- The wind capacity of North Dakota (class 3 and above)

**OR**

- 3,750 sq. miles of solar panels (approx. footprint of the White Sands Missile Range)

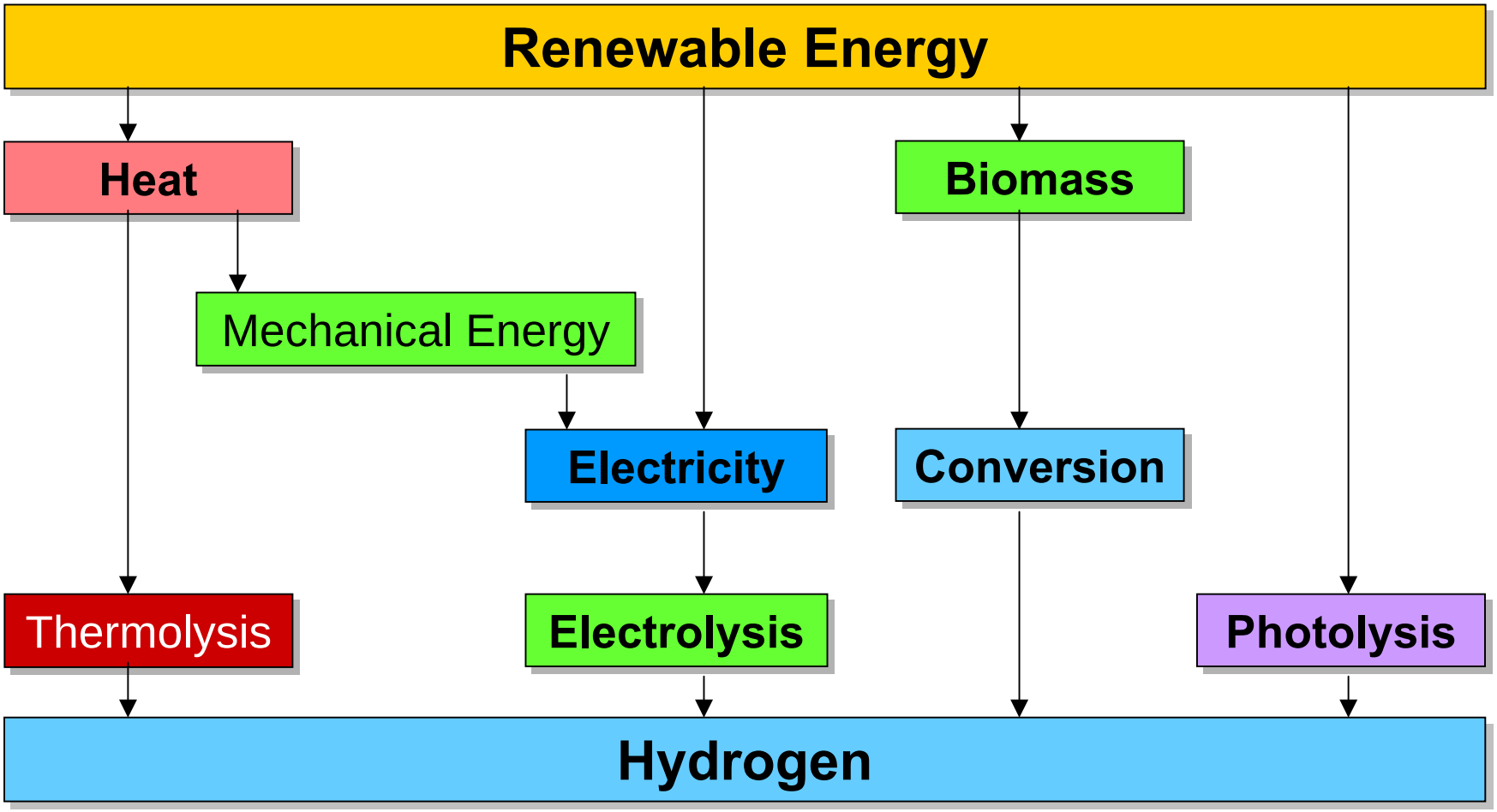
# Why Renewable Hydrogen

- **Energy Security**
  - Can replace imported petroleum
- **Source Flexibility**
  - Regional variations in traditional energy resources are no longer an issue
  - Every region in the U.S. has some indigenous fossil or renewable resource that can be used to make hydrogen




- **Urban Air Quality**
  - Water and heat are the only products when used in a fuel cell for power and heat generation
  - In combustion systems - produces heat, water and small amounts of NOx
- **Global Climate Change**
  - Renewable hydrogen can reduce greenhouse gas emissions

# Renewable Paths to Hydrogen

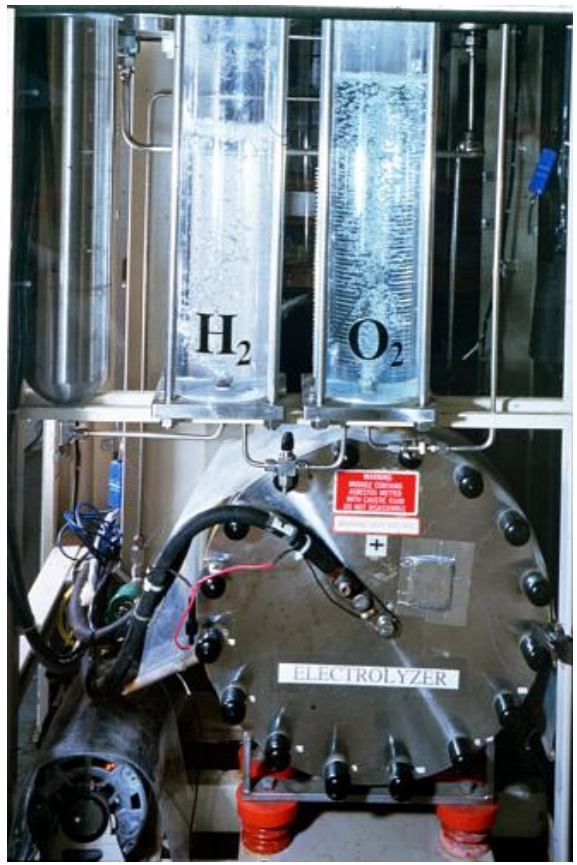


# Renewables Now - Electrolysis

- **Geothermal**
  - Could benefit from development of high(er)-temperature electrolyzers
- **Hydro**
  - Traditional large-scale hydro could benefit from hydrogen for energy storage where pumped storage is not permissible
- **Intermittent renewables**
  - Wind/electrolysis is likely to be the first economical *intermittent* renewable system
  - “Hydrogen Turbine” concept for efficient production of hydrogen from wind

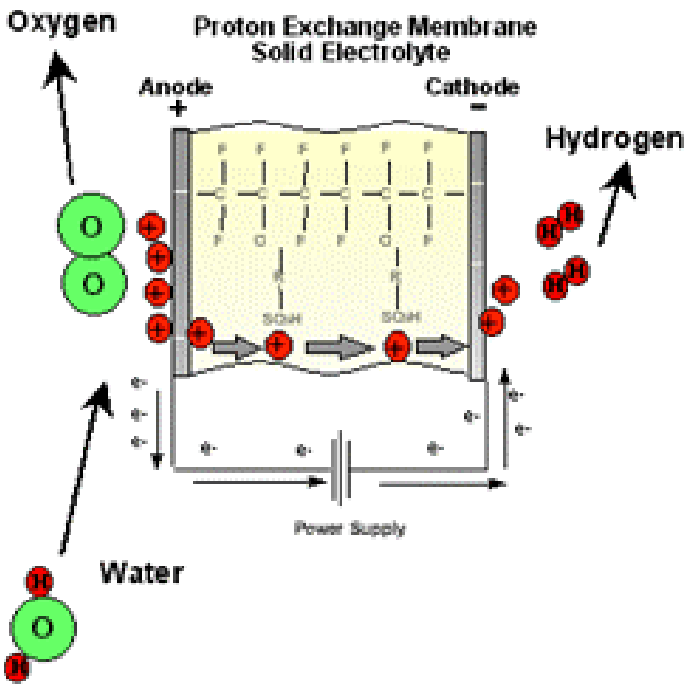
# Electrolysis

- 75-85% electrical efficiency for alkaline (KOH) systems (efficiency is about ~25% from primary resource)
- Capacity is relatively small (100,000 SCFD or 250 kg/day)
- Small number of manufacturers
- On-site for user control of production rate and quality




Overall reaction: $H_2O \Rightarrow H_2 + \frac{1}{2}O_2$

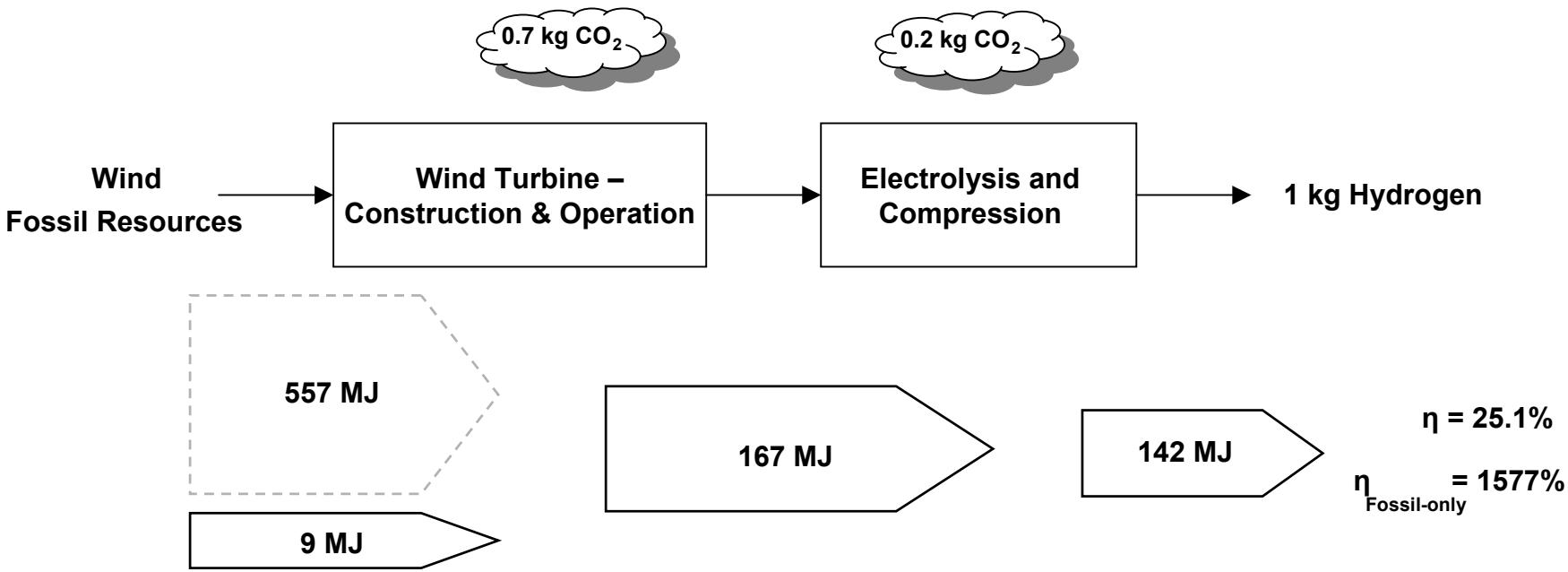
# Electrolysis




- **Significant overall efficiency increases likely only at higher temperatures**
  - Replace premium electricity with heat for required “heat” of reaction
- **Systems under development**
  - Lower capital cost
  - PEM-based
  - Smaller systems (2-5 kg/day)
  - High-temperature electrolysis

# Energy Requirements and GHG Emissions

## Distributed Hydrogen from Wind Electrolysis



# What is Left to Learn?

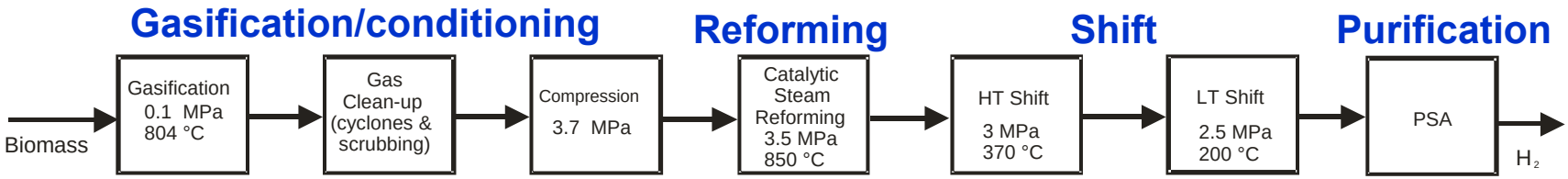
- **Opportunities for improvement in commercial technologies, particularly when comparing delivered costs**
  - Liquefaction
  - Compression
  - Purification/separation
- **Opportunities to develop on-site production processes**
  - Biomass at small or medium scale (on-site or semi-central production)
  - Electrolysis (efficiency, capital cost, size)

# What is Left to Learn?

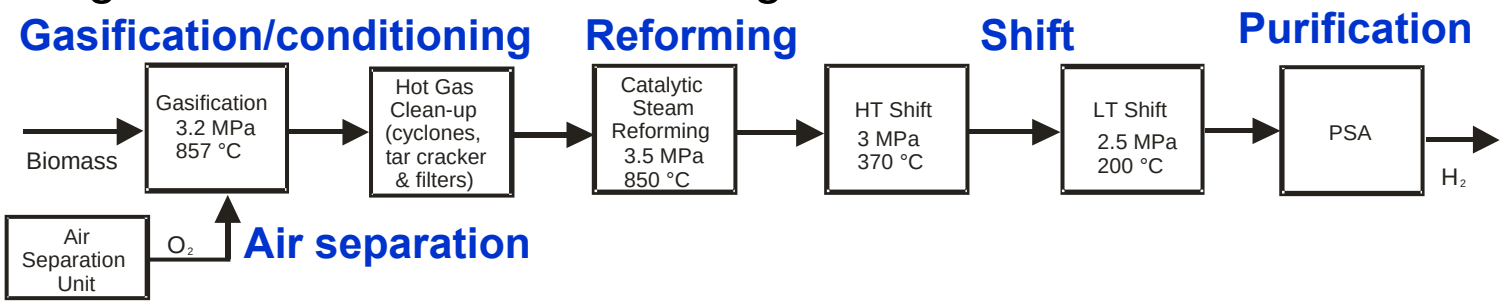
- **Renewable hydrogen production**
  - Biomass (wastes, agricultural residues, forest thinnings; long-term use of dedicated feedstocks)
  - Intermittent renewables (conventional and advanced wind turbines, PV, solar thermal)
- **General improvements (any scale)**
  - Feedstock flexibility
  - Efficient operation (controls) at variable or low demands

# Thermochemical Routes for Making $H_2$ from Biomass

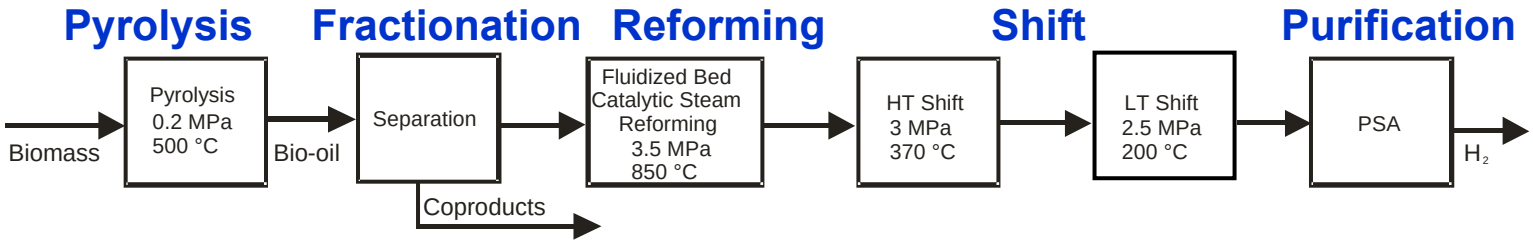
## Indirectly-heated gasification / steam reforming:




## $O_2$-blown gasification / steam reforming




## Pyrolysis / steam reforming, with coproducts

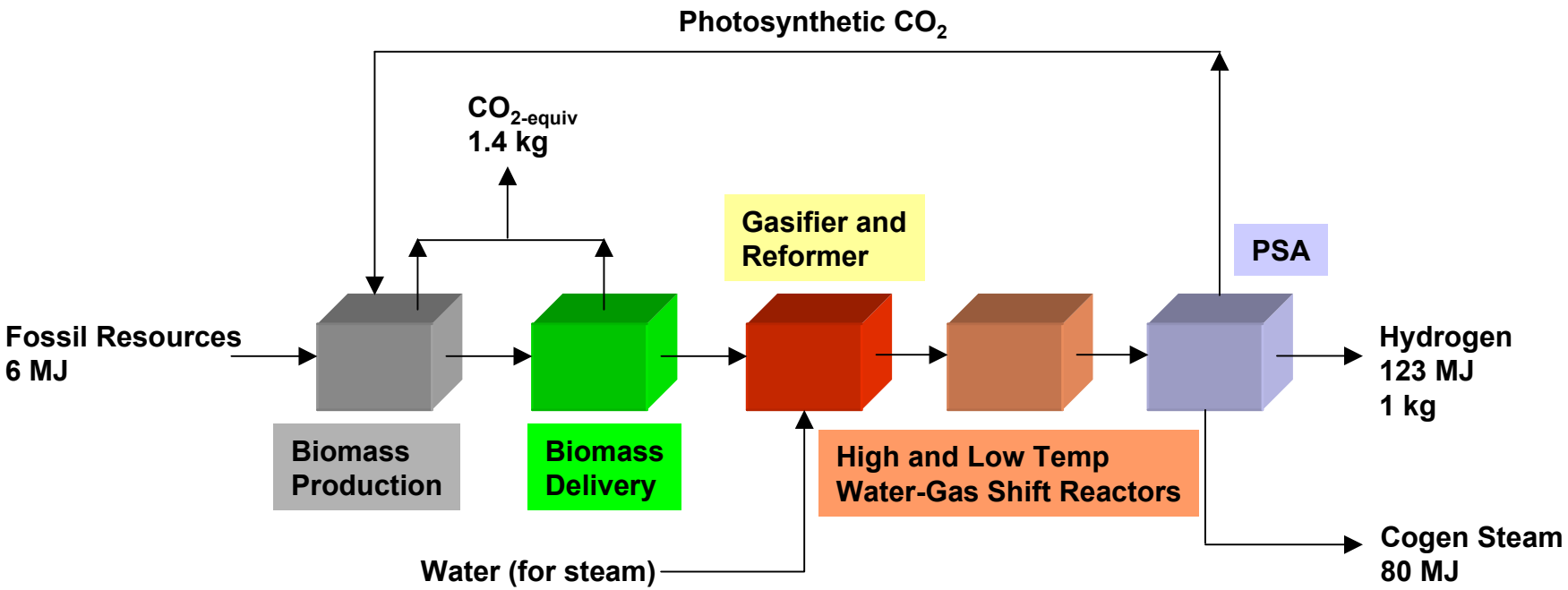


# Reforming of Pyrolysis Streams

- **Potential Impact**
  - Many regions have suitable materials in sufficient quantities to provide significant economic and environmental benefits
  - Potential markets for byproducts
- **In the Future**
  - Biomass producers (farmers, loggers, recyclers, etc.) work with bio-refinery operators, who work with energy service providers, who work with urban and rural developers, who work with transit agencies and consumers….
  - Essential aspect of the bio-refinery concept to provide food, fuels, materials, heat, power, and chemicals

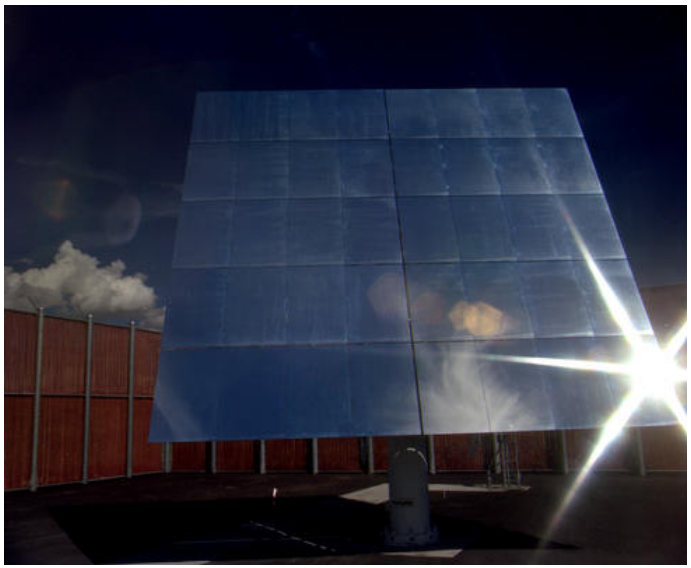
# Energy Requirements and GHG Emissions

## Biomass Gasification / Reforming from Dedicated Energy Crop




Energy Ratio: (123 MJ + 80 MJ) / 6 MJ = 33.8

# Solar-Assisted Hydrogen Production

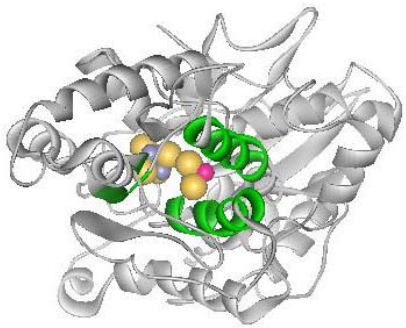


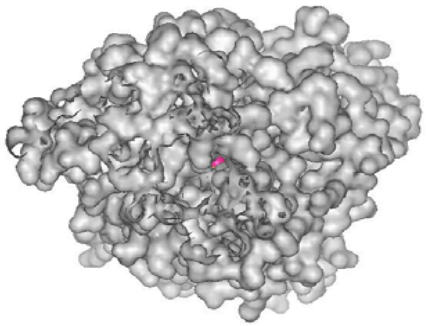
- **Potential Impact**
  - Pure hydrogen or hydrogen/natural gas blends could be produced for refueling stations
  - High flux requirements limit contribution potential, but process could provide hydrogen in certain situations
- **In the Future…**
  - Apply reactor system to thermochemical cycles (for eventual use with HTGR systems)
  - Direct water splitting using concentrated solar power or nuclear

# What is Left to Learn?

- **Direct hydrogen production – the "Holy Grail"**
  - Photobiological water splitting
    - Algal systems with modified metabolic pathways that split water under certain conditions
    - Low-tech solution, scalable
  - Photoelectrochemical water splitting
    - "Unitized" PV + electrolyzer for increased efficiency, reduced manufacturing complexity, and reduced capital cost
    - Simple and scalable

# Algal Systems for Hydrogen Production

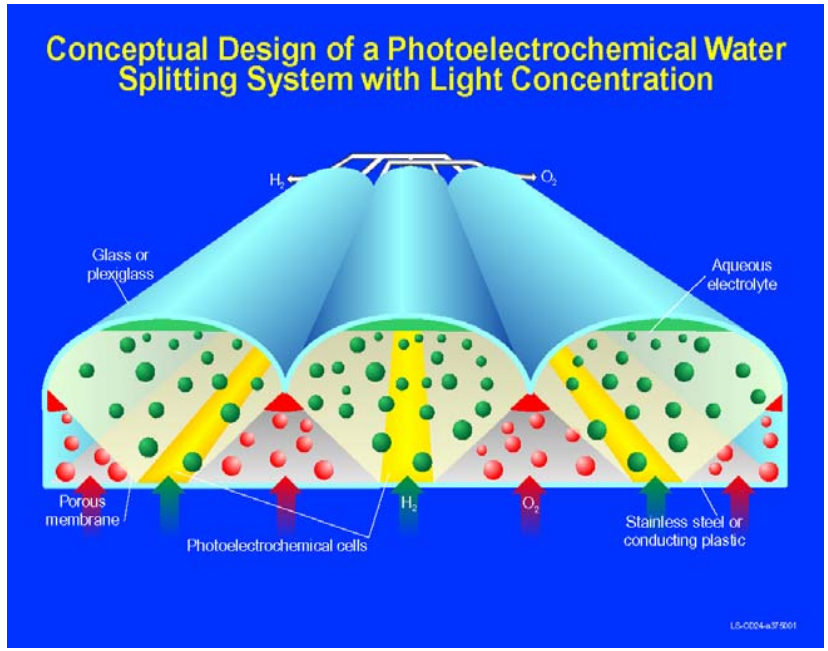




- **Potential Impact**
  - Process can operate effectively in regions with reasonable solar insolation (algae actually dissipate excess photons as heat)
  - Systems can be small or large
  - Markets for bioproducts should be explored to improve economics
- **In the Future…**
  - Ocean-based systems with super-low-tech designs using brackish or salt water
  - Integrated into an overall bio(logical)-refinery concept

# Photoelectrochemical Water Splitting

- **Potential Impact**
  - Process operates most effectively in regions with good-to-excellent solar insolation
  - Systems can be small or large – modular design scales linearly
- **In the Future…**
  - Systems designed to operate with low solar insolation (nanostructured materials)
  - Low-tech designs for roof-mounted systems provide personal hydrogen supply



# Moving beyond the hype

- **Hydrogen production technologies are mature**
  - Can produce the hydrogen we will need for the next “few” years using fossil-based processes or electrolysis (likely to be, on average, from fossil-based electricity)
  - Near-term new production processes are based on existing processes (that is, they do not require “leap frog” advances), although cost reductions and operating experience are required
- **To reap the benefits of a Hydrogen Future, we need low-emission production technologies**
  - Fossil with carbon capture and sequestration
  - More biomass-based and renewable/electrolysis-based production
  - Direct water-splitting
  - Nuclear/electrolysis and high-temperature direct water splitting processes

# Hydrogen, Fuel Cells & Infrastructure Technologies Program Website Address

**www.eere.energy.gov/hydrogenandfuelcells**

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- Technical reports
- Programmatic documents
- News
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