Hydrogen Workshop for Fleet Operators

ALLIANCE TECHNICAL SERVICES, Inc.

Module 2, “Hydrogen Production, Distribution and Delivery”

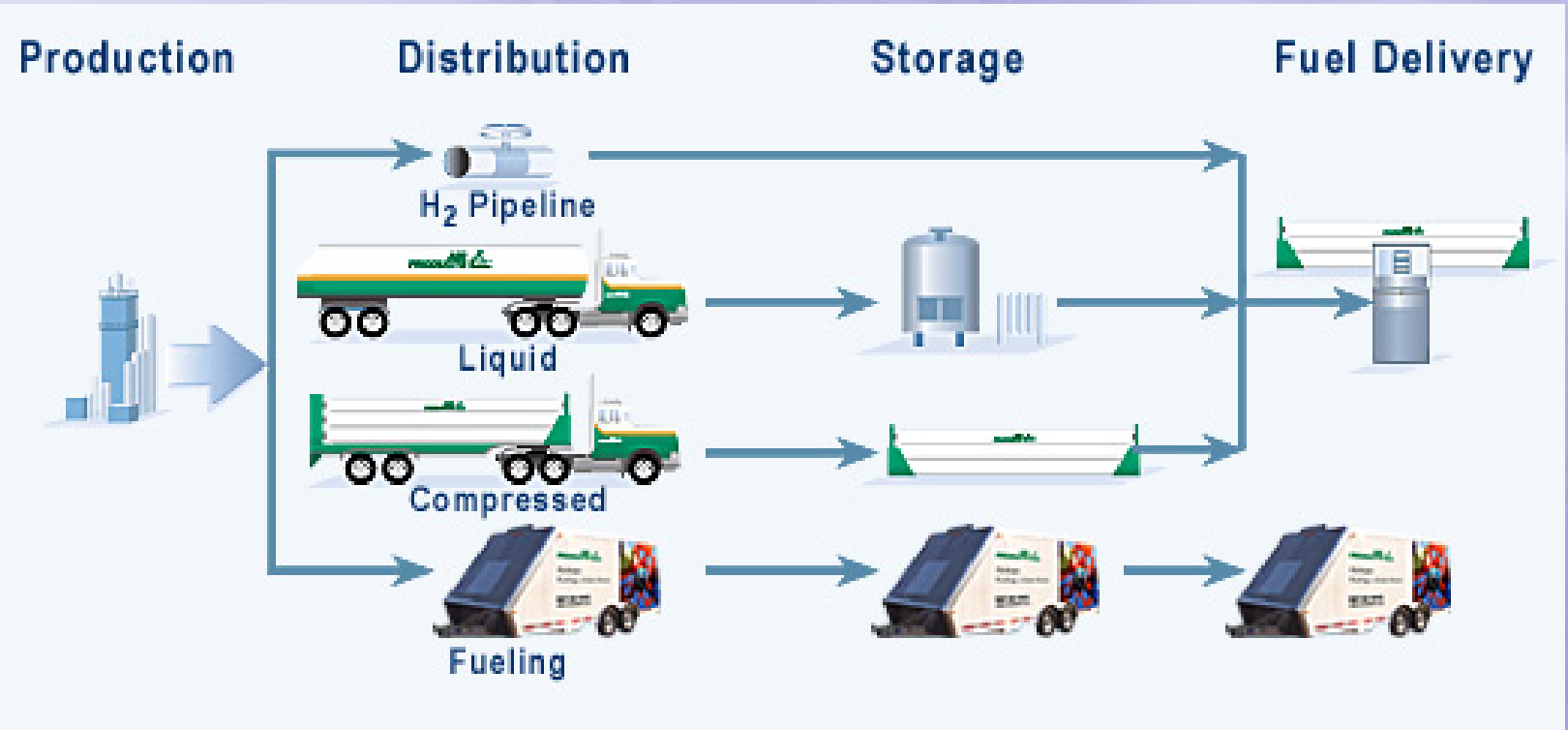
Hydrogen Production, Distribution, & Delivery Outline

1. Hydrogen Production
2. Hydrogen Delivery
   - Pipeline
   - On-site production
   - Cryogenic truck, tube trailer, rail car
3. Hydrogen Storage
   - Gaseous
   - Cryogenic liquid
4. Cost Components of Hydrogen Fuel
5. Hydrogen Fueling Stations

Air Products delivery truck drops off a load of liquid hydrogen for a Space Shuttle launch. It takes about 50 loads transported from Louisiana to launch a Space Shuttle

Hydrogen Production

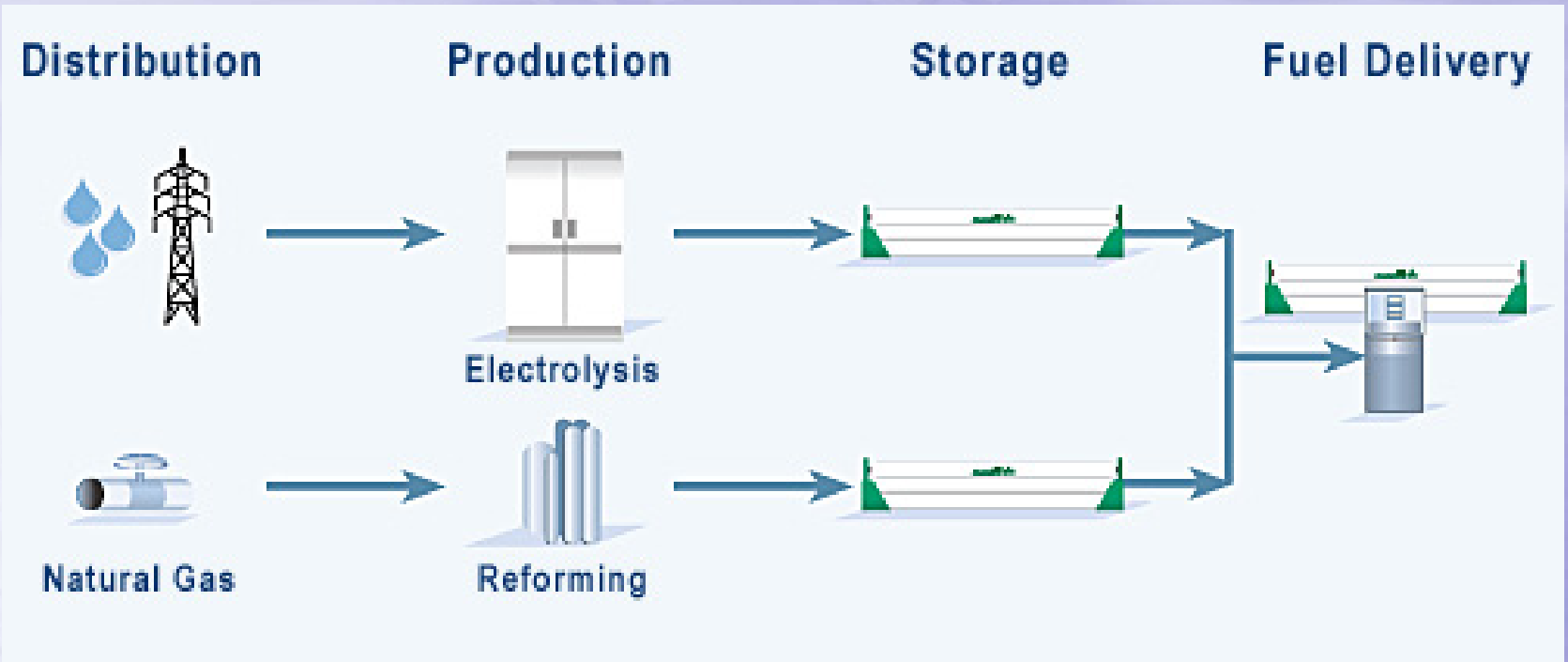
- Hydrogen can be produced at a central location and delivered to the user/fueling station



Air Products and Chemicals, Inc

Hydrogen Production

- Hydrogen can be produced on a smaller scale, locally at the fueling station, business, home, etc.

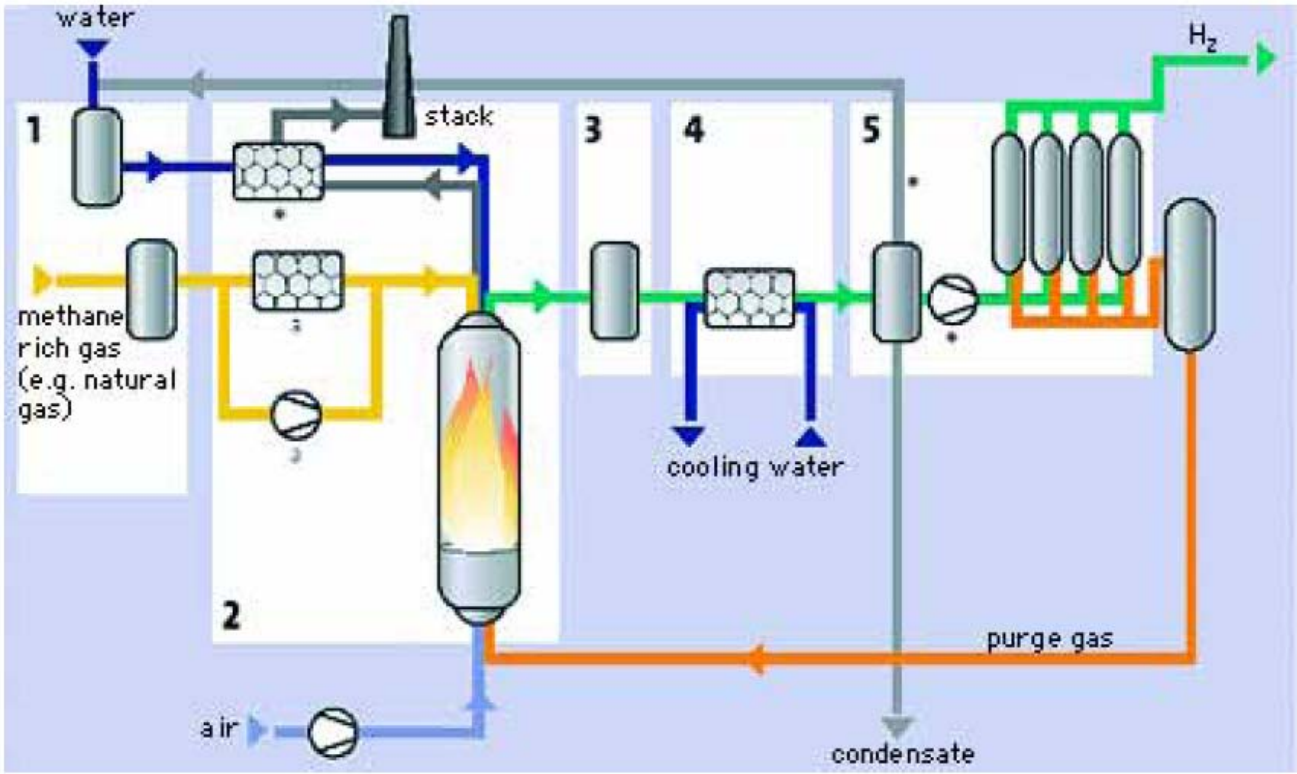


Air Products and Chemicals, Inc

Hydrogen Production

- Steam Reforming
  - Currently the least expensive method to produce hydrogen
  - Converts hydrocarbons, mainly natural gas (CH_4), into hydrogen and CO by reaction with steam (1,292-2,012°F) over a nickel catalyst
  - 95% of the hydrogen used in the United States comes from this method (48% worldwide)
  - Existing infrastructure
  - Produces CO_2 as a by-product

Hydrogen Production



1	Feed Pre-Treatment[7]
2	Reforming and Steam Generation
3	High Temperature Conversion
4	Heat Exchanger Unit
5	Purification Unit

* Optional, depending on reformer design, either a heat exchanger for low-pressure reformer or compression to 16 bar for high-pressure reformer

Source: CUTE, Hydrogen Supply Infrastructure And Fuel Cell Bus Technology, 2004

Hydrogen Production

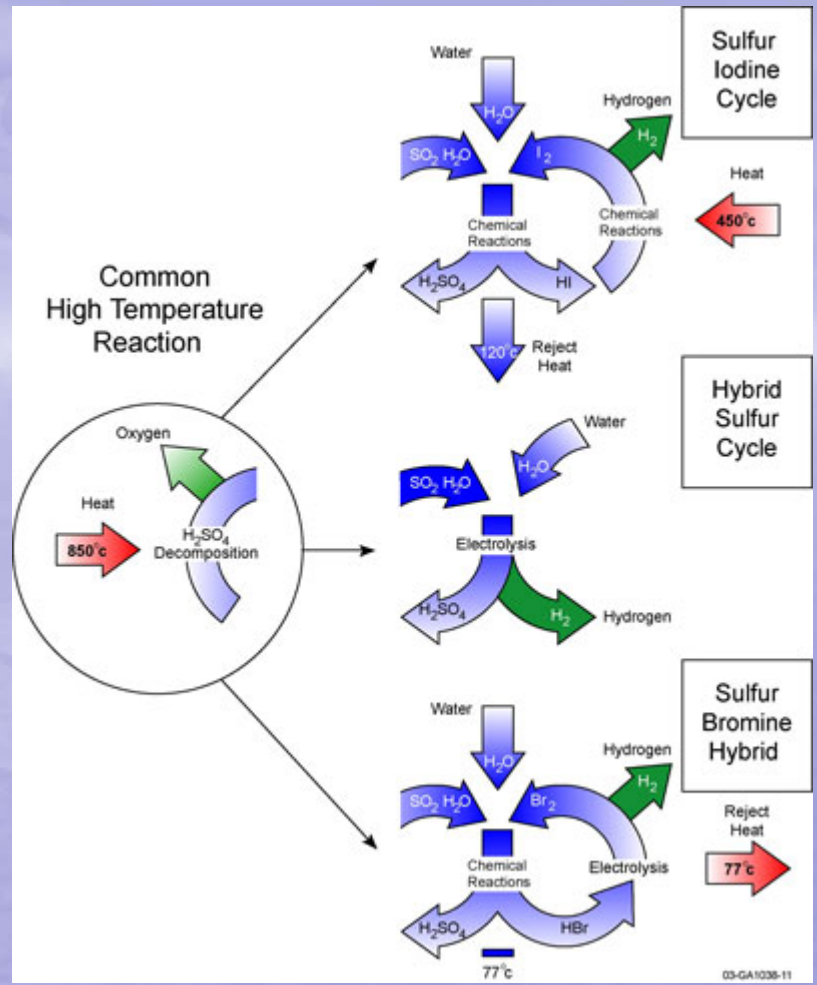
- Electrolysis
  - Produces hydrogen by using electrical current to separate water into hydrogen and oxygen
  - Electrolyzer consumes 56 to 67 kWh per kg of hydrogen
  - Cost of hydrogen mostly dependent on cost of electricity
  - Renewable energy applications such as wind, solar and hydro
  - Ideal for distributed production and storage of renewable resources

Proton Energy Systems Hydrogen Generation

Hydrogen Production

- Nuclear thermochemical water-splitting cycles
  - Series of chemical reactions that convert water to hydrogen and oxygen using chemical catalysts at high temperatures
  - Potential for high efficiency hydrogen production at large-scale production rates
  - Technology is relatively immature

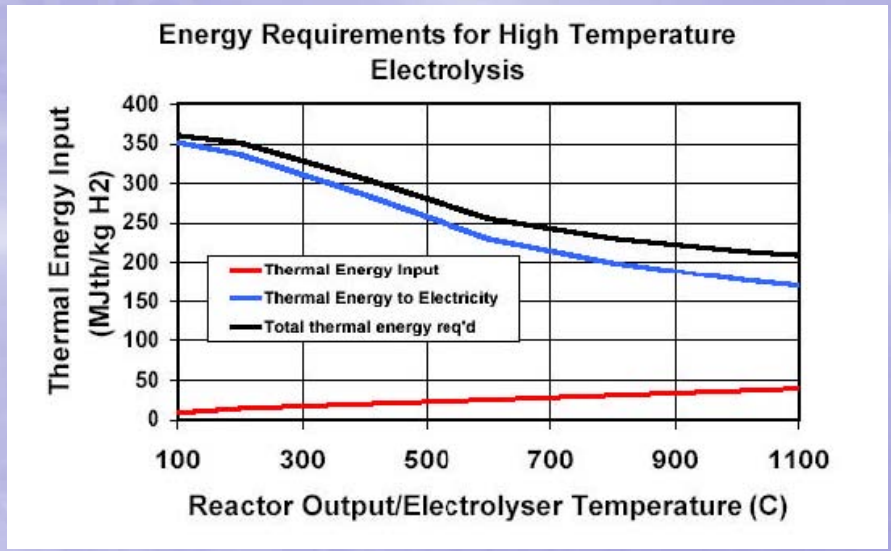
Schematic representation of the sulfur family of cycles



Office of Nuclear Energy, Science and Technology

Hydrogen Production

- Nuclear high temperature electrolysis
  - Uses electricity to produce hydrogen from steam instead of liquid water
  - Higher efficiencies than standard electrolysis, which is employed commercially today
  - Involves several technical challenges including development of high-temperature materials and membrane



About 350 MJ are need to produce 1 kg of hydrogen at 100℃ whereas it takes approximately 225 MJ at 850℃

Office of Nuclear Energy, Science and Technology

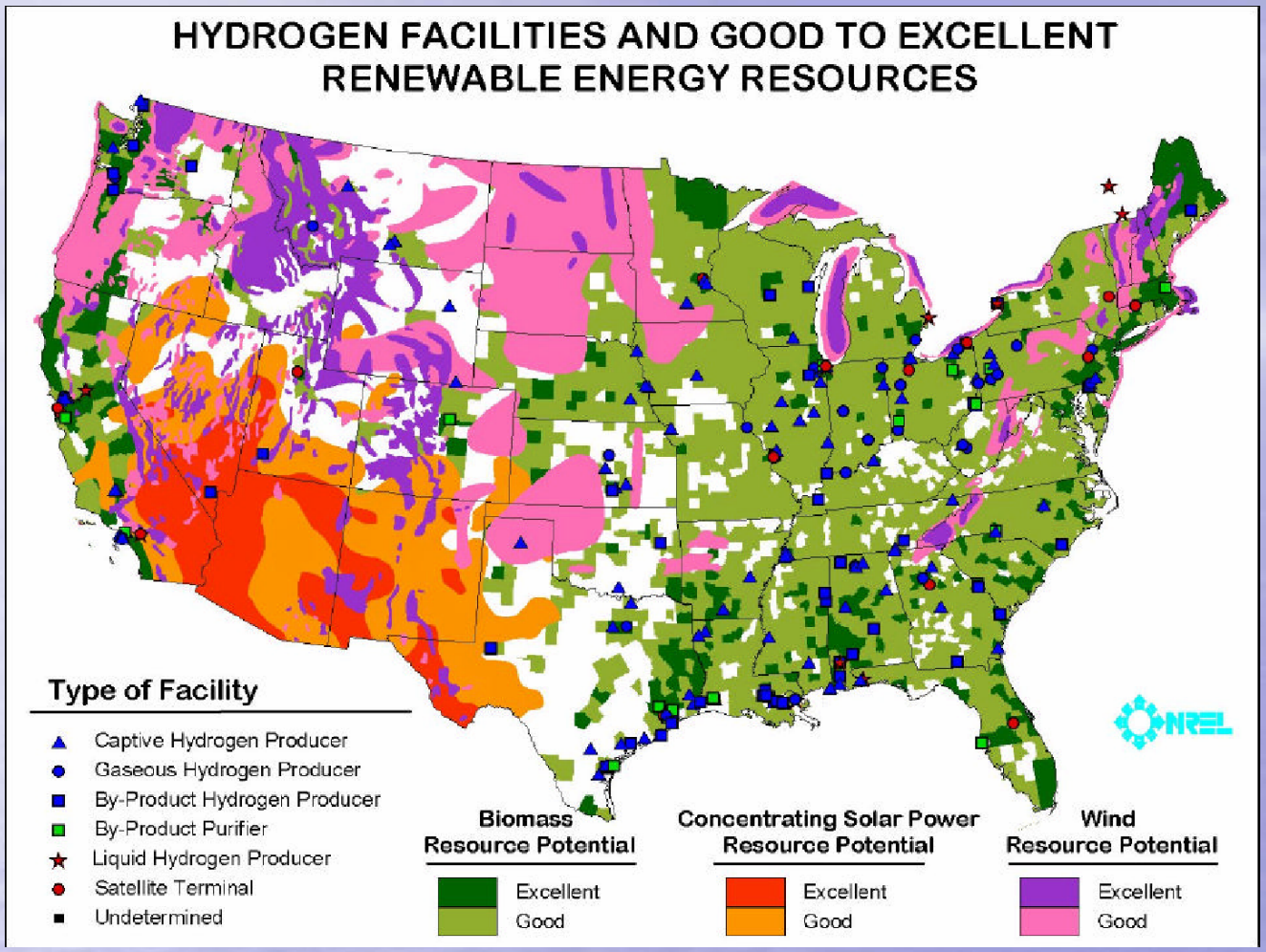
Hydrogen Production

- Photoelectrolysis
  - Light harvesting systems that generate sufficient voltage to split water
  - Eliminates most of the costs of the electrolyzer
  - Still in the RD&D phase
- Biomass Gasification
  - Carbon neutral
  - Thermally converts plant material to simple chemical building blocks that can be transformed to fuels, products, power and hydrogen

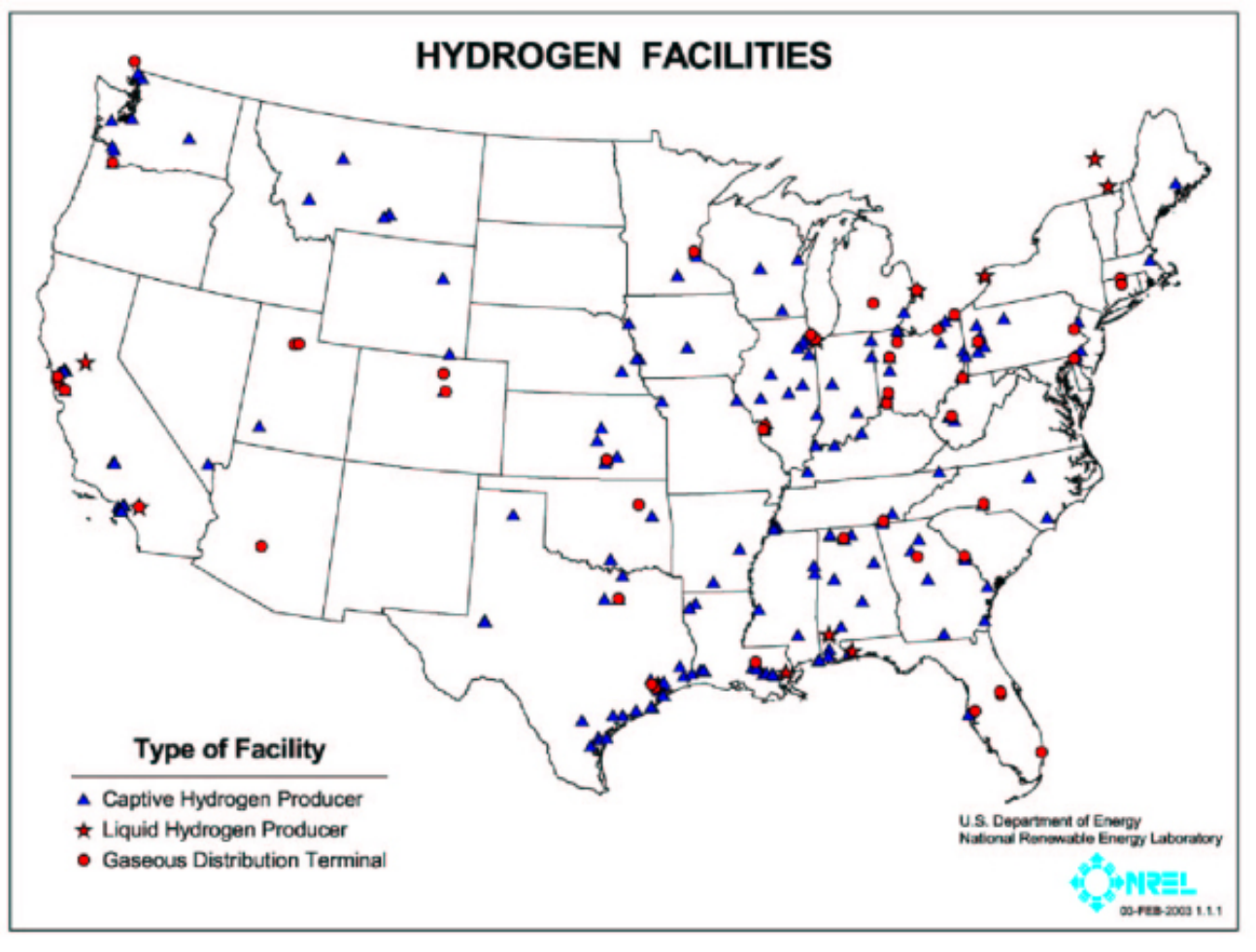
Light shining on a photoelectrochemical cell immersed in water produces bubbles of hydrogen and oxygen

Hydrogen can be produce from biomasss, such as switchgrass, via gasification

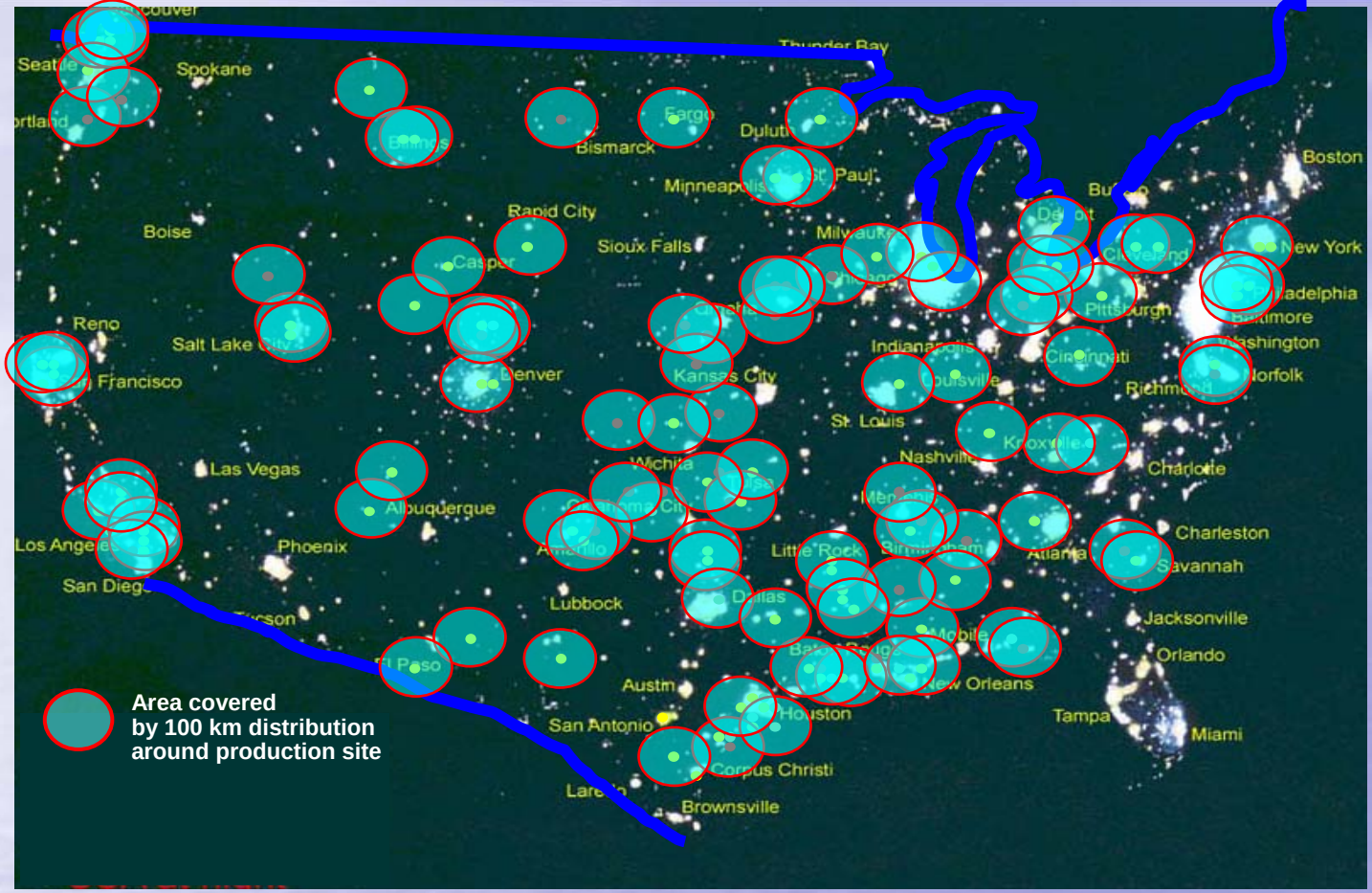
Hydrogen Production



Hydrogen Production



Hydrogen Production



Shell Hydrogen

Hydrogen Delivery

- Cryogenic liquid (-423°F)
  - 9 hydrogen liquefaction plants in North America
  - Transported by cryogenic truck, tube trailer, or rail car
  - Hydrogen liquefaction plants were first built in the 1950s to support the Apollo program
  - Typical unit uses 12.5 to 15 kWh per 1 kg of hydrogen
  - Range of >100 miles from the production facility
  - Hydrogen trailer carries 8,800 lbs (4,000 kg) of hydrogen

A delivery driver prepares to drops off a load of liquid hydrogen.

Praxair

Hydrogen Delivery

- Compressed gas
  - Hydrogen is difficult to compress (very small molecule)
  - Energy intensive
    - 1,000 psi, 0.6-0.7 kWh/kg
    - 3,000 psi, 2.6-3.6 kWh/kg
  - 5,000-10,000 psi fueling station delivery pressures (small scale)
  - High maintenance cost due to wearing components (valves)
  - Lowest cost option
  - <100-mile delivery by truck

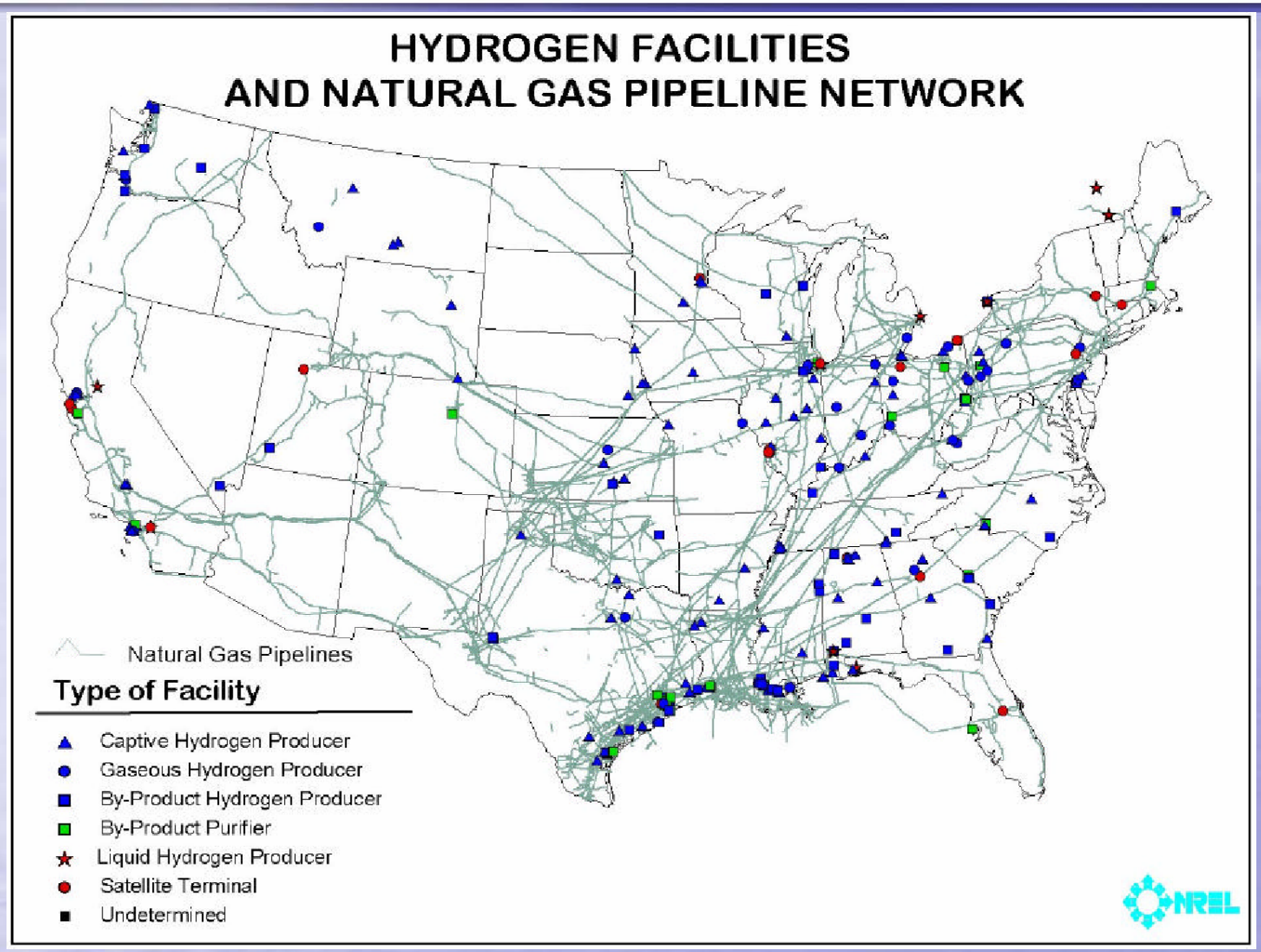
Praxair

Hydrogen Delivery

- Pipeline (Compressed Gas)
  - Most efficient transportation for large consumers
  - 10,000 miles worldwide
  - 700-1,000 psi pipeline delivery pressures (large volume)
  - Best for short distance delivery (capital intensive $0.5-$1.5 million/mile)
  - Cheapest delivery cost, once pipeline is built
- On-site production
  - Higher cost/kg due to small scale production
  - Dramatically reduces delivery costs

Honda hydrogen production and fueling station for fuel cell vehicles in Torrance, CA

Hydrogen Delivery



Cost Components of Hydrogen Fuel

Cost Components ($/kg)	Merchant Liquid Hydrogen*	On-Site Reformer	On-Site Electrolysis
Natural gas reforming	0.82	0.82	N/A
Cost of electricity	N/A	N/A	1.80**
Purification	0.03	0.03	N/A
Compression	N/A	0.24	0.16
Liquefaction	0.30	N/A	N/A
Handling, storage gasification, and dispensing	0.60	0.10	0.06
Delivery from a central production location to station	0.70	N/A	N/A
Other Costs***	0.35	0.30	0.48

*Merchant gas prices were estimated using the cost of centrally reforming large quantities of natural gas without carbon sequestration and transporting to the facility in liquid form.

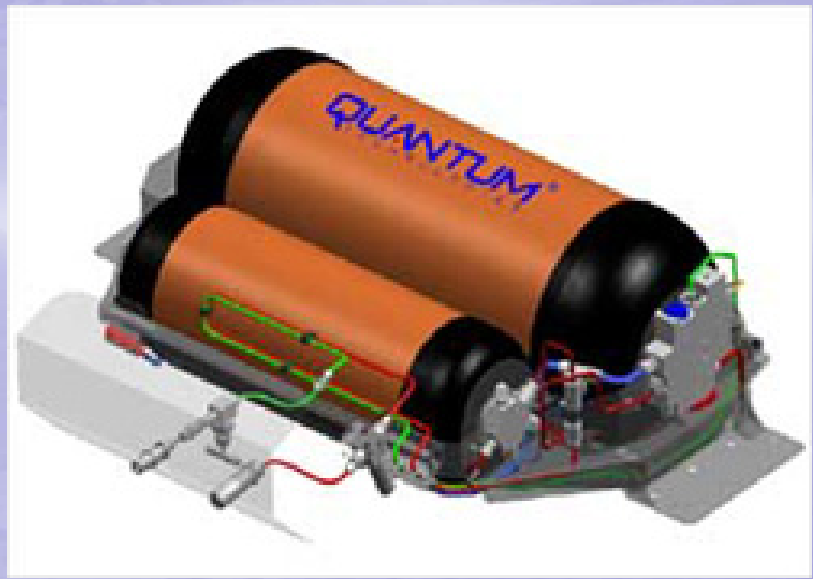
**DOE calculations based on $0.035 kWh of electricity

***Includes site preparation, controls, capital costs, balance of plant, rent, utilities, maintenance, etc.

"Transforming the Future: Moving Toward the Fuel Cell-Powered Fleets in Canadian Urban Transit Systems", Natural Resources Canada, February 2005

Hydrogen Storage

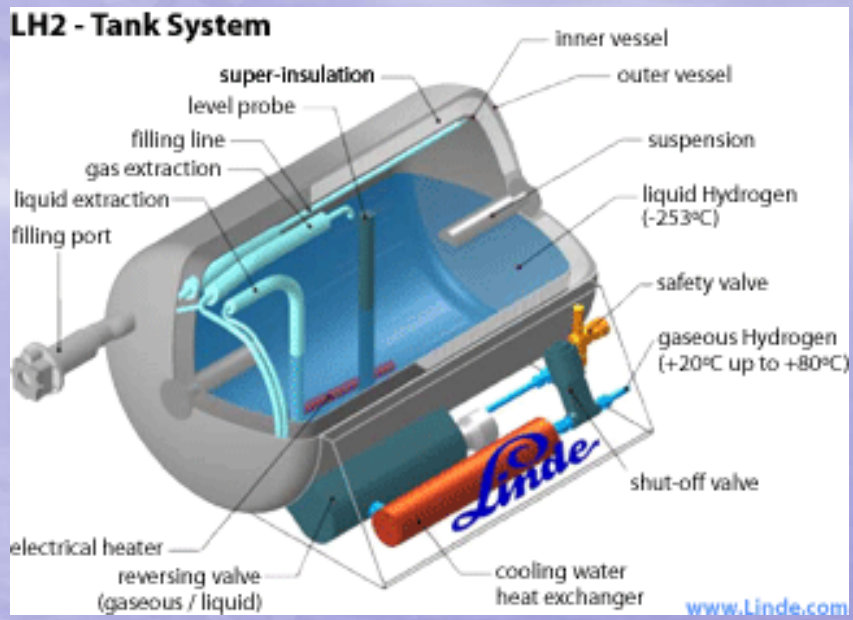
- Gaseous
  - Requires high pressure tanks (5,000-10,000 psi) to improve energy density
  - Carbon fiber reinforced wrapped with an aluminum or plastic liner
  - Cost of tanks is largely dictated by the cost of carbon fiber
  - 10,000 psi tank can extend vehicle range by 60% when compared to an equivalent-sized 5,000 psi tank



Carbon fiber reinforced 5,000 psi -10,000 psi compressed hydrogen tanks under development from Quantum Technologies

Hydrogen Storage

- Cryogenic liquid
  - Hydrogen boils at -423°F at 1 atmosphere
  - Boil-off rate of about 1% of the stored volume per day
  - 30% of the heating value of hydrogen is required for liquefaction
  - Can store more hydrogen in a given volume compared to a 10,000 psi compressed tank (0.58 lbs/gallon for liquid, 0.25 lbs/gallon for gas)



Liquefied hydrogen storage tank

Hydrogen Fueling Stations

- Can be designed to operate on delivered hydrogen or hydrogen generated on-site
- Uses pressure from the hydrogen supply
- Can be used to fuel fleets as small as 2 light-duty vehicles to as large as 6 buses

Hydrogen Fueling Stations

- Similar to the gasoline fueling experience
- Driver connects the fuel dispensing nozzle to the vehicle and follows the on-screen instructions
- Safety features
  - Automatic shutdown with leak detection
  - Standard operator grounding
  - Fuel by PIN to only allow access by qualified users
- Precautions similar to that of a gasoline station

Hydrogen Fueling Stations

Hydrogen Fueling Stations

- Mobile hydrogen fueling stations
  - Small fleet fueling
  - Can fuel 5 vehicles for up to 3 weeks without swapping or refueling
  - No utility hook-up required
  - Fueling procedure is fully automated
  - Can be used for off-site events (promotional or endurance testing)

Hydrogen Fueling Stations

- Stationary dispenser
  - Full fill in comparable times to gasoline/diesel fueled vehicle
  - Airtight lock prevents leaks
  - Standardized nozzle/receptacle geometries to prevent filling a low pressure tank with high pressure hydrogen
  - Automated and simple to use
  - Options
    - Multiple fueling pressures
    - Blended fuels
    - Product metering

Hydrogen Fueling Stations

- Shell Hydrogen/Gasoline Fueling Station
  - 1,500-gallon hydrogen storage tank and dispensing equipment
  - Visitor Center
    - Invite students, local, federal, and international officials to observe hydrogen fueling
- Safety features
  - Hydrogen storage tank installed below ground
  - Hydrogen and gasoline deliveries scheduled at different times

Shell Hydrogen/Gasoline Station, Washington, DC

Hydrogen Fueling Stations

- California Fuel Cell Partnership Headquarters Fueling Station
  - Installed jointly by 6 leaders in energy and industrial gas supply
  - Used to fuel vehicles with gaseous or liquid hydrogen
  - Performed over 3,000 fueling events safely
  - Hydrogen is delivered by truck (the same way gasoline is delivered)
  - Stored cryogenically at -423F
  - Meets or exceeds safety standards set by NFPA and ASME

California Fuel Cell Partnership Headquarters, West Sacramento, California

Hydrogen Fueling Stations

- Major components
  - One 4,500-gallon storage tank
  - Vaporizer that warms the liquid hydrogen to gas
  - Compressor to raise the gas pressure to 6,250 psi
  - 3 gaseous hydrogen tubes
  - 2 gaseous dispenser
    - 1 at 3,600 psi
    - 1 at 5,000 psi
  - 1 liquid hydrogen dispenser

California Fuel Cell Partnership hydrogen fueling station

Hydrogen Fueling Stations

- Fast fill protocol takes less than 5 minutes
  - Driver connects communication cable
  - Establishes safety and vehicle systems are functioning properly
- Time fill protocol takes under 15 minutes
  - Does not use communications link
- Safety features
  - Wireless and remote monitoring
  - IR fire detection
  - Hose breakaways
  - Manual emergency stops
  - Passive pressure relief devices

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