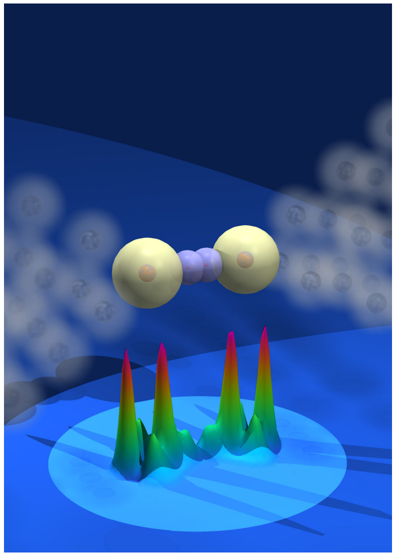


HYDROGEN ECONOMY

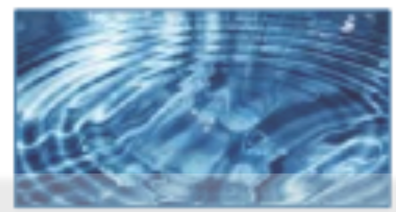
H_2: Fuel Cell Summary

Fuel Cell Type	Output	Electrical Efficiency	CHP Efficiency	Cost (estimated)
Polymer Electrolyte Membrane (PEM)	<1kW –250kW	53-58% (transport) 25-35% (stationary)	70-90% (low-grade waste heat)	$75-110/kW
Alkaline (AFC)	10kW – 100kW	60%	>80% (low-grade waste heat)	$80–200/kW
Phosphoric Acid (PAFC)	50kW – 1MW (250kW module typical)	>40%	>85%	$1500-2000/kW (target)
Molten Carbonate (MCFC)	<1kW – 1MW (250kW module typical)	45-47%	>80%	$1200/kW (target) >$2400/kW
Solid Oxide (SOFC)	<1kW – 3MW	35-43%	<90%	$400/kW (target)

Hydrogen: Three Components

- Generation
  - Thermal processes
  - Electrolytic processes
  - Photolytic processes
- Storage
  - Gaseous or Liquid
  - Materials-based
- Utilization
  - Combustion
  - Fuel Cells



Thermal or Electrolytic Processing?

HYDROGEN GENERATION

Hydrogen Generation

- Hydrogen is an energy carrier
- Hydrogen (H_2 gas) not naturally occurring
  - Must be formulated
- Three classes of technoloies
  - Thermal Processes
  - Electrolytic Processes
  - Photolytic Processes

H_2 Generation: Three Classes

Thermal Processes

- Natural Gas Reforming
- Bio-Derived Liquids Reforming
- Coal and Biomass Gasification
- Thermochemical Production

Electrolytic Processes

- Water Electrolysis

Photolytic Processes

- Photoelectrochemical Production
- Biological Production

Thermal Processes

- Natural Gas Reforming (steam)
- Coal and Biomass Gasification
- Bio-derived Liquids Reforming

High temperature (700 ˚C – 1000 ˚C)

High pressure (3–25 bar)

$$C_xH_yO_z + O_2 + H_2O \longrightarrow CO + CO_2 + H_2 + \text{other species}$$

(Shift reaction)

Thermal Processes (cont)

Water-gas Shift Reaction (convert CO to CO_2)

$$CO + H_2O \longrightarrow CO_2 + H_2$$ (exothermic)

Pressure Swing Adsorption (PSA)

– Adsorption properties of gasses at higher pressure

– Facilitate CO_2 removal (for sequestration)

Thermal Processes (cont)

Thermochemical[a] (water splitting)

– Solar thermal

- Up to 2000 ˚C
- ZnO catalyst

$$2ZnO + heat \longrightarrow 2Zn + O_2$$

$$2Zn + 2H_2O \longrightarrow 2ZnO + 2H_2$$

– Nuclear

- Up to 1000 ˚C
- H_2SO_4 and I_2 catalyst

$$2H_2SO_4 \xrightarrow{850^\circ C} 2H_2O + 2SO_2 + O_2$$

$$4H_2O + 2SO_2 + 2I_2 \longrightarrow 2H_2SO_4 + 4HI$$

$$4HI \xrightarrow{300^\circ C} 2I_2 + 2H_2$$

[a] Identified by the DOE as research focuses

Electrolytic Processes

Water Electrolysis

- Electrolyzer - fuel cells in reverse (75 % efficient)
  - Renewable or nonrenewable sources
  - Increase temperature, increase efficiency
- Types
  - PEM
  - Alkaline

$$\text{Anode Reaction: } 2H_2O \longrightarrow O_2 + 4H^+ + 4e^-$$

$$\text{Cathode Reaction: } 4H^+ + 4e^- \longrightarrow 2H_2$$

  - Solid Oxide

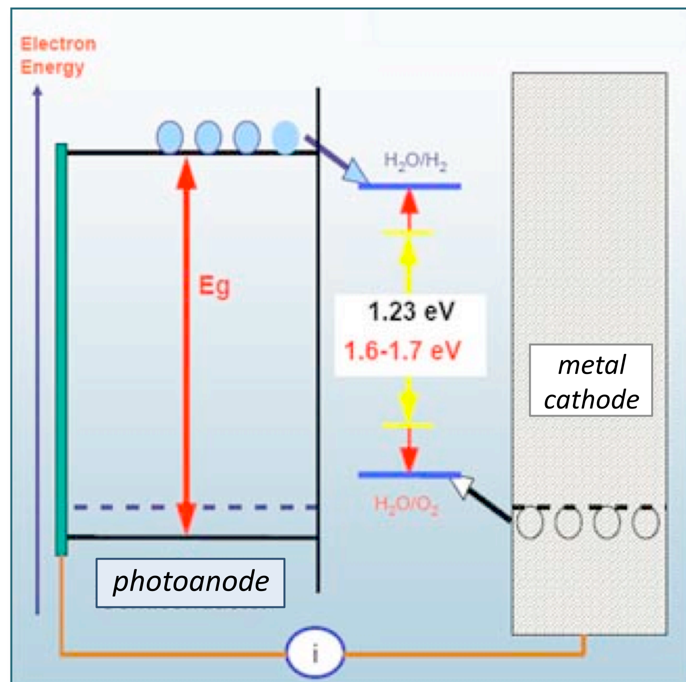
$$\text{Cathode Reaction: } 2H_2O + 4e^- \longrightarrow 2H_2 + 2O^{2-}$$

$$\text{Anode Reaction: } 2O^{2-} \longrightarrow 2O_2 + 4e^-$$

Photolytic Processes

Photoelectrolysis: Light energy to split H_2O

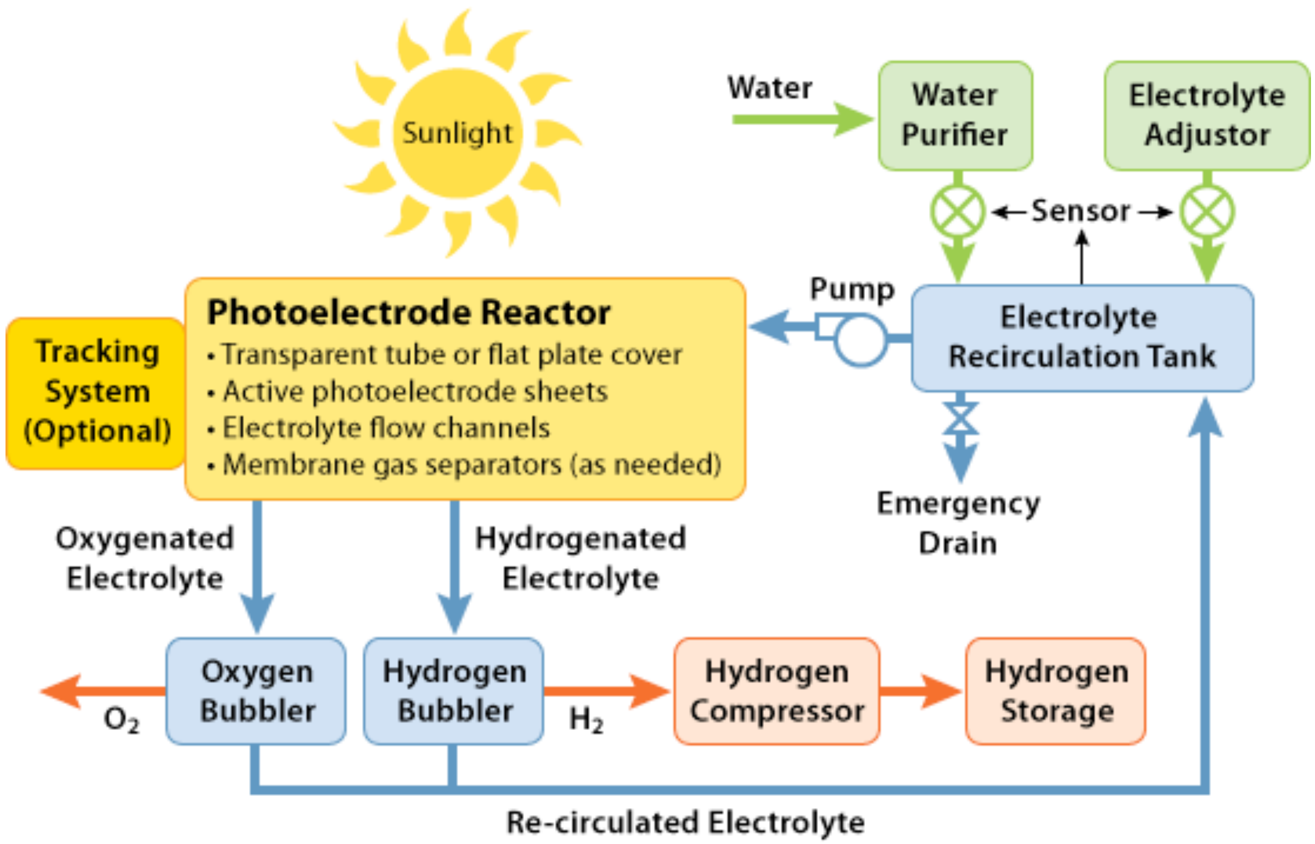
- Photosensitive semiconductor anode
- Photosensitive catalyst/anode
- Light absorption
  - Excites electron
  - Electron transferred to anode
  - 4 electron process



$$H_2O + * \rightarrow HO* + H^+ + e^-$$
$$HO* \rightarrow O* + H^+ + e^-$$
$$H_2O + O* \rightarrow HOO* + H^+ + e^-$$
$$HOO* \rightarrow O_2 + * + H^+ + e^-$$

Photolytic Processes

Photoelectrochemical Production



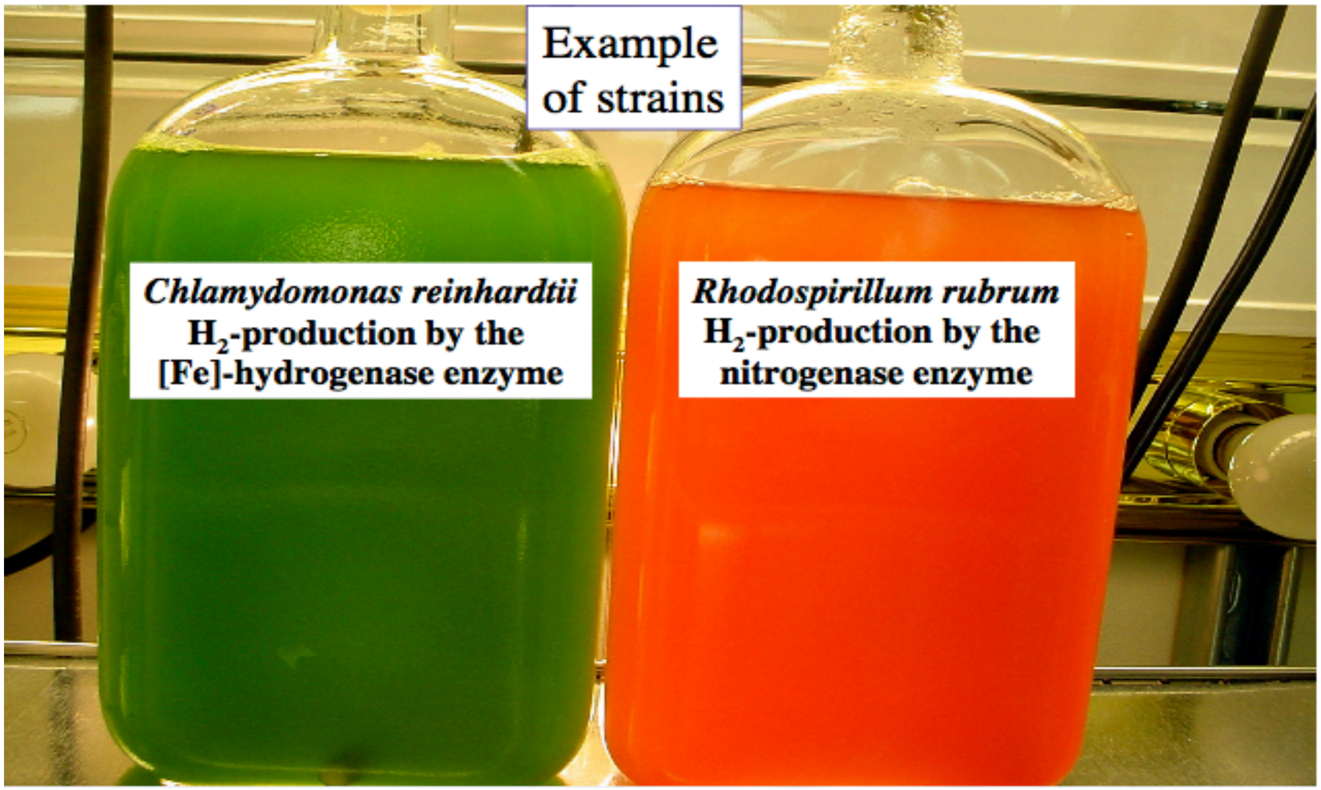
Photolytic Processes

Biological Production

- Specialized microorganisms produce H_2
  - byproduct of natural metabolic processes.
- Examples
  - Unicellular green algae
  - Cyanobacteria
  - Photosynthetic bacteria
  - Dark fermentative bacteria
- Long-term technology
  - microbes split water much too slowly (currently)

Photolytic Processes

Biological Production



Green algae

$2H^+ + D_{red} \rightarrow H_2 + D_{ox}$
D = cytochrome c_3 and c_6

Photosynthetic bacteria

$N_2 + 8\ H^+ + 8\ e^- + 16\ ATP \rightarrow$
$2\ NH_3 + H_2 + 16\ ADP + 16\ P_i$

Three Classes Revisited

Thermal Processes		
Natural Gas Reforming	High energy^	CO_2-emitting
Bio-Derived Liquids Reforming	High energy^	CO_2-emitting
Coal and Biomass Gasification	High energy^	CO_2-emitting
Thermochemical Production	High energy*	CO_2-emitting/neutral
Electrolytic Processes		
Water Electrolysis	High energy*	CO_2-emitting/neutral
Photolytic Processes		
Photoelectrochemical Production	Low energy(?)	CO_2-neutral
Biological Production	Low energy(?)	CO_2-neutral

*depending upon source of energy
^established processes

Conventional or Novel

HYDROGEN STORAGE

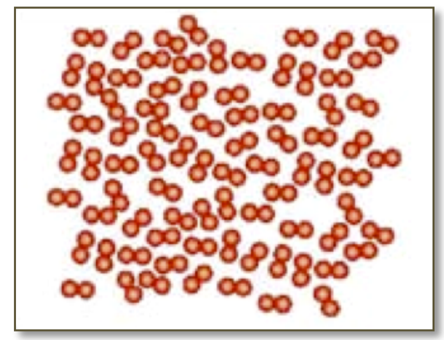
Hydrogen Storage

- Conventional technologies – Tank-based
  - High-pressure cylinders
  - Low temperature liquid storage

- Novel technologies – Material-based
  - Adsorption (surface)
  - Absorption (bulk)
  - Chemical reaction (hydrides)

H_2 Storage: Conventional

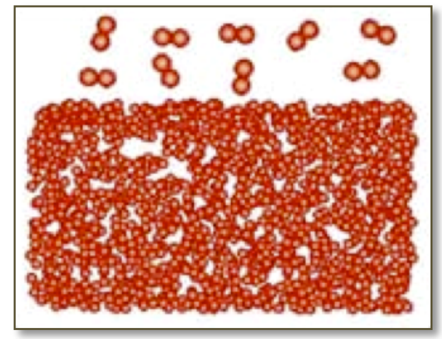
- High pressure storage
  - 5,000 to 10,000 psi (35 to 70 MPa)
- Improve energy density
  - 0.030 kg/L (10,000-psi tank)
- Carbon fiber reinforced tank
- Issues: compression technology
  - Improve efficiency
  - Reduce cost



Compressed gas

H_2 Storage: Conventional

- Cryogenic (liquid) storage
  - Temperature: -253 ˚C
- Improve energy density
  - 0.070 kg/L
- Issues
  - Huge liquefaction energy penalty
  - Hydrogen boil-off
  - Requires insulation – reduces capacity

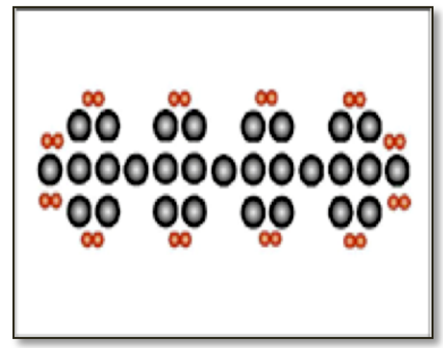


Cryogenic liquid

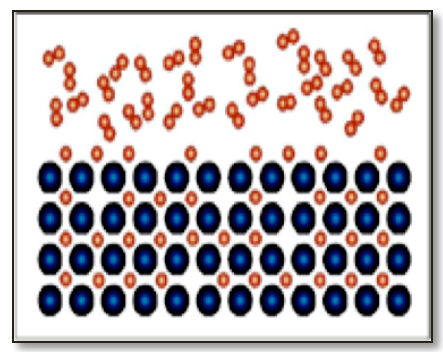
H_2 Storage: Physical

- Process controlled by physical changes
- Issues
  - Temperature
  - Pressure
  - Electrical
- Issues (current)
  - Low density/capacity
  - Reproducible reversibility

Adsorption



Absorption



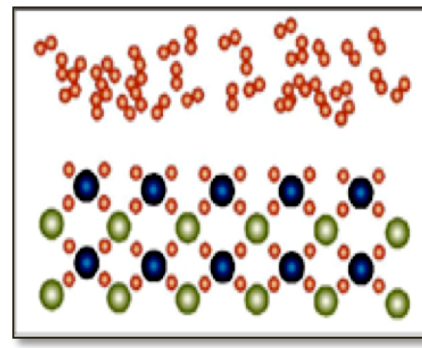
H_2 Storage: Physical

- Adsorption
  - H_2 adsorbs onto surface of material
    - Graphene/graphane – (1 atom thick carbon sheets)
    - Metal doped-carbon nanotubes
    - High porosity carbon materials (aerogels, activated)
- Absorption
  - H_2 absorbs into the bulk material
    - Metal-organic frameworks
    - Metal-doped fullerenes

H_2 Storage: Chemical

Metal Hydrides

- Reversible solid-state materials
  - Potential on-board storage
- Boron or aluminum hydrides
  - Alanate (one example)



$$NaAlH_4 \xrightarrow{>33^\circ C} 1/3\ Na_3AlH_6 + 2/3\ Al + H_2 \qquad (3.7\%)$$

$$Na_3AlH_6 \xrightarrow{>110^\circ C} 3\ NaH + Al + 3/2\ H_2 \qquad (1.8\%)$$

- Issues
  - Reversibility
  - Thermal management (refueling)

H_2 Storage: Chemical

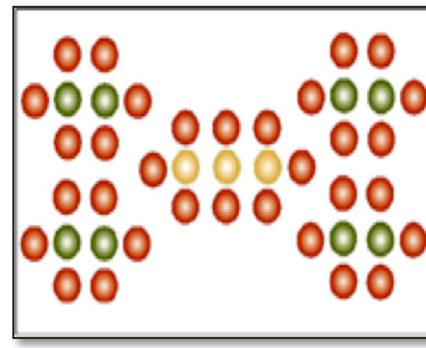
Chemical Hydrides

- H_2 generated by chemical reaction
- Two types:
  - Hydrolysis

    $NaBH_4 + 2H_2O \longrightarrow NaBO_2 + 4H_2$ (~4%)

  - Hydrogenation/Dehydrogenation

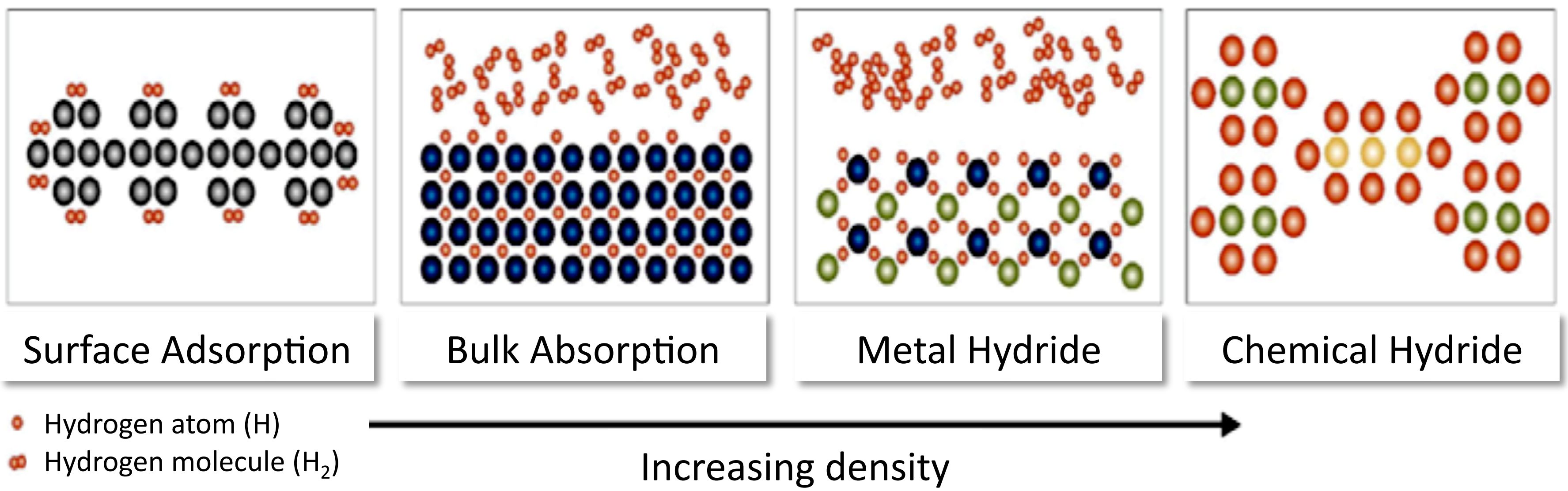
    $C_{10}H_{18} \xrightarrow[\text{Pt-cat}]{210^\circ C} C_{10}H_8 + 5H_2$ (7.3%)



- Issues
  - Spent fuel has to be removed
  - Regenerated off-board

Hydrogen Storage

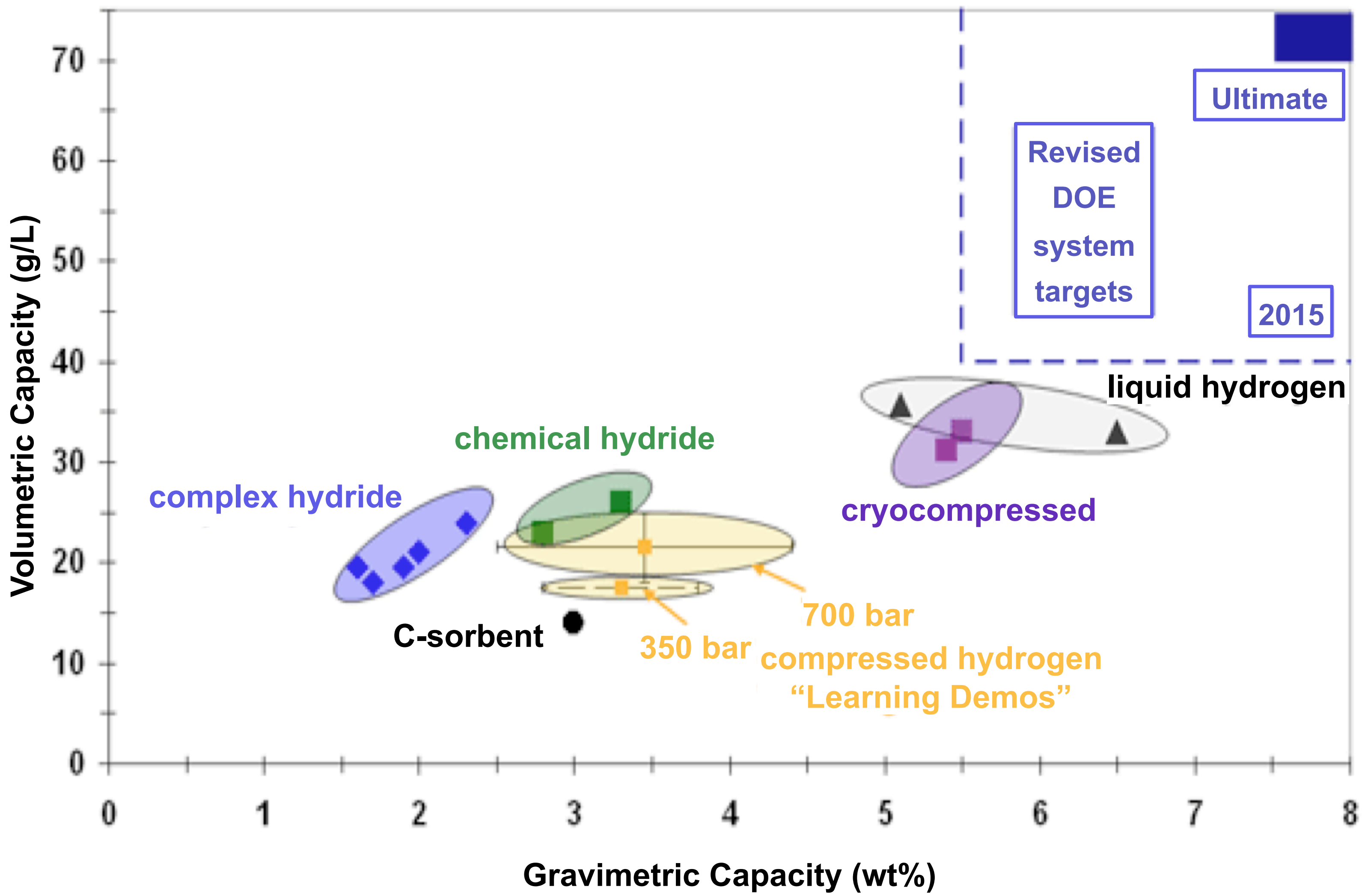
Materials-based



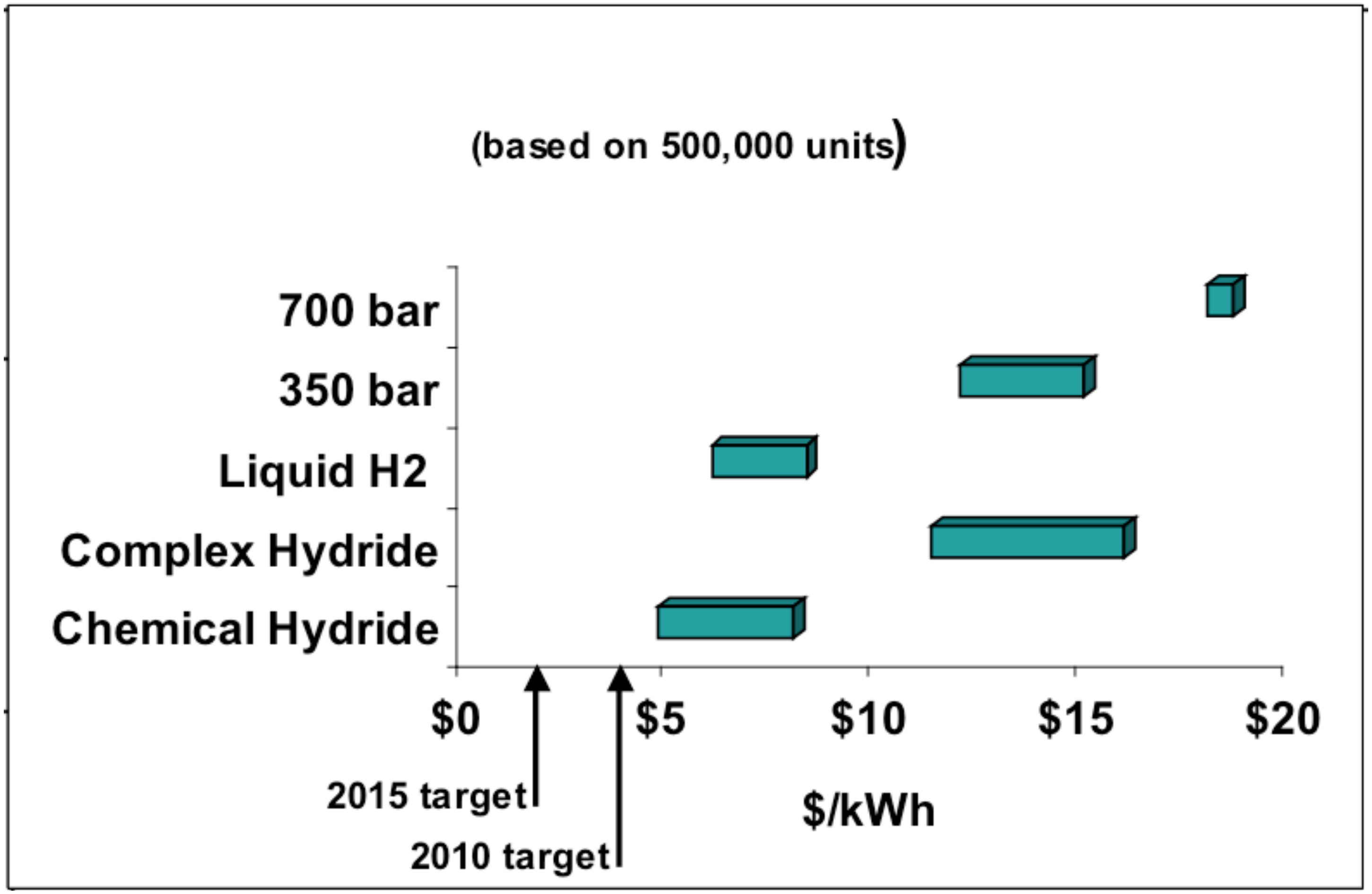
H_2 Storage Objectives

- By 2010: on-board hydrogen storage
  - 0.045 kg H_2/kg (4.5 wt%)
  - 0.028 kg H_2/L
  - $4/kWh
- By 2015: on-board hydrogen storage
  - 0.055 kg H_2/kg (5.5 wt%)
  - 0.040 kg H_2/L
  - $2/kWh

Hydrogen Density



H_2 Storage: Cost Estimates



H_2 Storage Summary

Tank-based			
High pressure cylinders	High density	Energy intensive	On-board
Low temperature liquids	Highest density	Energy intensive	On-board
Materials-based			
Adsorption process	Lowest density	Least intensive	On-board
Absorption process	Low density	Less intensive	On-board
Metal hydrides	High density	Less intensive	Off-board
Chemical hydrides	Higher density	Energy intensive	Off-board

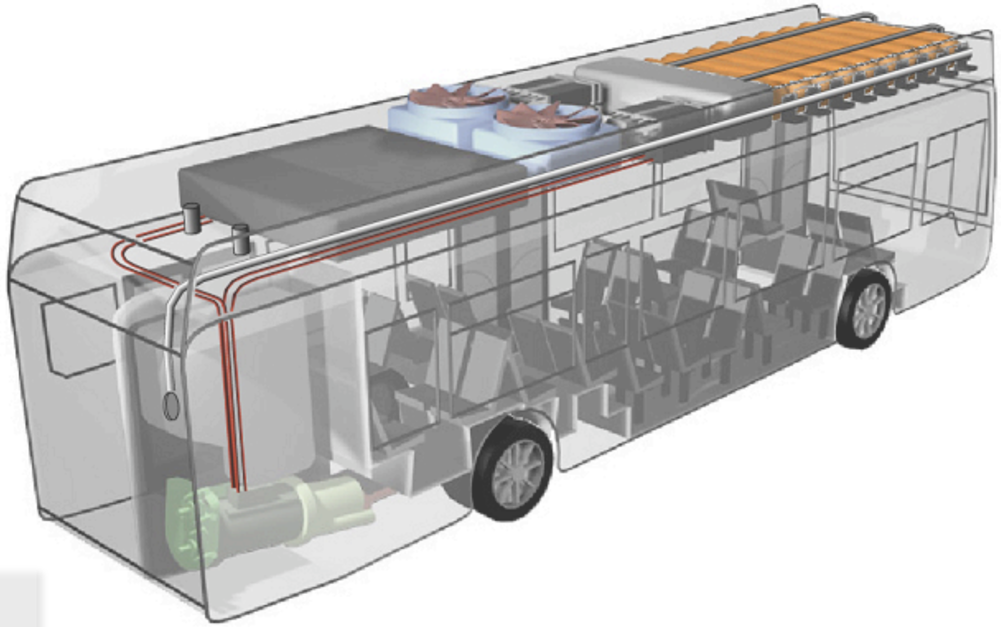
Hydrogen Economy

- Generation
  - Transport
- Storage
  - Transport
- Utilization

Generation:
- Thermal processes
- Electrolytic processes
- Photolytic processes

Storage:
- Gaseous or Liquid
- Materials-based

Utilization:
- Fuel Cells



A Case Study

ICELAND

Why Hydrogen?

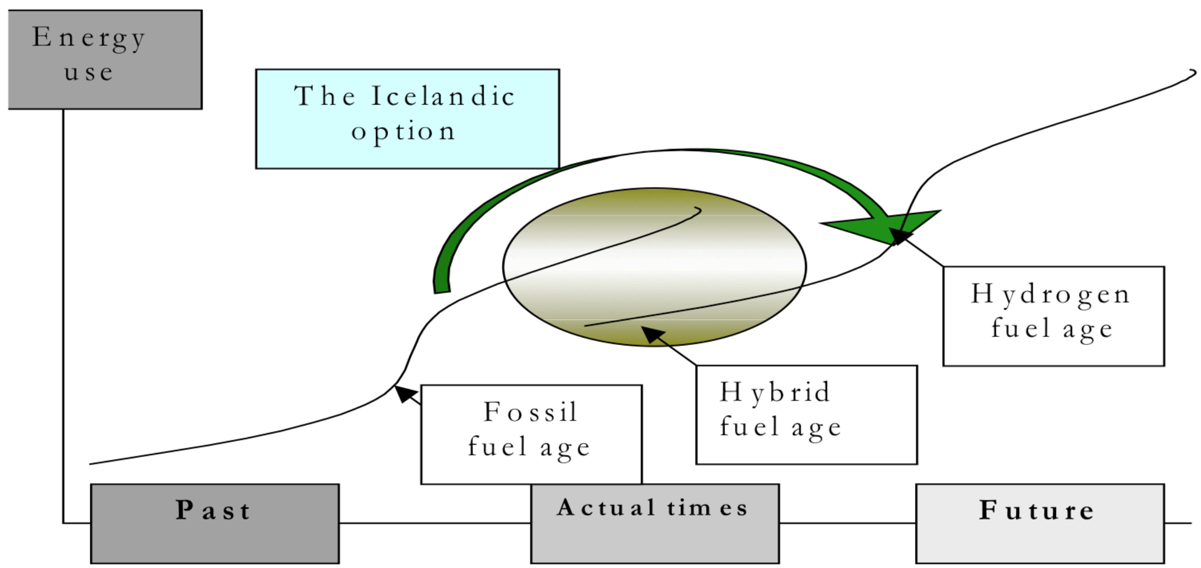
Iceland

Volcanic origins
+
Viking history

Lack of carbon-based energy

- 70% sustainable energy
  - Hydroelectric - Main source of electricity
  - Geothermal - District heating and electricity
- Fossil fuels – 30%
  - All imported - Transportation and commercial fishing
  - Replace with domestic energy

Hydrogen Plan



Multi-part plan to meet energy needs

- H_2 powered-buses within public transport system
- Build/operate production-, compression- and storage site
- Fishing vessel run on H_2 fuel cells

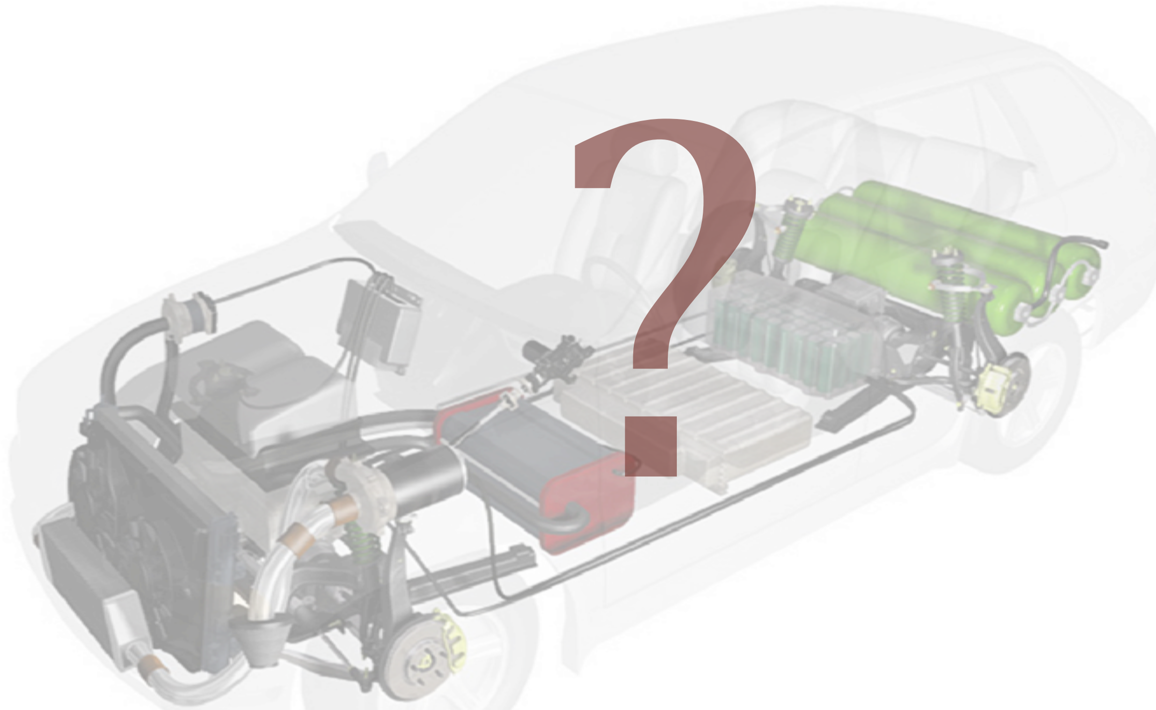
Demonstration Project: ECTOS

Ecological City Transport System

- 4 1/2 yr project - started March 1st 2001
- Operate 3 FC buses (75 bus fleet)
  - 5,216 operating hours
  - 89,243 km
- Hydrogen fuel station (at gasoline station)
  - Multi-module electrolyzer
  - Current: 1200 - 1500A
  - Pressure: 15 bars
  - 65-80% efficient (most efficient when run continuously)

What's Next

- HyFLEET:CUTE (2006-2009)
  - 47(30) buses in 10 cities on three continents (1 yr)
- Iceland: SMART-H2 (2007-2010)
  - Personal cars (20-30 by 2009)
    - DaimlerChrysler FC A-Class: 225 mile (362 km)
    - Prius ICE: 102 mi (165 km)
    - Ford FC Focus: 150-200 mi (241-322 km)
    - Ford FC Explorer: 350 mi (563 km)
  - Fuel cell equipped tour boat
    - Auxiliary power unit (for onboard electricity)
    - 10 kW



DOES A HYDROGEN ECONOMY MAKE SENSE?

Energy Needs

- Energy to synthesize H_2/convert electricity
- The stats
  - 1kg Hydrogen = 1 gal gasoline
  - Electrolysis method
    - 200 MJ (55 kWh) electricity
    - 9 kg of water
- Heating Values
  - HHV = Enthalpy of H_2O formation (285 kJ/mol)
  - LHV = Heat of combustion then return to 150 ˚C

Hydrogen Production

- Electrolysis – renewable sources (wind)
  - Process efficiency of 75%
  - Dismisses high-temp solar or nuclear process.
  - High-temp electrolysis?
- Biomass
  - Questions the need for conversion
  - Biomethane is “perfect fuel”
  - Current systems are 90% efficient
  - Not considered in this context. Why?

Hydrogen Packaging

- Compression
  - More energy to compress than methane (9x)
  - Multi-stage compression consumes 8% HHV H_2
  - Including all losses $\rightarrow$ 20% HHV H_2
- Liquefaction
  - More energy consumptive than compression
  - For 10,000 kgLH_2/h: 25% HHV (no existing plant)
  - Boil-off losses

Metal Hydrides

- Physical Hydrides
  - Storage density 78-85% of liquid hydrogen
  - 50 kg hydride/1 kg H_2 (1 gal gasoline)
  - Energy density comparable to Li-Ion batteries
- Chemical Hydrides
  - Energy to produce alkali metal hydrides too high
  - Synthesized from pure metals/H_2
  - At least 1.6x more energy/ 1 energy unit H_2

Hydrogen Transport

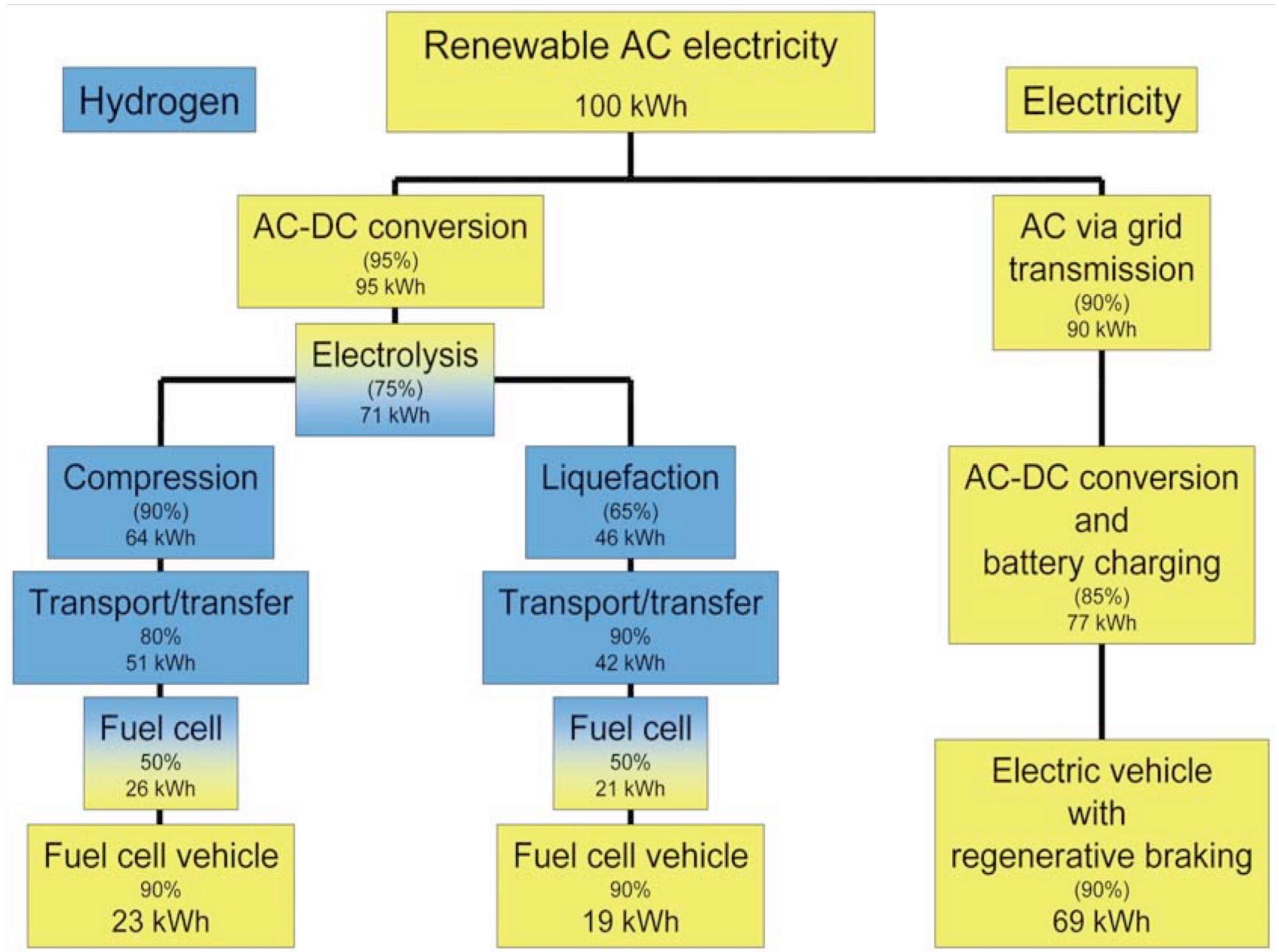
- Road Delivery
  - 22 H_2 trailers = 1 gasoline tanker
  - 80% delivered H_2 = 100% delivered liquid fuels
  - Diesel fuel consumption
    - 0.5% HHV liquid fuels
    - 7% HHV compressed/1.9 % HHV liquid H_2
- Pipeline Delivery
  - 3.13x energy flow for methane
  - Transport: 3.85x more energy than natural gas
  - 35% mass consumption vs 20% for natural gas

Energy Efficiency

- On-Site Generation
  - H_2 via electrolysis
  - Fuel cells
    - 1.5x more efficient than ICE
    - 2.5x efficiency not justified: diesel and hybrid systems
  - 1.6 units energy/1 unit energy H_2
- Transfer of Hydrogen
  - Fuel tanks
    - H_2: load under pressure
    - liquid fuels: drain into tank

Hydrogen or Electron Economy

- 1.6-2.0x energy/ 1 energy units H_2
- Motion efficiency:
  - 50% fuel cell
  - 45% ICE
- Overall efficiency:
  - 20-25% H_2
  - 60% EVs



Hydrogen or Electron Economy?

- No direct comparison to EVs (except one instance)
- Most comparisons are to liquid fuels
- No discussion
  - Commercial transport applications
  - Mass transportation application
  - Stationary power applications
  - Marine vessel applications
- Battery electric cars: more work needed
  - Electricity storage
  - Converters
  - Drive systems
  - Electricity transfer

Current Energy Economy

Transportation Technologies

- Diesel
- Gasoline
- Other oil-derived fuels

Stationary Power Technologies

- Coal
- Natural gas (heating)
- Nuclear
- Hydroelectric

Sustainable Energy Future

Transportation Technologies

- Biofuels
- Hydrogen (i.e. fuel cells)
- Electric vehicles (EVs)

Stationary Power Technologies

- Wind
- Solar
- Geothermal
- Hydroelectric
- Hydrogen (i.e. fuel cells)