Part 2. Hydrogen and Related Topics

1. Introduction and hydrogen economy
2. Production of hydrogen from water
3. Hydrogen storage
4. Usage of hydrogen
5. Safety aspects

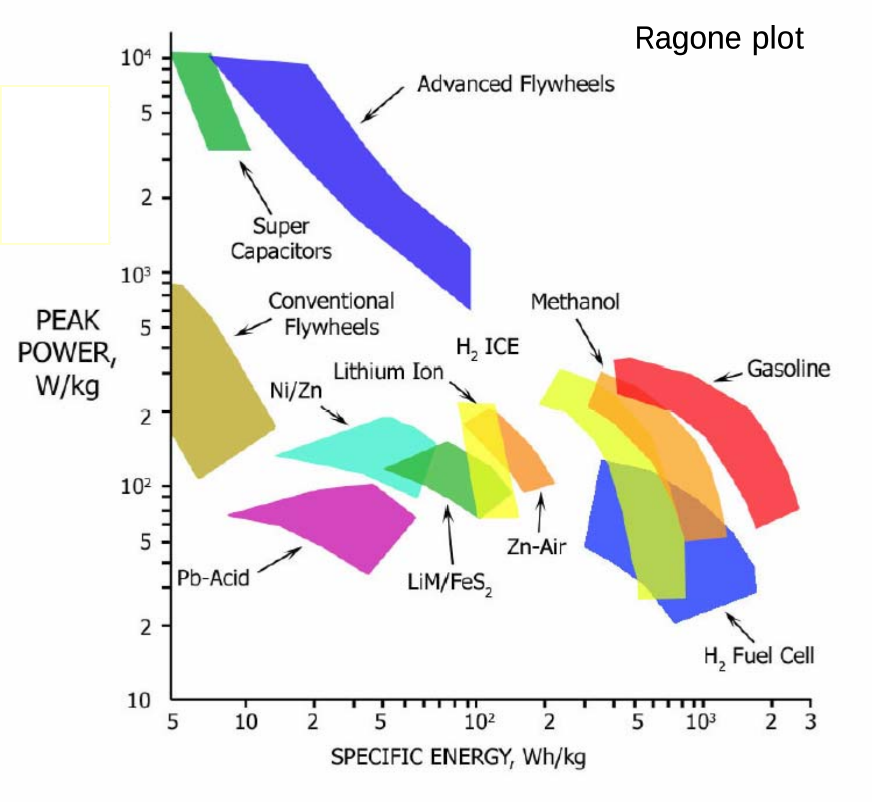
The objective of these lectures is to provide the required knowledge of using hydrogen as a medium of energy.

Our focus here is energy storage and fuel for transportation in a distributed energy scenario.

Renewable Energy Storage

Solar and wind energy sources are intermittent and regional.

They will become major sources of power if we find efficient ways to store and transport their energy.



Source: J.W.Tester, Sustainable Energy, MIT, 2005

Renewable Energy Storage and Fuel for Transportation

Hydrogen, the simplest molecule, can be used for storing energy and make it available where and when it is needed.

When used as a chemical fuel, it does not pollute

Hydrogen is not an energy *source* , but it is an energy *carrier* that has to be manufactured like electricity.

Hydrogen can be manufactured from many primary sources (from clean water and solar energy) - reduces the chances of creating a cartel.

Hydrogen Cycle: electrolysis → storage → power conversion

Hydrogen Properties

Hydrogen has several important chemical properties that affect its use as a fuel:

* It readily combines with oxygen to form water, which is absolutely necessary for life on this planet.

* It has a high energy content per weight (nearly 3 times as much as gasoline), but the energy density per volume is quite low at standard temperature and pressure. Volumetric energy density can be increased by storing the hydrogen under increased pressure or storing it at extremely low temperatures as a liquid. Hydrogen can also be adsorbed into metal hydrides.

* Hydrogen is highly flammable; it only takes a small amount of energy to ignite it and make it burn. It also has a wide flammability range, meaning it can burn when it makes up 4 to 74 percent of the air by volume.

* Hydrogen burns with a pale-blue, almost-invisible flame, making hydrogen fires difficult to see.

* The combustion of hydrogen does not produce carbon dioxide (CO_2), particulate, or sulfur emissions. It can produce nitrous oxide (NO_X) emissions under some conditions.

* Hydrogen can be produced from renewable resources, such as by reforming ethanol (this process emits some carbon dioxide) and by the electrolysis of water (electrolysis is very expensive now).

Source: www.eere.energy.gov

Hydrogen Properties

Energy Content for 1 kg (2.2 lb) of Hydrogen = 424 Standard Cubic Feet (Reacting with oxygen to form water)

Higher Heating Value	Lower Heating Value
134,200 Btu	113,400 Btu
39.3 kWh	33.2 kWh
141,600 kJ	119,600 kJ
33,800 kCal	28,560 kCal

Fuel Properties

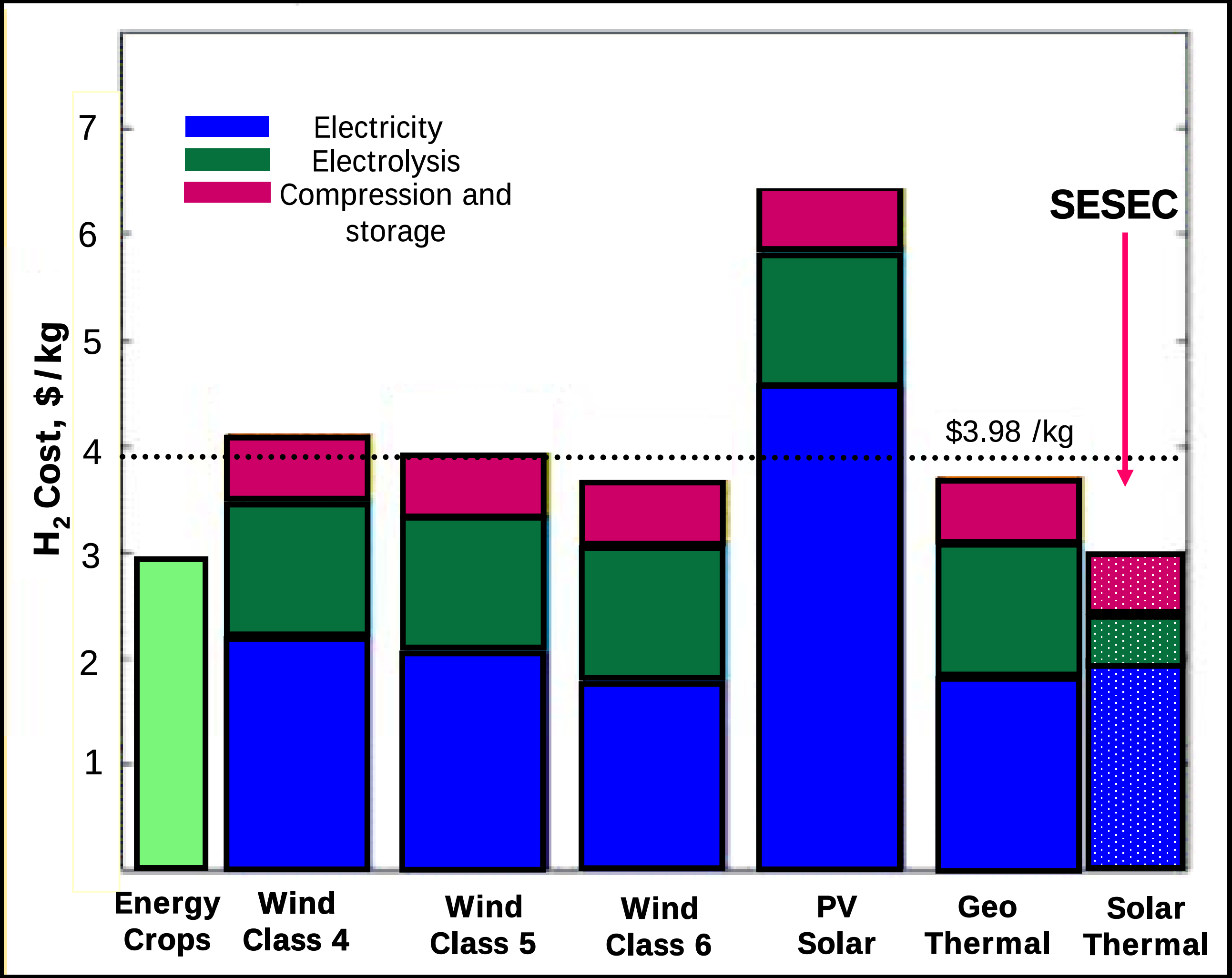
Comparison with other fuels

Fuel	Energy [kJ/g]	Energy [kJ/l]
Coal	29.3	-
Brown coal	8.1	-
Wood	14.6	-
Gasoline	43.5	30590
Diesel	42.7	29890
Methanol	19.6	15630
Natural gas	50.02	31.7
Hydrogen	119.9	10

- High energy content per unit mass
- Low energy content per unit volume

TUDelft

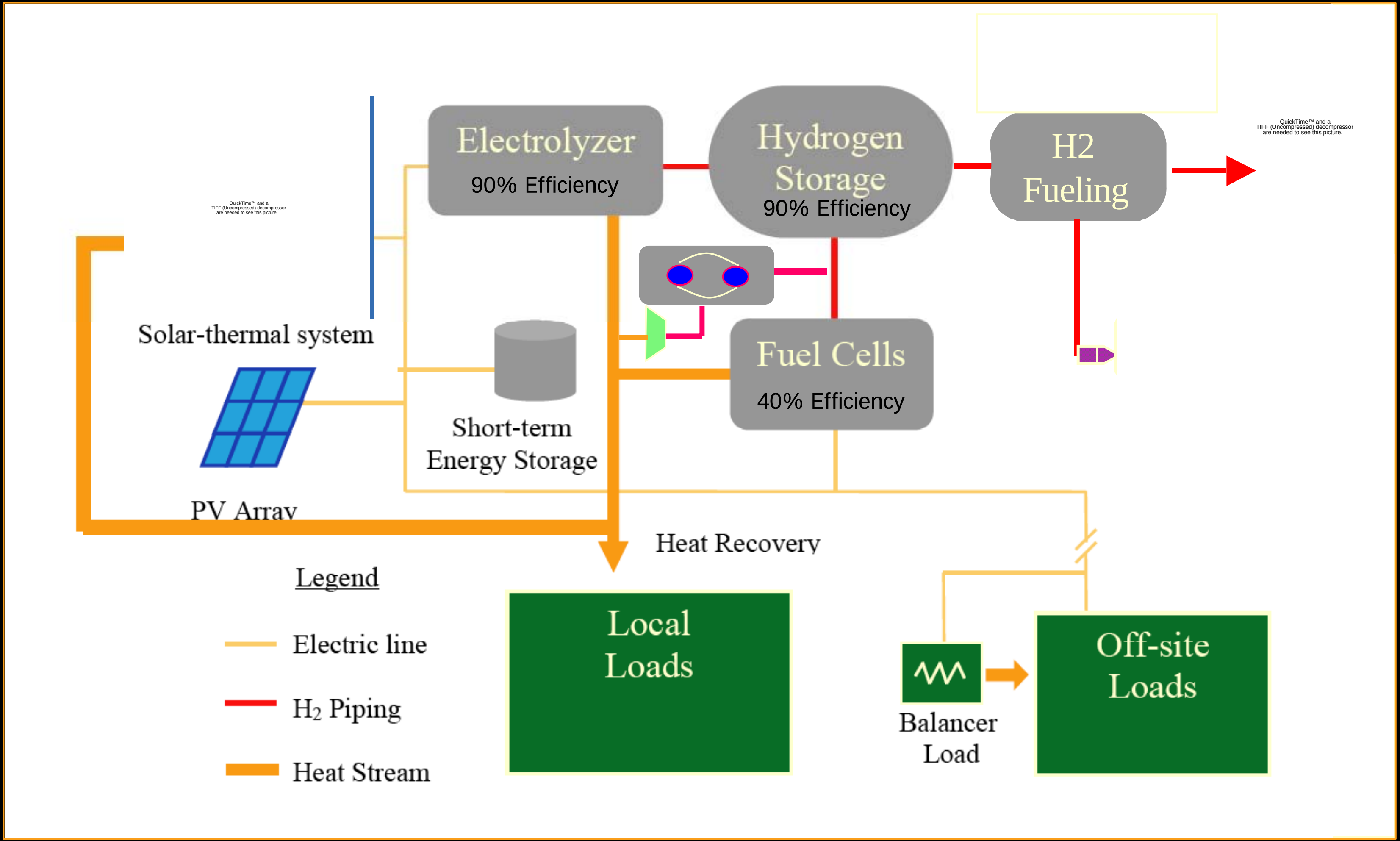
Renewable Hydrogen Cost



One Kg of hydrogen has roughly the same amount of energy as in one gallon of gasoline

Duane B. Myers et al., 2003, Hydrogen from Renewable sources, Direct Technologies, inc, Arlington, VA 22201

SESEC Project - $1000 / kW



5 kW Solar-electricity & hydrogen generation System

Hydrogen Economy

Production: sustainable energy like wind, solar or biomass would produce electricity to be used to split water into hydrogen as fuel and oxygen as a valuable by-product. "Renewable Hydrogen"

Storage: Hydrogen would be used as an energy-storage medium - as a gas under pressure, as a cryogenic liquid, in hydrogen absorbing alloys (hydrides) or in carbon nanostructures.

Distribution: As a gas, hydrogen can transport energy in pipelines over long distances.

Fuel: As a chemical fuel, hydrogen can be used in a much wider range of energy applications - internal combustion engines, gas turbines and fuel cells etc. When used properly produces no nitrogen oxides and no hydrocarbons.

Hydrogen Economy

Why did not hydrogen make significant inroads into existing energy systems years ago?

Fossil fuels were cheap and hydrogen was several times more expensive.

Environment degradation was a concern of a tiny minority and environmental health is not high on the list of priorities.

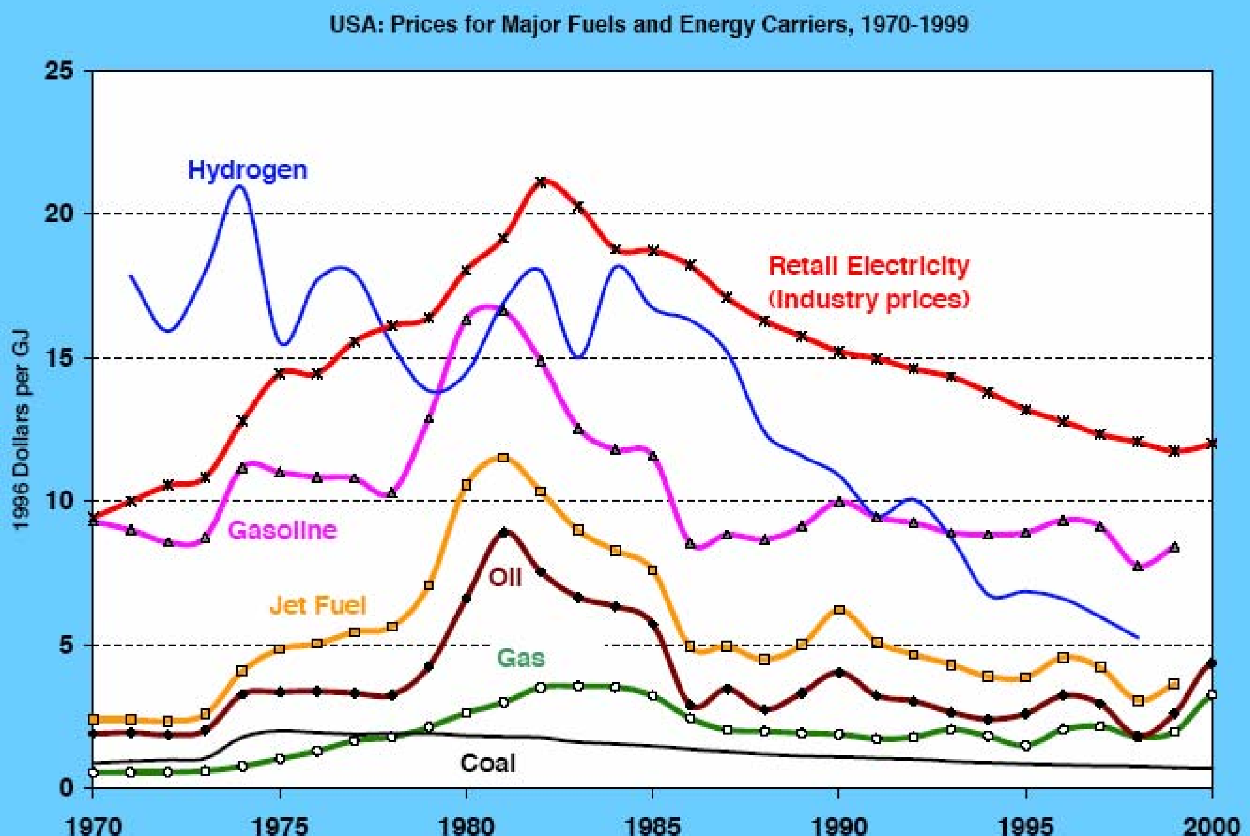
Inadequate technology for routine production, handling and storage of hydrogen.

Societal issues such as replacing an entire technologically advanced energy system of immense infrastructure with something else is huge undertaking.

Society does not yet place value on sustainability.

Hydrogen in our Energy Future

Hydrogen and Its Competitors

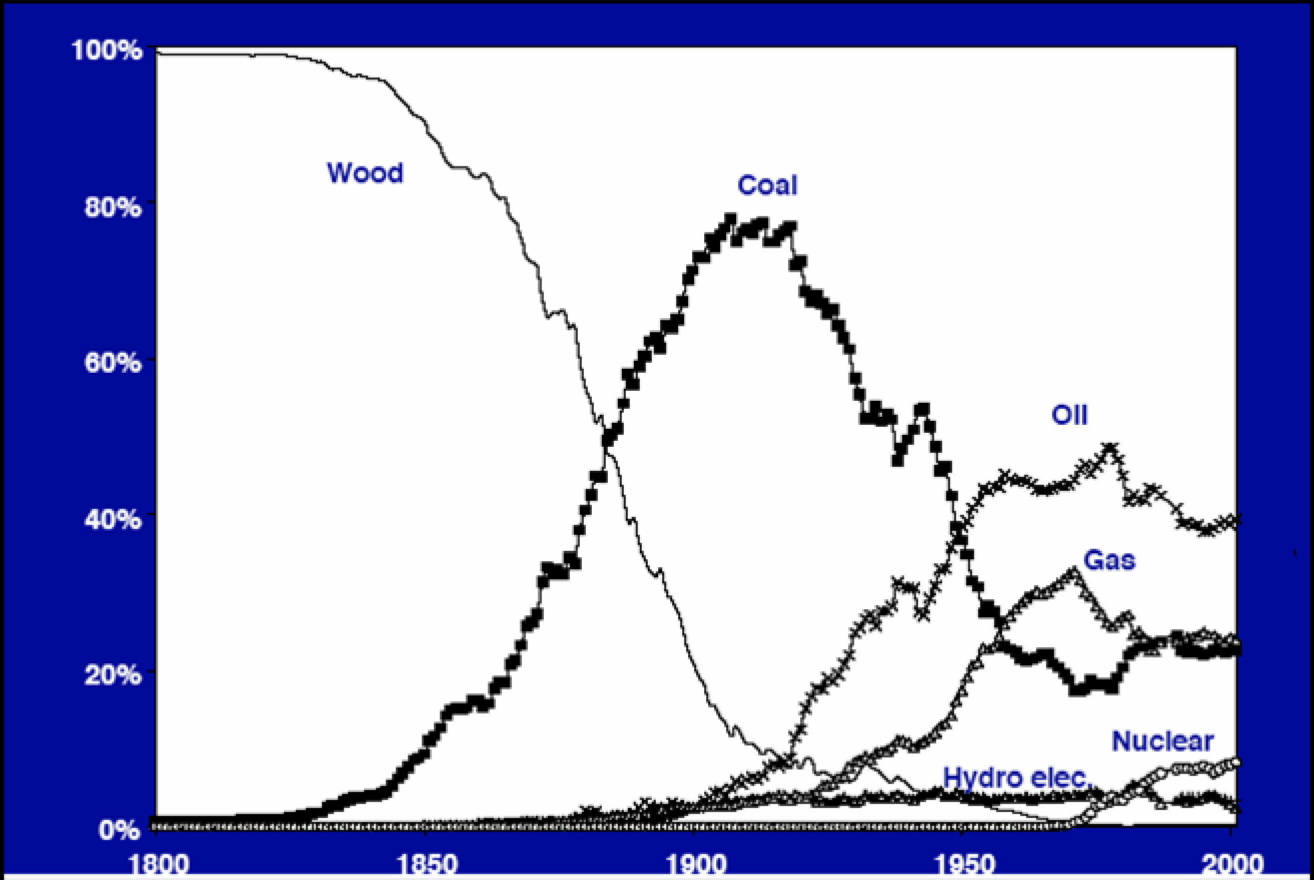


Source: David G. Victor

Program on Energy & Sustainable Development
http://cesp.stanford.edu/pesd

Sustainable Energy Science and Engineering Center

Evolution of Primary Energy Systems



Source: David G. Victor

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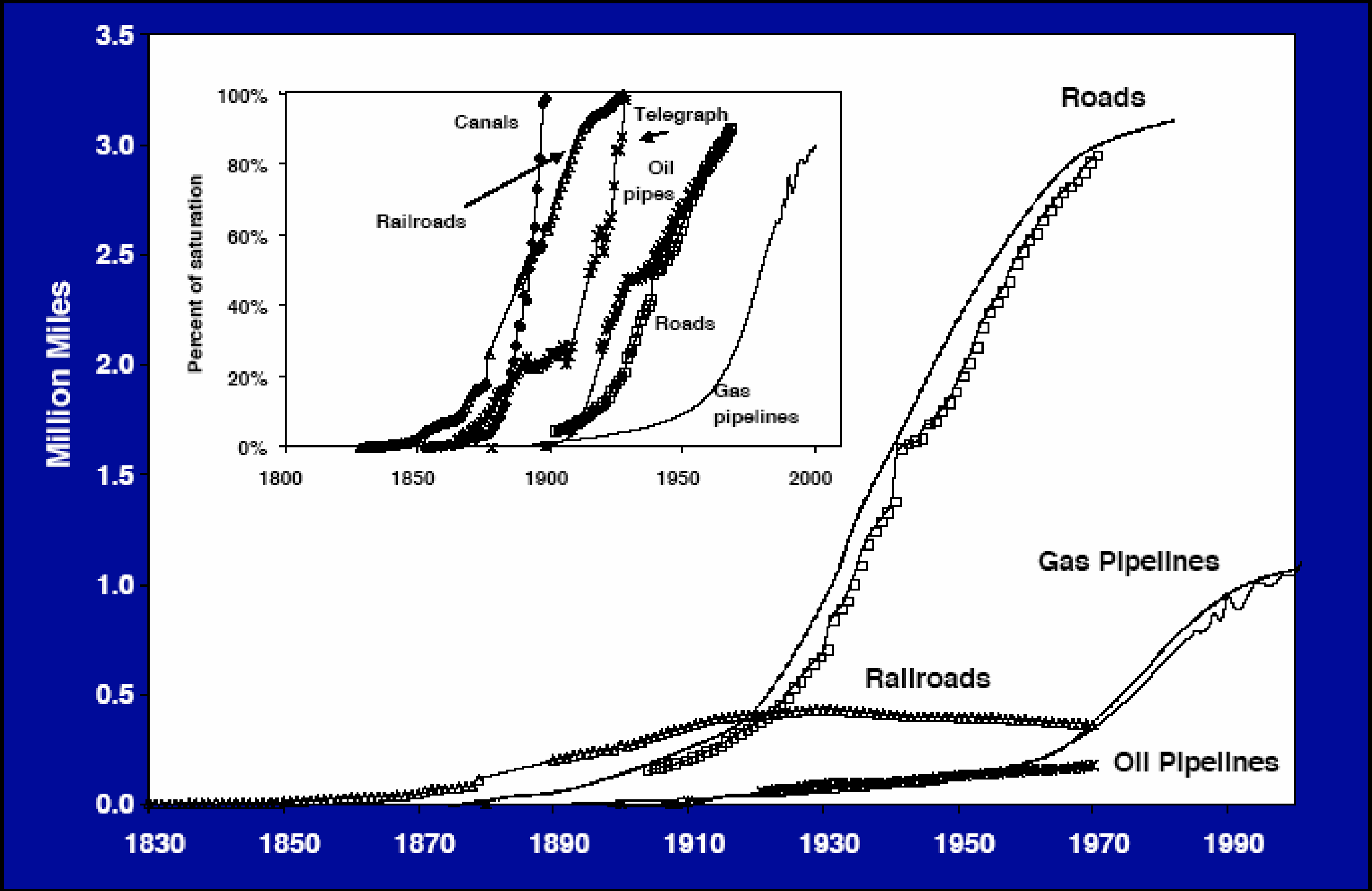
Sustainable Energy Science and Engineering Center

Infrastructure Evolution



Source: David G. Victor

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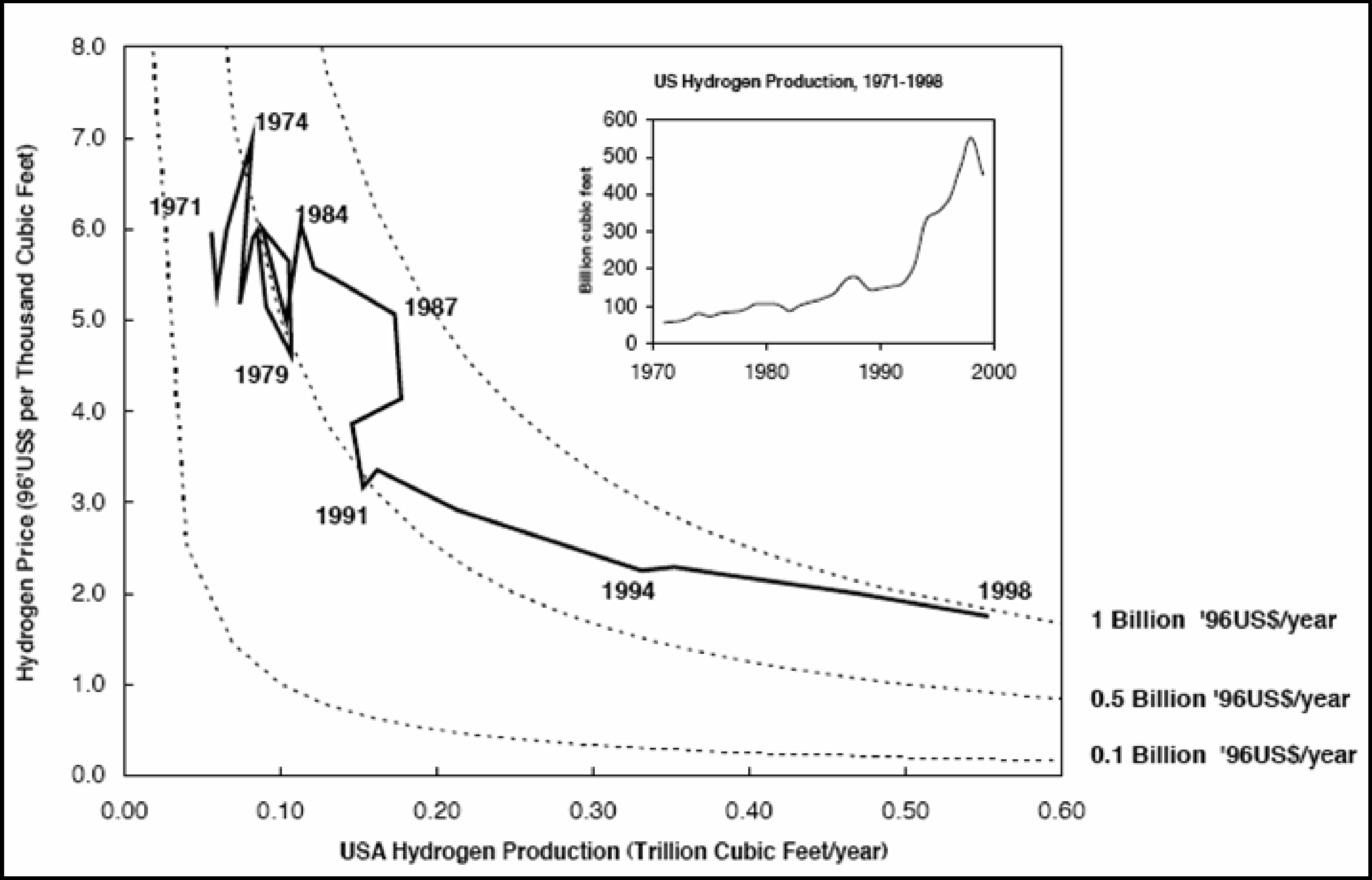
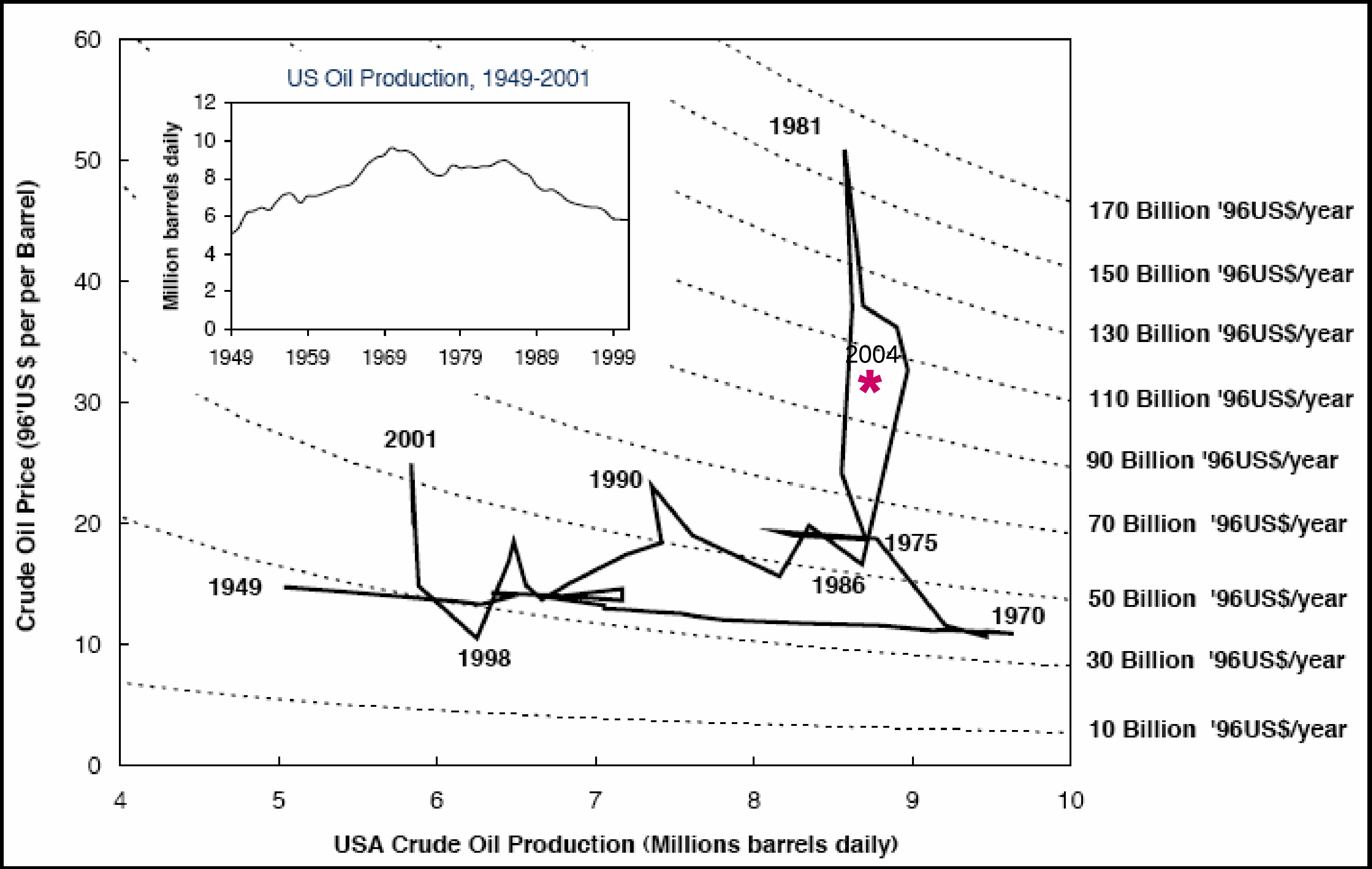
US Hydrogen Output and Price



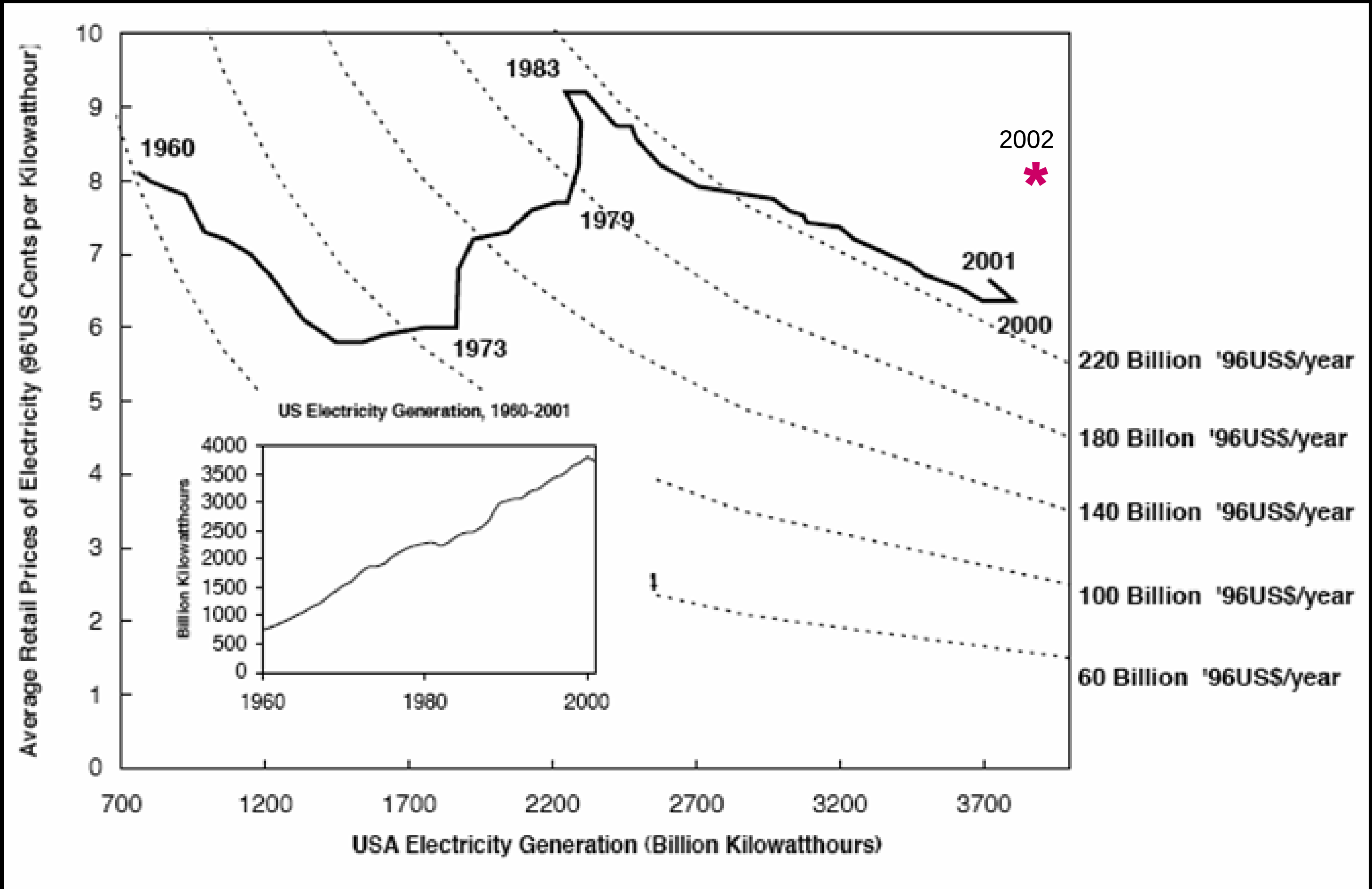
Source: David G. Victor

US Oil Output and Price



Source: David G. Victor

US Electricity Output and Cost



Source: David G. Victor

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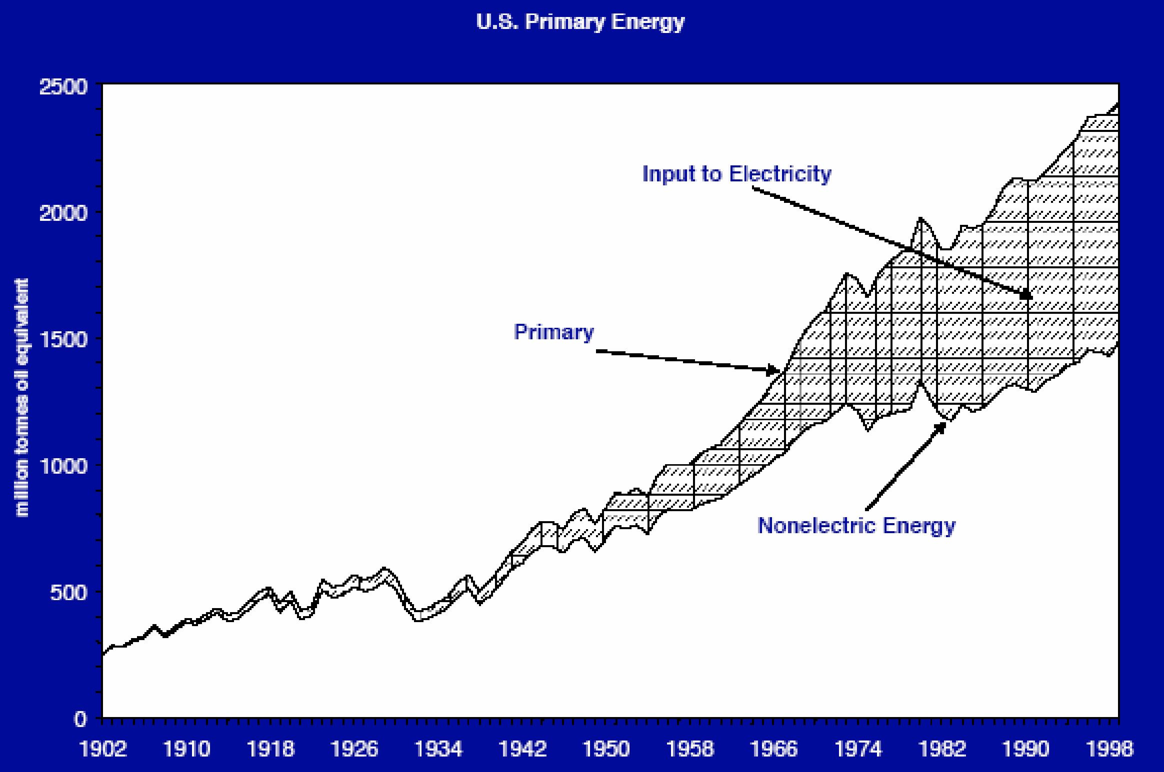
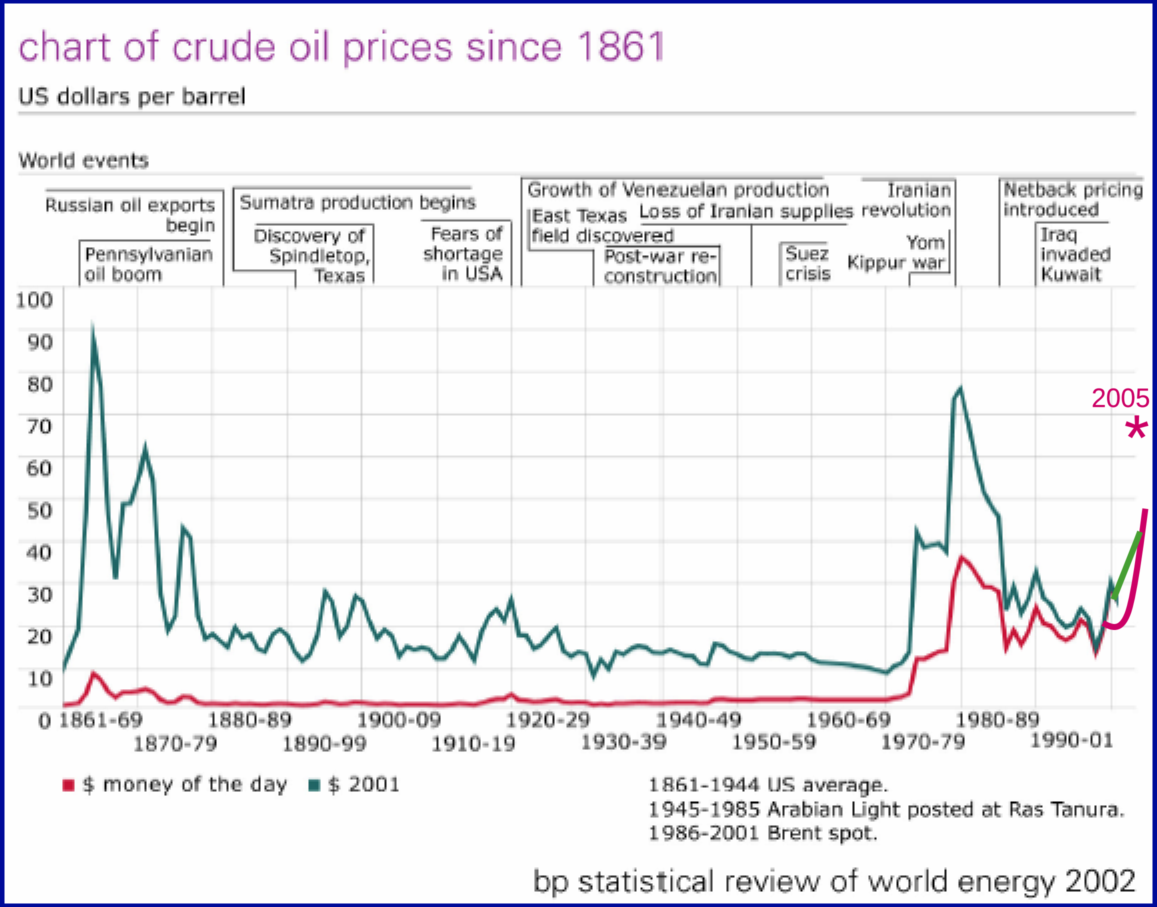
Electrification

Electrification of Industrial and Post-Industrial Societies



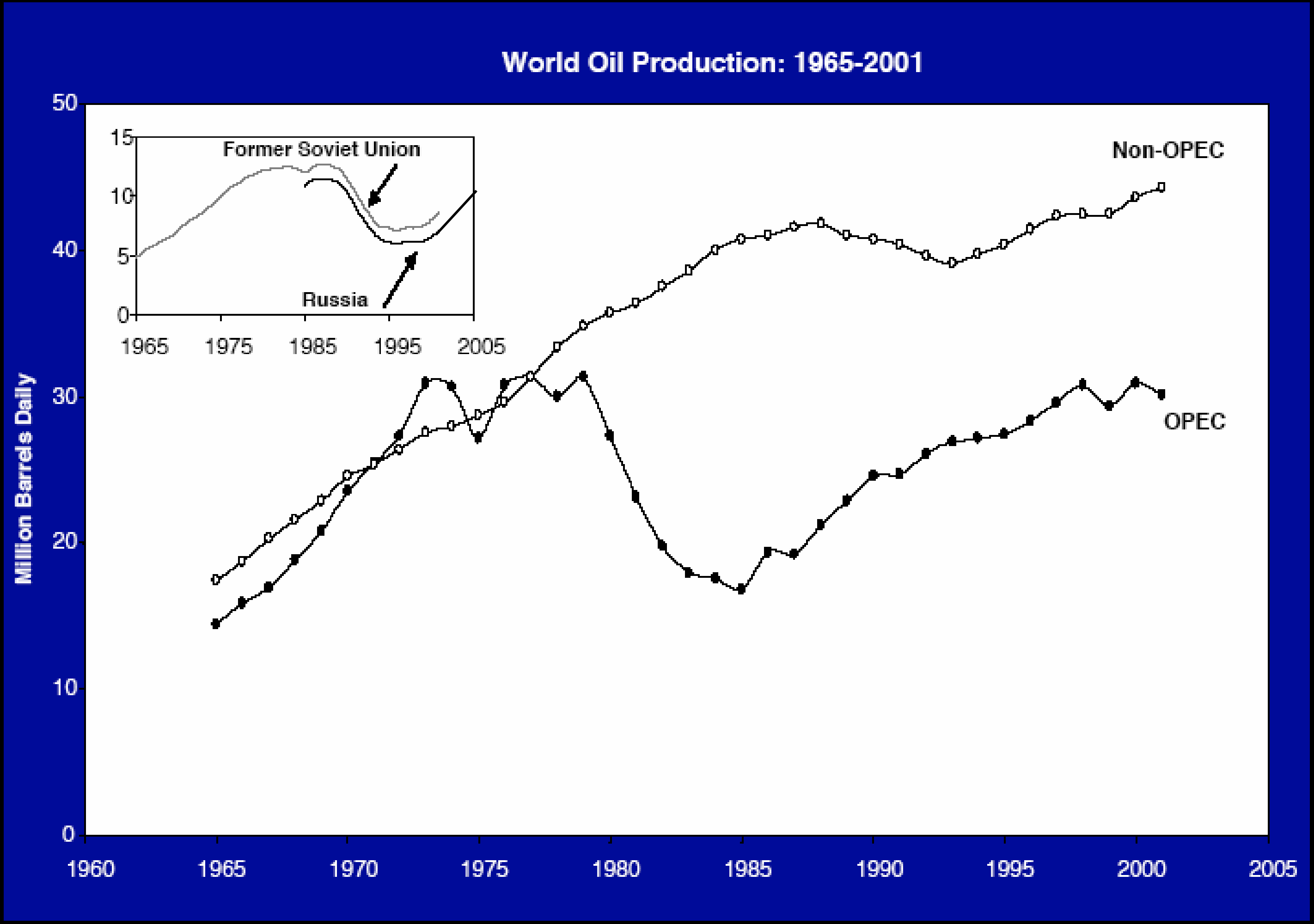
Source: David G. Victor

Crude Oil Prices



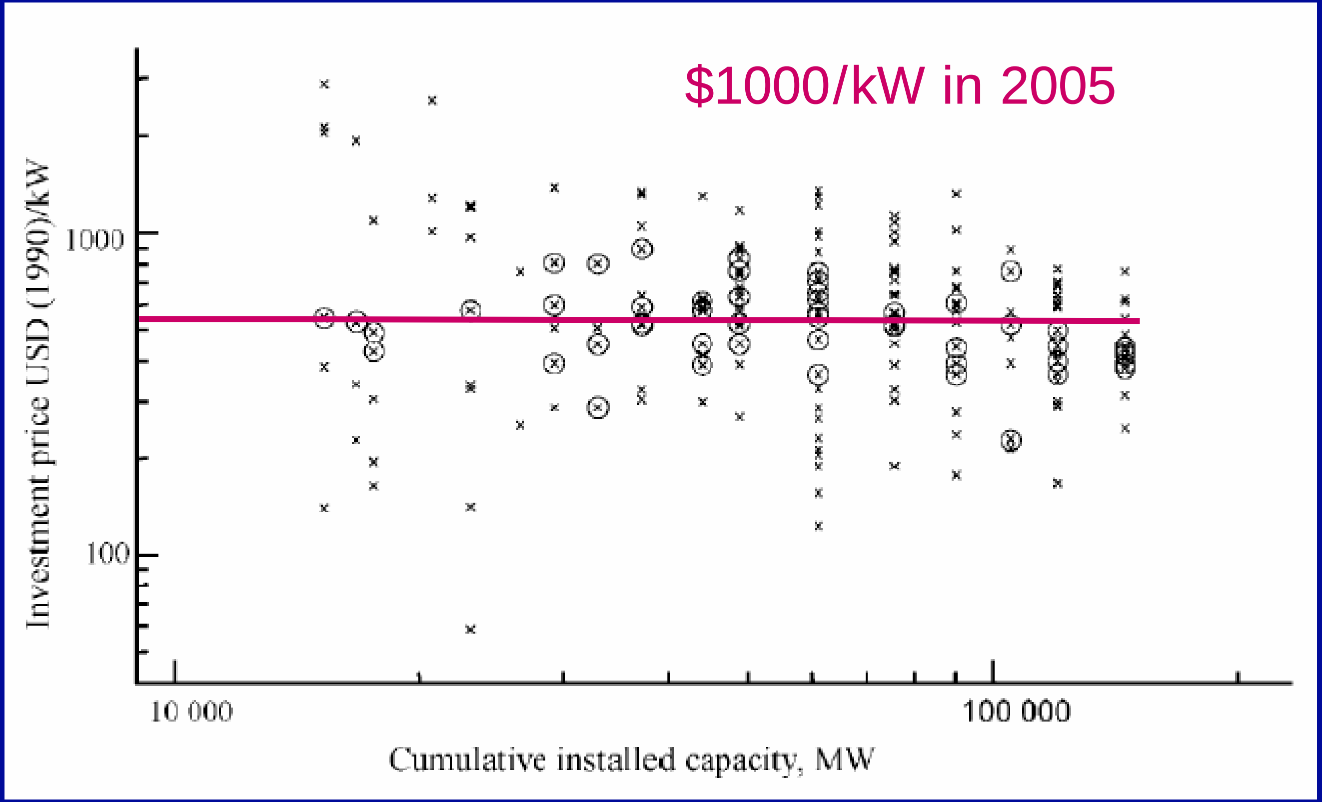
Source: David G. Victor

World Oil Production



Source: David G. Victor

Investment Price per kW



Source: Colpier and Cornland. 2002. "The Economics of the Combined Cycle Gas Turbine – An Experience Curve Analysis." *Energy Policy* 30: 309-316.

Hydrogen Implementation in Iceland

University of Iceland

Iceland has almost no fossil resources but plenty of sustainable energy

Iceland has harnessed about 8TWh out of its

potential of more than 55TWh(el.)

in the form of hydroelectric or geothermal energy

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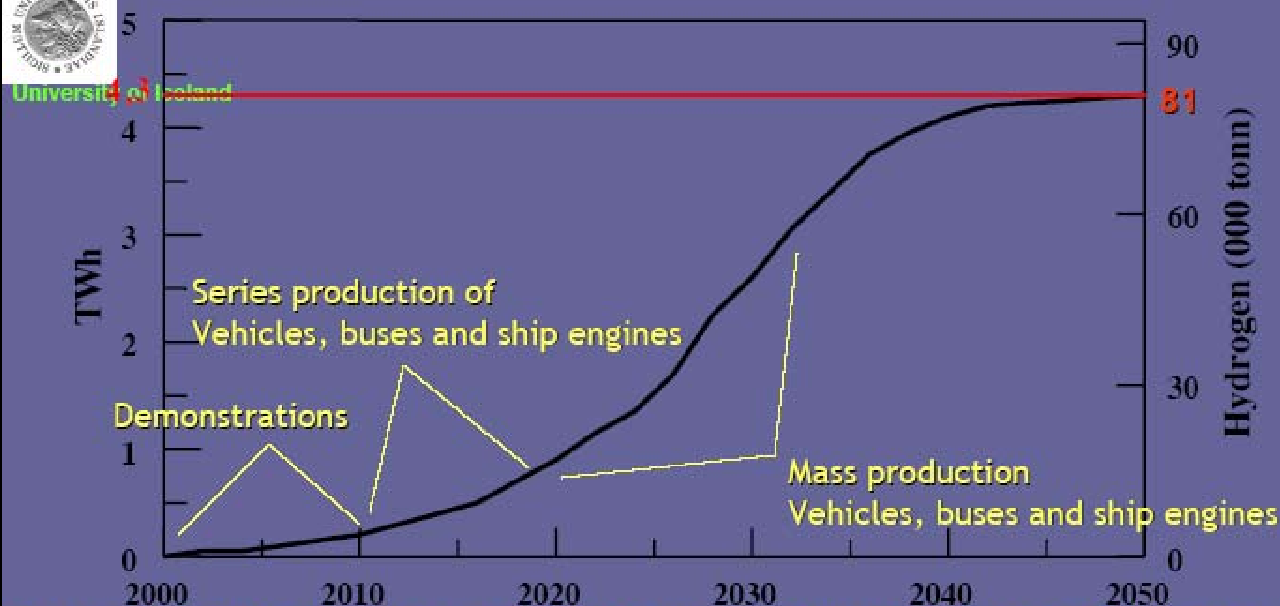
Hydrogen Implementation in Iceland

Estimated energy use for the hydrogen society



Forecast for the development of the usage of hydrogen as a fuel in cars and ships. Technical developments during the next few years could considerably influence the graph.

Hydrogen Implementation in Iceland

Fueling Infrastructure

Hydrogen Implementation in Iceland

PRODUCTION:

University of Iceland

- Not likely to be a serious implementation barrier in Iceland
- Electrolysis - ample supply of primary renewable energy to provide for transportation hydrogen needs
- Fossil - no indigenous sources of fossil fuels in Iceland
- Geothermal –Steam Turbine Electricity and Hydrogen separation from geothermal gases
- In addition to Thermo-electric production and storage from waste heat of thermal power plants

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STORAGE

University of Iceland

- Potentially large world wide implementation barrier and research opportunity
- Established expertise in liquid and compressed gas storage in other countries/private industry
- Hydride storage remains a relatively nascent field
- University of Iceland/Icelandic New Energy/Varmaraf plan to focus research on hydride storage

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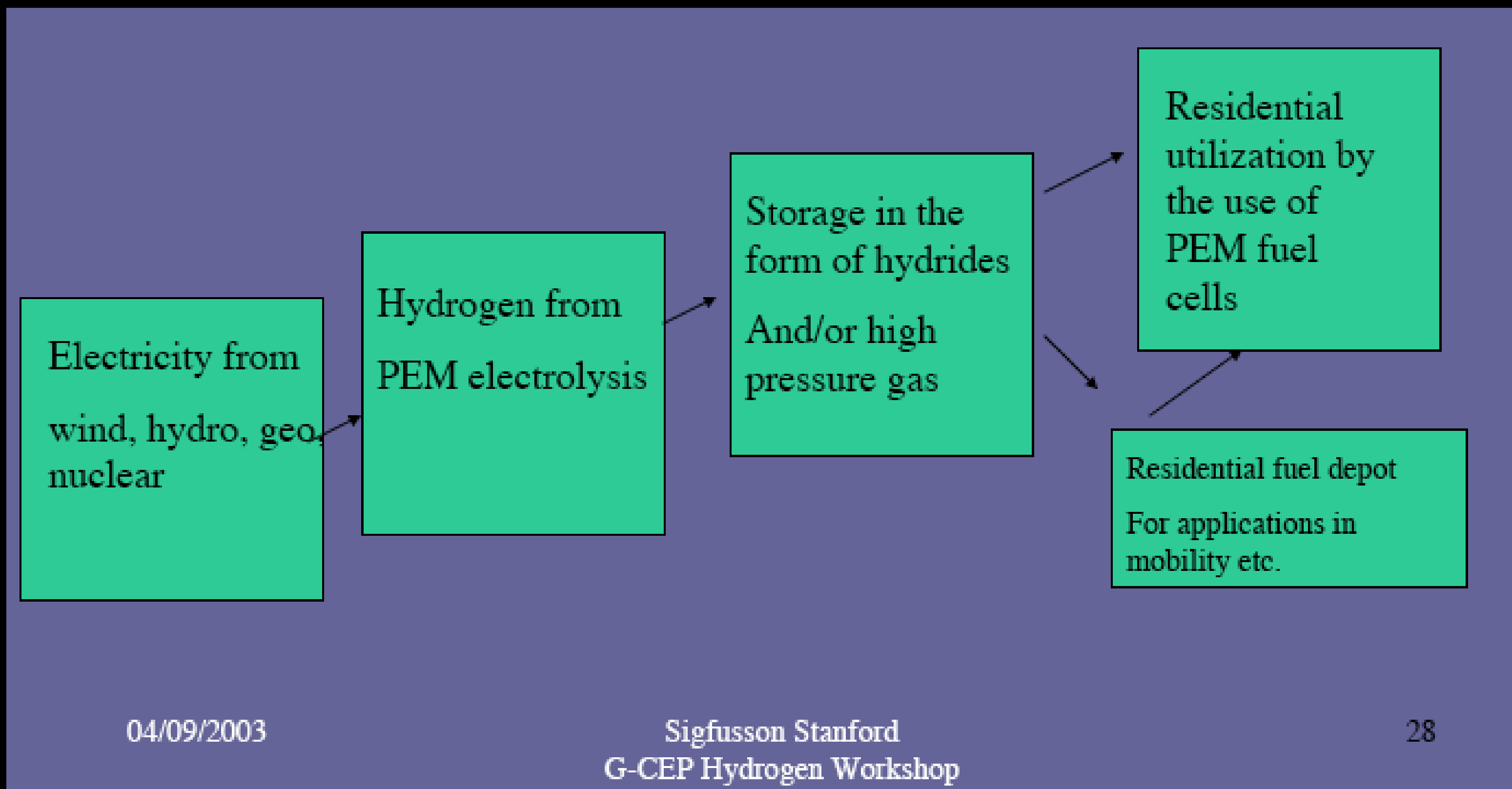
University of Iceland

A technology for solid state electricity generation from heat has been developed in Iceland and an interesting merger of this technology and hydrides is emerging

Japan Steel Works, one of the world´s foremost producers of metal hydrides is becoming a close partner in this field

Hydrogen Implementation in Iceland



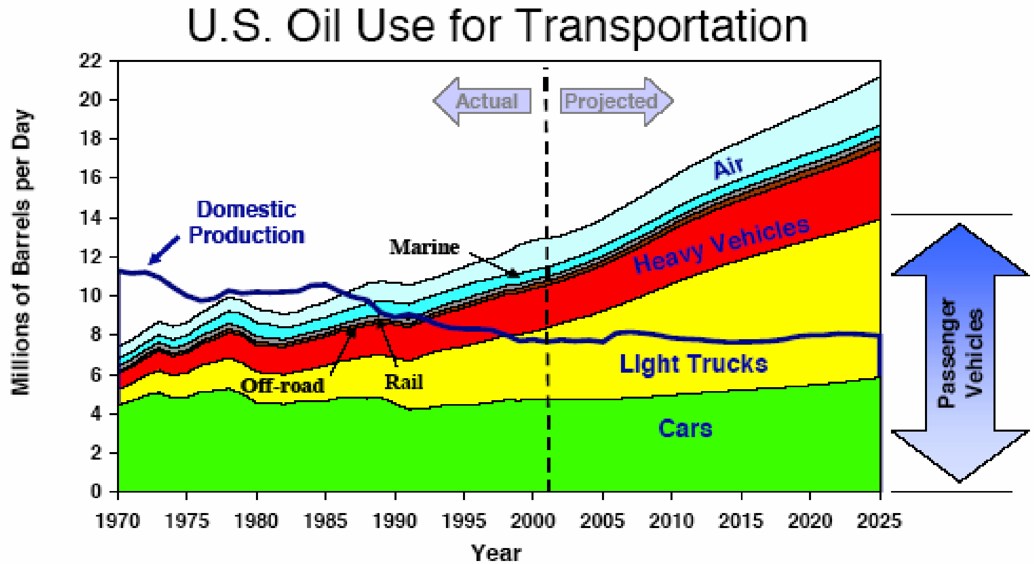
Hydrogen Implementation in Iceland

- Being independent of fossil fuel imports is a beautiful vision, which could be partly realised in Iceland during the next decades and finished around mid century
- Major barriers do exist and need appropriate policy and research attention
- Working together in dedicated groups we hope to bring about

"A HYDROGEN SOCIETY"

DOE Hydrogen Roadmap

U.S. Energy Dependence is Driven By Transportation



Source: Transportation Energy Data Book: Edition 22, September 2002, and EIA Annual Energy Outlook 2003, January 2003

- Transportation accounts for 2/3 of the 20 million barrels of oil our nation uses each day.
- The U.S. imports 55% of its oil, expected to grow to 68% by 2025 under the status quo.
- Nearly all of our cars and trucks currently run on either gasoline or diesel fuel.

George Sverdrup
National Renewable Energy Laboratory -

DOE Hydrogen Roadmap

President Bush Launches the Hydrogen Fuel Initiative

"Tonight I am proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles.

"A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes.

"With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution-free.

"Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy."

2003 State of the Union Address
January 28, 2003

DOE Hydrogen Roadmap

Stationary and Distributed Generation Partnership Timeline

2000 | 2005 | 2008 | 2012 | 2015

	Phase 1: Cost Reduction/ Technology Improvement Small System (2000–2005)	Phase 2: Cost Reduction/ Technology Improvement/ Limited Commercialization Small System (2005–2008)	Phase 3: Large Scale Commercialization/ Multiple Applications Small System (2008–2012)	Large System Demonstration and Commercialization; Fuel Cell/ Turbine Hybrids Distributed Generation; Coal Based Central Generation (2012–2015)
Objectives	•Develop stack design •Develop manufacturing methods	•Incorporate lower cost, robust materials	•Optimize system, thermal integration	•Use small system technology in larger hybrid and coal based systems •Hybrid efficiency - 60-70% •Coal based efficiency – 60%
	R&D to establish initial performance and reliability Limited 3 to 50 kW prototype tests	R&D to improve cost, durability and efficiency Target 2 to 25 MW sited by 2008	R&D to improve cost, durability and efficiency Target: 500 MW sited by 2012	Investment to establish full manufacturing capacity and product warranty to successfully compete in the market
Go/No Go Decision Points	Proposed Decision Criteria: R&D and limited demonstrations results in acceptable durability, 35-55% efficiency, and potential to approach $400/kW. (Projection based on 100,000 units production, exact cost targets depend on specific applications.) Verified by independent audit and testing	Proposed Decision Criteria: Validated Phase 2 systems achieve improved durability, 40-60% efficiency, and assurance that $400/kW can be achieved (Projection based on 100,000 units production, exact cost targets depend on specific applications).	Commercialization: Goals of $400/kW, 40-60%, 5 years stack life and 25 year system life achieved. Industry decides on commercialization.	

George Sverdrup
National Renewable Energy Laboratory -

DOE Hydrogen Roadmap

Transportation and Infrastructure Partnership Timeline

2000 — 2004 — 2009 — 2015

	Phase 1 Technical Feasibility	Phase 2 Controlled Fleet Test and Evaluation	Phase 3 Commercial Readiness Demonstrations	Commercialization Phase
Vehicle Objective	Test fuel cell (FC) vehicle performance and feasibility	Evaluate use of FC vehicles under real-world conditions	Demonstrate commercial viability of FC fleet vehicles	Invest to establish manufacturing plants and sales/service
Infrastructure Objective and Hydrogen Source	Demonstrate H_2 fueling station; Analyze fuel options Primarily trucked in liquid	Generate hydrogen from multiple feedstocks Renewable & fossil fuels	Provide sufficient stations for consumer convenience Most cost effective sources by region	Invest in substantial numbers of all stations to be H_2 capable
Go/No-Go Decision Points				

Proposed Decision Criteria – Phase 1: Hydrogen vehicles achieve 1000 hrs durability, $200/kW cost (projection based on 500,000 units production), R&D results project 2000 hrs durability, $125/kW, $3.00/gallon gasoline equivalent (untaxed).

Proposed Decision Criteria – Phase 2: Hydrogen vehicles achieve 2000 hrs durability, $125/kW cost (projection based on 500,000 units production) & hydrogen at $3.00/gallon. R&D results project 5000 hrs durability, $45/kW, $1.50-$2.60/gallon gasoline equivalent (untaxed), and 120 g/mi greenhouse gases..

Proposed Commercialization Decision Criteria: Based on capability to achieve 5,000 hrs durability, $30/kW fuel cell system cost (at 500,000 units), $1.50 /gallon gasoline equivalent (untaxed), 120 g/mi greenhouse gases, and other market factors. The decision to enter a commercialization phase will be made by industry.

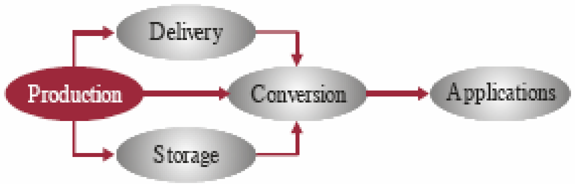
R&D Continues Concurrently to address key cost and performance barriers

DOE Hydrogen Roadmap

Hydrogen Production

Key RD&D Needs

Low cost distributed production using natural gas reforming
Prove large scale hydrogen production using nuclear and thermo-chemical processes
Accelerate direct production using biological, photolytic, and other techniques
Improved gasification for greater fuel flexibility
High efficiency and low cost electrolysis
Improved separation and purification methods and materials
Economic, scalable carbon capture and sequestration techniques



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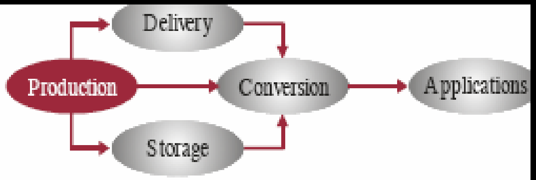
DOE Hydrogen Roadmap

Hydrogen Production

Technical Barriers from HFCIT Multi-Year Plan



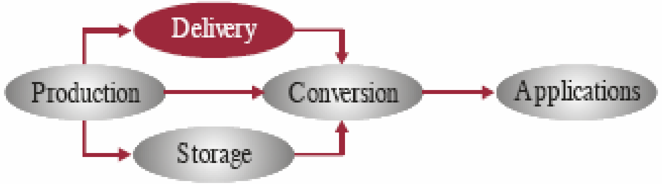
Low cost distributed production using natural gas reforming - improved catalysts for reforming and water-gas-shift - purification
Economic production using nuclear and thermo-chemical processes
Photoelectrcochemical production from water– improved materials
Biological production - photobiological processes (organic substrate & water substrate) - dark fermentation
Biomass to hydrogen - improved gasification for greater fuel flexibility - improved catalysts for reforming gasification & pyrolysis product streams - economic generation of valuable co-products
High efficiency and low cost electrolysis
Improved separation and purification methods and materials
Economic, scalable carbon capture and sequestration techniques

DOE Hydrogen Roadmap

Hydrogen Delivery

Key RD&D Needs

Codes and standards for pipelines and transport
Prove performance of hydrogen delivery infrastructure
Systems and economic analysis tools and data to improve evaluation of alternative delivery technologies
Evaluate efficacy of existing infrastructure for use in hydrogen delivery
Testing and validation of existing and improved delivery systems



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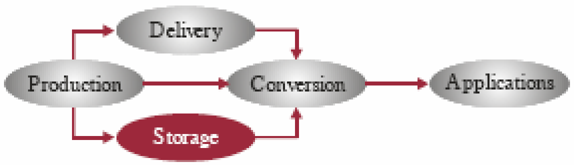
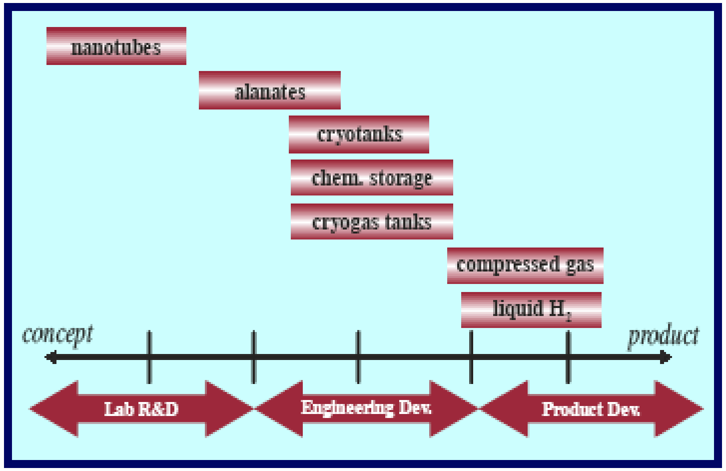
DOE Hydrogen Roadmap

Hydrogen Storage

Key RD&D Needs

Large scale demonstrations of hydrogen storage devices
Improved materials for containment of compressed and liquid hydrogen
Codes and standards development for hydrogen storage devices
Materials performance evaluation and testing
Manufacturing scale-up processes
Novel materials and advanced storage techniques for 9% by weight storage in 2015





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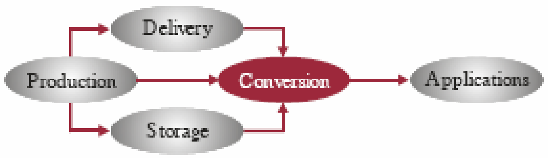
DOE Hydrogen Roadmap

Hydrogen Conversion

Key RD&D Needs

Fundamental research on electrochemistry, interface, and advanced materials for fuel cells
Lower cost, more durable, and easier-to-manufacture fuel cells
Optimized hydrogen combustion in engines and turbines for stationary and mobile applications
Demonstrations of fuel cells, engines, and turbines in mobile and stationary applications including distributed power and combined heat & power
Product safety standards for hydrogen based fuel cells, engines, and turbines



Technology	Application
Combustion	
Gas Turbines	Distributed power Combined heat and power Central station power
Reciprocating Engines	Vehicles Distributed power Combined heat and power
Fuel Cells	
Polymer Electrolyte Membrane (PEM)	Vehicles Distributed power Combined heat and power Portable power
Alkaline (AFC)	Vehicles Distributed power
Phosphoric Acid (PAFC)	Distributed power Combined heat and power
Molten Carbonate (MCFC)	Distributed power Combined heat and power
Solid Oxide (SOFC)	Truck APUs Distributed power Combined heat and power

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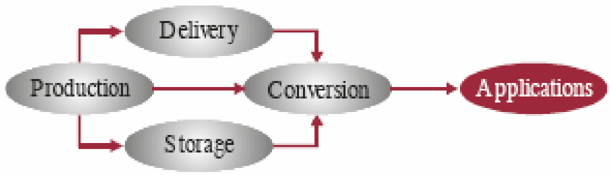
DOE Hydrogen Roadmap

Hydrogen Applications

Key RD&D Needs

Product safety standards and environmental regulations for vehicles
Large scale demonstrations of existing technologies – vehicles and distributed power
Government as early adopter customer
Infrastructure development
Community-based clustered applications and installations
Publicize existing and future showcase demonstrations



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DOE Hydrogen Roadmap

Codes and Standards

Key Activities

Hydrogen Codes and Standards Coordinating Committee: communication across hydrogen community and development of consistent codes and standards
Proposed amendments to International Code Council model building codes
International Standards Organization Technical Committee 197: development of international standards for hydrogen technologies

ICC INTERNATIONAL CODE COUNCIL

SAFETY REPORT H2

Online publication
www.hydrogensafety.info

ISO

NFPA INTERNATIONAL

CSA AMERICA INC

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