A review of potential hydrogen production and delivery costs

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H2NET Hydrogen Energy Systems

Wednesday 1 May 2002

Tyndall°Centre for Climate Change Research

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A review of potential hydrogen production and delivery costs

- Introduction
- Hydrogen Production
- Hydrogen Storage
- Hydrogen Transport and Distribution
- Hydrogen Systems and Economics
- Conclusions

The Hydrogen Energy Economy
- its long term role in greenhouse gas reduction

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The Hydrogen Economy & the Tyndall Centre

Objective:

– to determine the potential contribution and viability of the hydrogen economy towards making changes in the UK energy mix in a manner that will significantly reduce carbon dioxide emissions

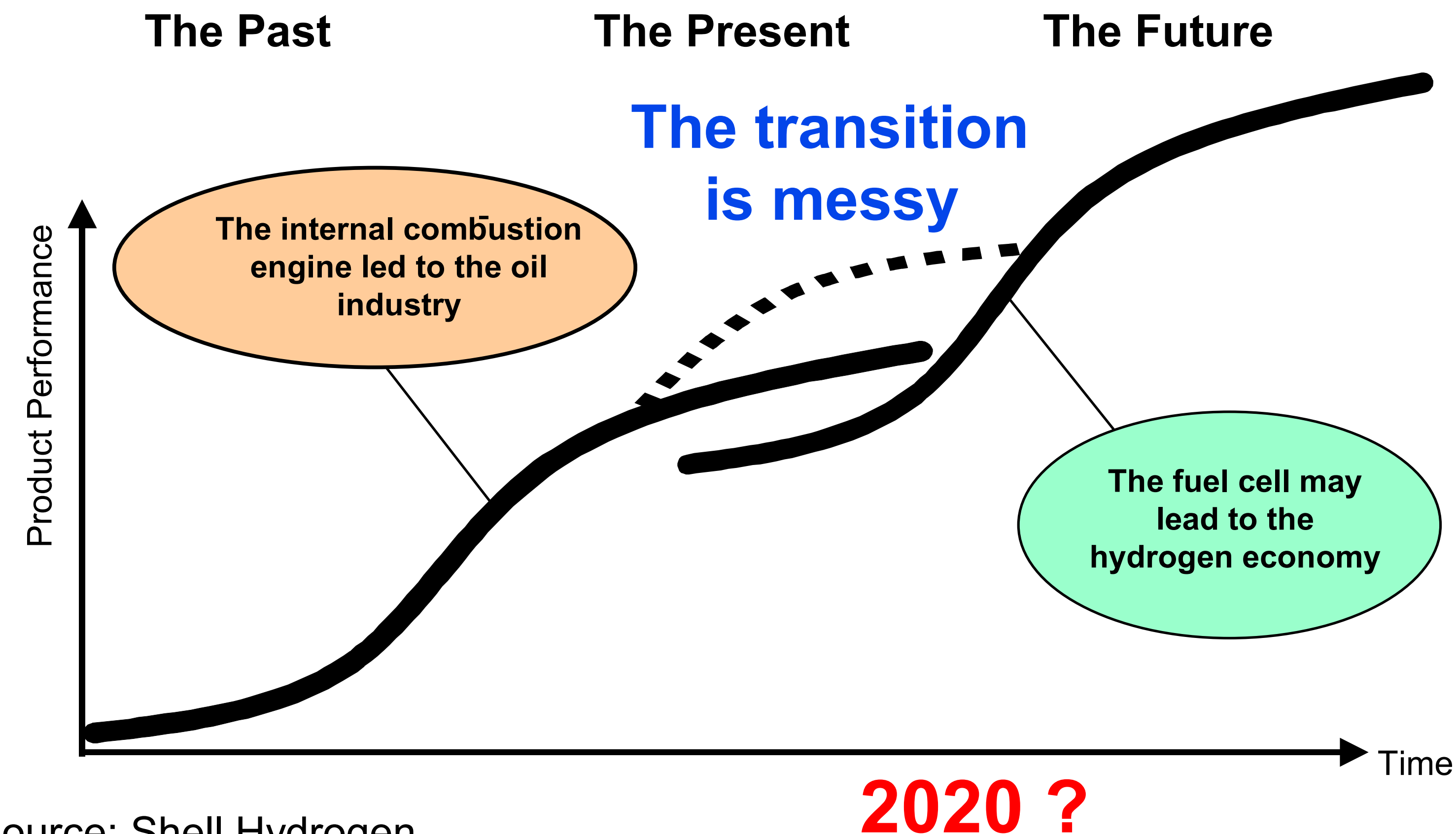
Phase I : Scoping studies

- Hydrogen Energy Technology
- Development of large technical systems
- Role of hydrogen in powering land transport

Definition of parameters for Phase II

Phase II : Infrastructural requirements and long term prospects

The route to the hydrogen economy



Source: Shell Hydrogen

Useful references & acknowledgements

- Main sources

  - Lakeman, J.B., Browning, D.J., DERA, *Global Status of Hydrogen Research*, ETSU F/03/00239/REP, 2001
  - Padro, C.E.G., Putsche, V., *Survey of the economics of hydrogen technologies*, NREL Technical Report NREL/TP-570-27079, 1999
  - Amos, W.A., *Costs of storing and transporting hydrogen*, NREL/TP-570-25106, November 1998
  - Ogden, J.M., *Prospects for building a hydrogen energy infrastructure*, Annual Review Energy Environ. 1999, Vol. 24, 227-279
  - UK Hydrogen Energy Network meetings

Hydrogen Production - Current status

Hydrogen is currently used almost exclusively as an industrial chemical

- ~500 billion Nm^3 produced annually worldwide (Air Products is largest producer with > 50 plants, 7 pipeline systems totalling > 340 miles)
- 48% is produced by steam reforming of natural gas
- used for ammonia production, fertiliser manufacture, methanol production, refinery use for desulphurisation
- fuel for space exploration

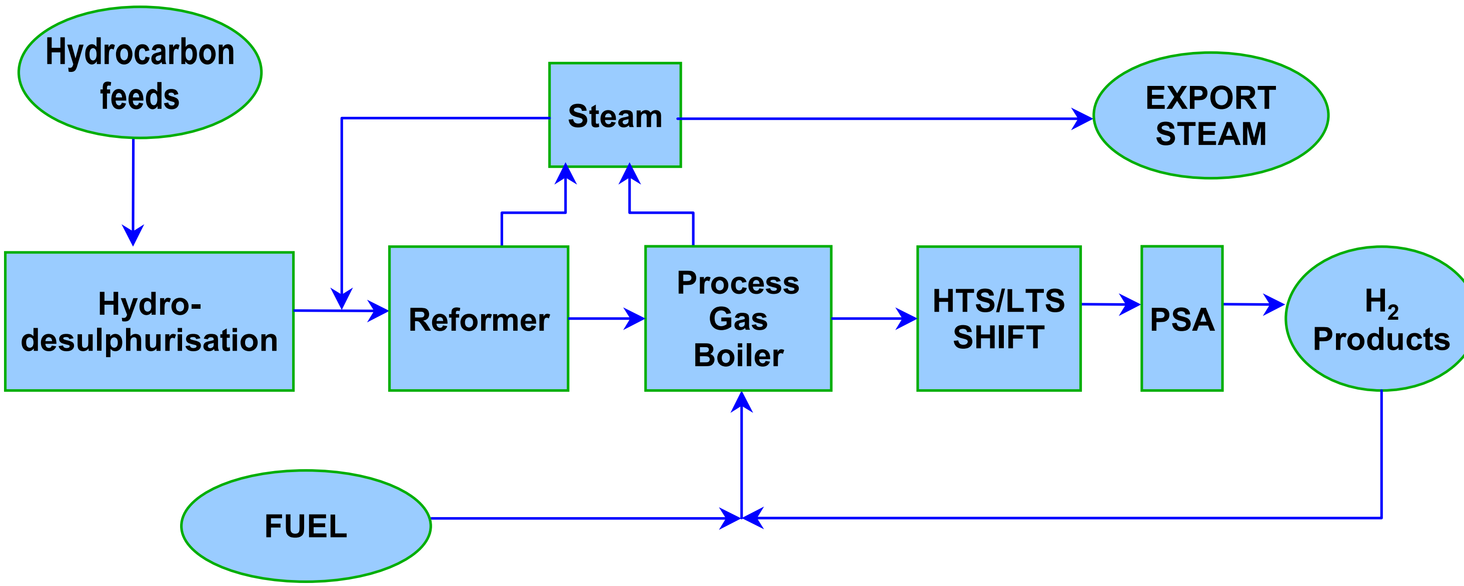
Hydrogen Production - Processes (1)

- Steam methane reforming (SMR) of natural gas
- Partial oxidation (POX) or reformation of other carbon-based fuels
- Coal gasification (IGCC)
- Biomass gasification
- Pyrolysis
- Dissociation of methanol or ammonia
- Electrolysis of water
  - if the source of electricity is renewable energy then the net emissions of carbon dioxide are zero

Hydrogen Production - Processes (2)

- Biological photosynthesis or fermentation
- Hydrogen bromide electrolysis
- Hydrogen production during manufacture of chlorine
- Photoelectrolysis
- Reversible fuel cell

Hydrogen Production - SMR



REFORMING

$CH_4 + H_20$ $3H_2 + CO$

880 °C

SHIFT

$CO + H_20$ $H_2 + CO_2$

Source : Air Products

Hydrogen Production - SMR

Tosco Martinez SMR, CA

Source : Air Products

Hydrogen Production - Pyrolysis

- Pyrolysis is the decomposition of hydrocarbons in the absence of oxygen
- Requires high T, endothermic process
- Methane "cracking" in presence of catalyst produces hydrogen and carbon black
- Kvaerner pilot plant since 1992, commercial plant started operation in Canada in 1999
- In principle, applicable to more complex hydrocarbons, biomass, and municipal solid waste

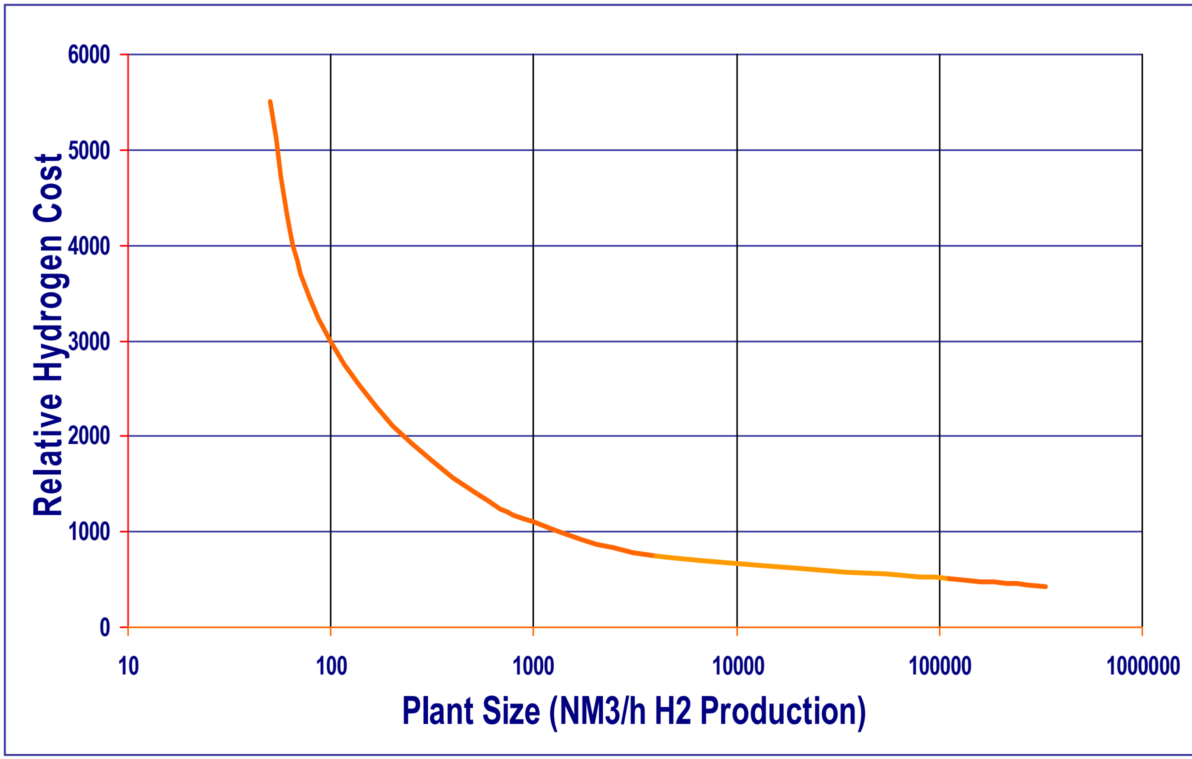
Hydrogen Production - Electrolysis of water

- Electrochemical water-splitting process:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

- Commercial electrolysers typical efficiency 75%
- Operating pressures up to 50 bar (< high pressure cylinders) $\rightarrow$ need for additional compression
- Improve efficiency by operating at higher T
- Develop high pressure electrolysers

Hydrogen Production - SMR H_2 costs



Source : Air Products

Hydrogen Production - Economics (1)

Type of facility	Fuel/Hydrogen price ($/GJ)
Petrol	3.5 (spot market $20/barrel) 7.9 (pre-tax) 31.0 (70p/litre)
Natural gas	1.8 (ave. wellhead 1990-99) 6.0 (wellhead Dec. 2000)
Steam methane reforming	5.4 (large plants) - 11.2 (small plants)
Partial oxidation	7.0 - 10.7
Coal gasification	9.9 - 11.6
Biomass gasification	8.7 - 13.1
Biomass pyrolysis	8.9 - 12.7
Methane pyrolysis	5.8 (C revenue) - 10.6 (No C revenue)
Steam methane reforming	6.0 (no CO_2 seq.) - 7.5 (with CO_2 seq.)
Wind-based electrolysis	11.0 (future 2010) - 20.2 (tech. 2000)
Solar-based electrolysis	24.8 (future 2010) - 41.8 (tech. 2000)

Sources : Padro & Putsche, 1999 & Author's estimates and other literature

Hydrogen Production - Economics (2)

- Mann et al. (1998) observe that economics of renewable powered electrolysis can be improved by:
  - use of off-peak electricity when wind/solar energy not available
  - sale of electricity from wind/solar energy during peak tarif times (i.e. suspend hydrogen production)
  - can improve economics by a factor of 2 (dependent on wind/solar regime, electricity tarifs, feed-in contracts, etc.)

→ **Consider further under Phase 2 Transitions**

Hydrogen Storage and Distribution

- Optimisation of storage system and distribution method depends on:
  - production rate (compressor/liquefaction plant size, operating costs)
  - storage time (overall capacity, hence unit size and cost)
  - infrastructure availability
  - distance to customer
  - end-use application (system pressure? liquid?)
  - capital costs
  - maintenance requirements
  - safety issues
- Centralised v local production of hydrogen

Hydrogen Storage

- Pressurised gas
  - underground chambers (e.g. depleted gas wells)
  - surface storage (conventional cylinders)
  - advanced high pressure composite cylinders
- Liquefied hydrogen
- Chemical (methanol, ammonia, etc.)
- Reversible metal hydride systems
- Carbon - cryo-adsorption and nanotubes
- Transmission by pipeline

Hydrogen Storage

Technology	Specific developments	Targets
Automotive applications		6.5 wt% (US DOE) 62 kg H_2 m^{-3}
Portable power systems (military)		11.0 wt%
Stationary systems		likely to be cost driven

Hydrogen Storage - Pressurised gas

- Conventional steel cylinders are heavy and bulky, 50 litre containers store compressed hydrogen at 200 bar (2.3 kWh/kg)
- Spherical pressure vessels for larger volumes
- Composite cylinder technology
  - inner aluminium or thermoplastic lining
  - glass or carbon fibre strengthening
  - lighter weight
  - pressures up to 350 bar (11.3 wt%), plans for 700 bar
  - additional compression cost
  - possible problems with filling speed

Hydrogen Storage - Liquefaction

- Energy intensive process (8.5 kWh/kg up to 13.0 kWh/kg for small plants)
- Magnetocaloric cooling may reduce liquefaction energy to 5.0 kWh/kg
- Requires efficient tank insulation to keep T ~ 20 K
- Sizes range from several litres to 3,800 m^3
- Used by BMW Clean Fleet
- Boil-off rates around 3% per day have been achieved (no problem for frequent use)
- Liquid hydrogen Dewar is a comparatively cheap technology (c.f. pressure vessels)

Hydrogen Storage - Metal hydride systems

$$M + xH_2 \rightleftharpoons MH_{2x}$$

- Principle of operation:
  – hydrogen adsorbed at or below atmospheric pressure
  – constant "plateau pressure" between about 10% and 90% of ultimate storage capacity
  – hydrogen released at higher pressure when the hydride is heated (the higher the temperature, the higher the pressure)

Hydrogen Storage - Metal hydride systems

- Conventional metal hydrides:
  - Ambient temperature hydrides (FeTi, $LaNi_5$, typically < 2.0 wt%)
  - Higher temperature hydrides (usually contain Mg, e.g. Mg_2Ni, can store up to 7.0 wt% but with slow kinetics)
- Novel metal hydrides
  - Sodium aluminium hydrides with titanium or zirconium catalyst, e.g. $NaAlH_4$, Na_3AlH_6 (again with slow kinetics, IEA target 5.0 wt%)
  - Lithium beryllium hydride (reversible hydrogen capacity of almost 9.0 wt%, but requires T > 250 ^{o}C to achieve useful pressures)

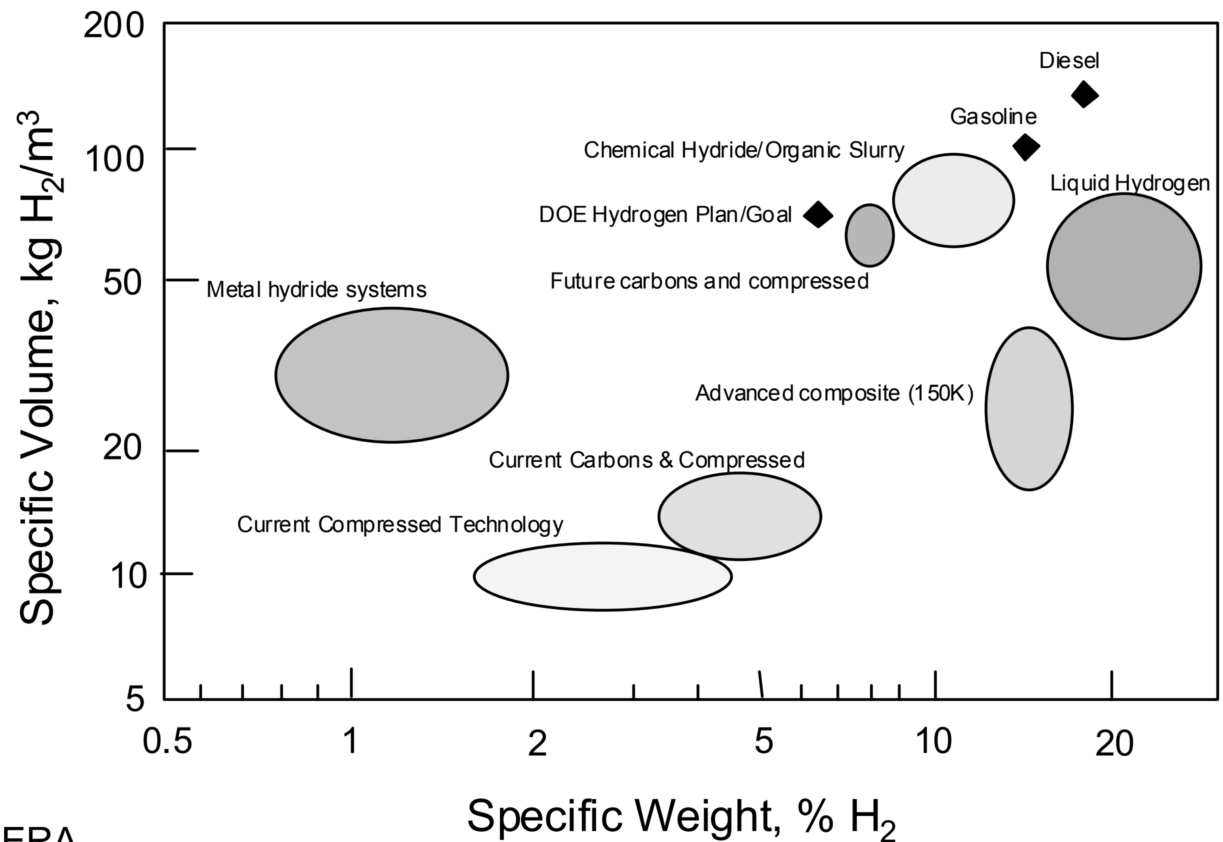
Metal hydride systems - Likely developments

- Conventional metal hydrides:
  - Capacity improvement unlikely
  - Improve kinetics, cycle life, impurity tolerance, T of operation
- Novel metal hydrides
  - Sodium aluminium hydride
    - capacity improvement under development
    - improve kinetics
  - Lithium beryllium hydride
    - seek system with similar properties that works nearer ambient temperature

Hydrogen Storage - Carbon based systems

- Claims of storage efficiencies up to 50 wt.% (and even 65 wt.% in one case) seem to be unfounded
  - failure to replicate results in independent laboratories
  - original claims attributed to water contamination
  - only a few wt.% likely to be achieved in practice
- Work on carbon systems remains very popular and is continuing under IEA Hydrogen Agreement Annex 12

Hydrogen Storage



Source: DERA

Hydrogen Storage - Economics (short term)

Facility size (GJ)	References	Specific TCI ($/GJ)	Hydrogen price ($/GJ)
Compressed gas storage - short term (1-3 days)			
131		9,008	4.21
130,600		1,726	1.53
Liquefied hydrogen - short term (1-3 days)			
131		35,649	17.12
130,600		3,235	5.26
Metal hydride - short term (1-3 days)			
131		4,191	2.89
130,600		18,372	7.46
Underground hydrogen storage - short term (1 day)			
			1.0-5.0

Source : Amos 1998, Padro & Putsche 1999

Hydrogen Storage - Economics (long term)

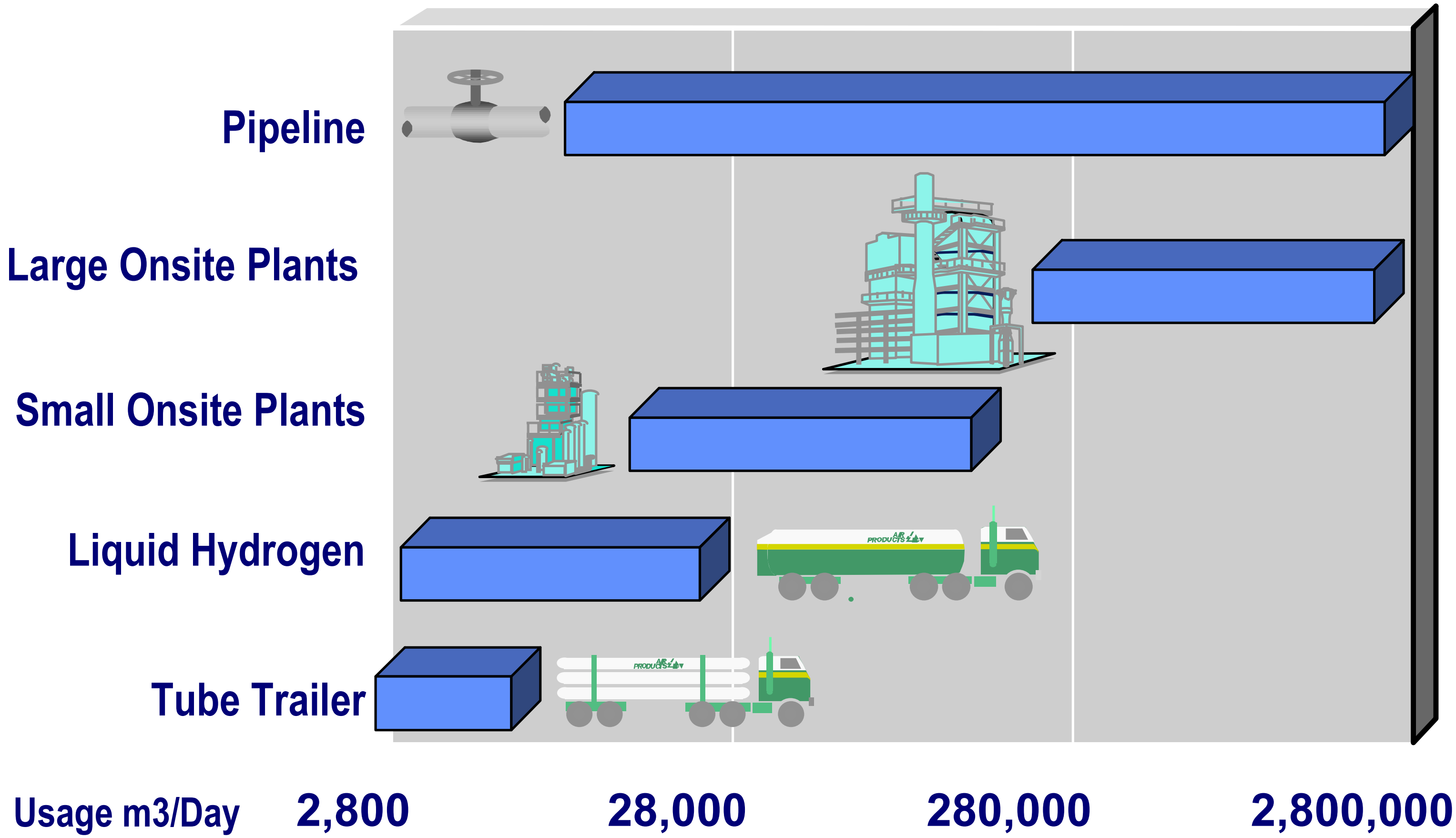
Facility size (GJ)	References	Specific TCI ($/GJ)	Hydrogen price ($/GJ)
Compressed gas storage - long term (30 days)			
3,900		3,235	36.93
3.9 million		580	7.35
Liquefied hydrogen - long term (30 days)			
3,900		1,687	22.81
3.9 million		169	5.93
Metal hydride - long term (30 days)			
3,900		18,372	205.31
3.9 million		18,372	205.31

Source : Amos 1998, Padro & Putsche 1999

Hydrogen Distribution and Transport

- Hydrogen is conventionally distributed in:
  - gaseous form cylinders or large pressure vessels
  - liquefied form by tanker
  - liquefied form by pipeline
- Large scale hydrogen pipeline distribution is feasible but is likely to be very expensive
- Existing natural gas pipeline network could be used:
  - dilution with H_2 by up to 10%
  - technical problems likely to prevent higher concentrations being allowed
  - logistic problems of changeover

Hydrogen Distribution and Transport



Source : Air Products

Hydrogen Distribution and Transport

Transmission distance (km)	Reference : Amos (1998)	Specific TCI ($/GJ)	Hydrogen price ($/GJ)
Hydrogen transmission costs (pipeline) - transmission rate 0.15 GW			
161		21.22	2.83
1609		210.32	27.23
Hydrogen transmission costs (pipeline) - transmission rate 1.5 GW (47.3 million GJ/year)			
161		2.83	**0.83**
1609		22.3	**3.53**
Hydrogen transport as liquefied hydrogen by truck - (45,418) - 45.6 million GJ/year			
16		0.44 - (11.0)	**0.24** - (1.60)
161		0.77 - (11.0)	**0.52** - (1.84)
1609		5.10 - (11.0)	**3.90** - (4.70)
Hydrogen transport as compressed gas by truck - truck tube unit capacity 21.72 GJ			
16		4.10	**4.70**
161		8.20	**10.60**
1609		57.60	**79.40**
Hydrogen transport via truck using metal hydrides			
16		7.54	2.63
1609		105.54	42.11
Costs of transporting conventional fuels (petrol)			4.4 ?

Source : Amos 1998, Padro & Putsche 1999

Hydrogen Storage and Distribution : Conclusions

- Underground storage is cheapest at all production rates and storage times (assuming low cost of cavern)
  - biggest cost electricity for compression
  - additional transport to consumer may be high
  - opportunity for seasonal storage
- Metal hydride storage has no economy of scale
  - does not compete at high production rate or long storage time
  - may be ideal for low flow rate / short storage time
  - seen as the safest option (ideal for vehicles)
  - improved energy density required

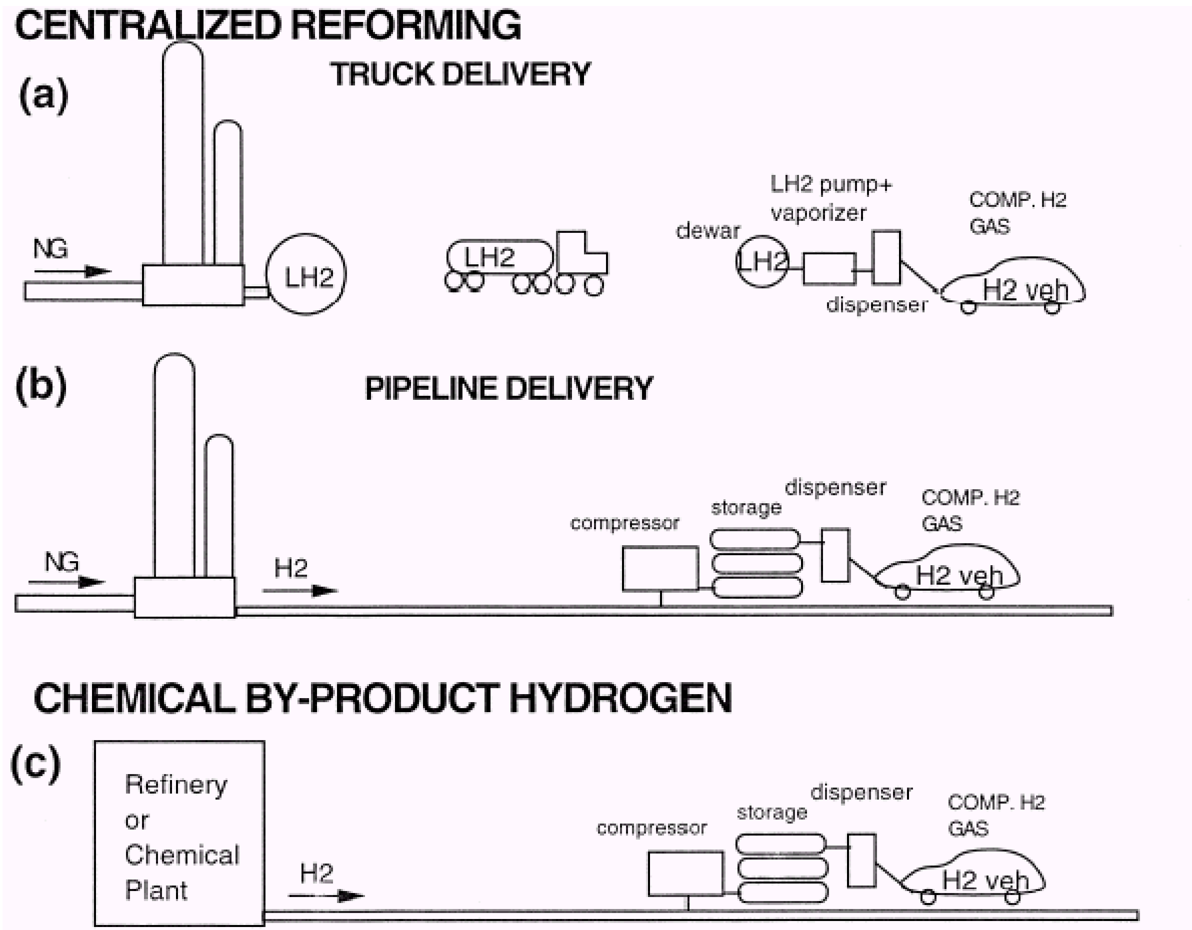
Hydrogen Storage and Distribution : Conclusions

- Liquid hydrogen
  - high energy density (ideal for vehicles)
  - uneconomic at low production rates (high capital cost)
  - ideal for high production rate / long storage time
  - relatively insensitive to storage time (low cost of Dewars)
  - limited by energy cost of liquefaction process
- Compressed gas
  - competitive for short storage times and low production rates
  - dominated by electricity cost of compression at high production rates
  - dominated by pressure vessel cost for long storage times (impetus for higher pressure levels)

Hydrogen Storage and Distribution : Conclusions

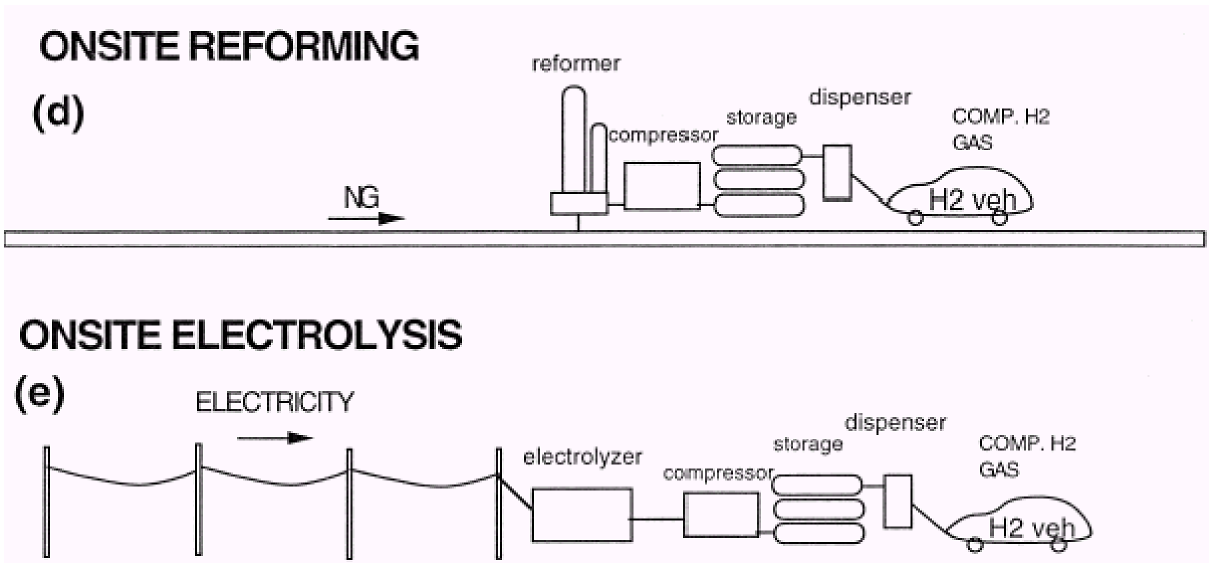
- Transport and distribution
  - liquid hydrogen transport by truck is likely to be the cheapest alternative...
  - ...except for very large flow rates when pipeline distribution becomes cost-effective
  - a liquid hydrogen tanker can carry around 20 times more hydrogen than a tube trailer
  - metal hydrides may become competitive over short distances due to high storage densities
- High storage and distribution costs can make small, on-site production plants cost-competitive

Hydrogen Economy - System Topography



Source :
J.M. Ogden (1999)

Hydrogen Economy - System Topography



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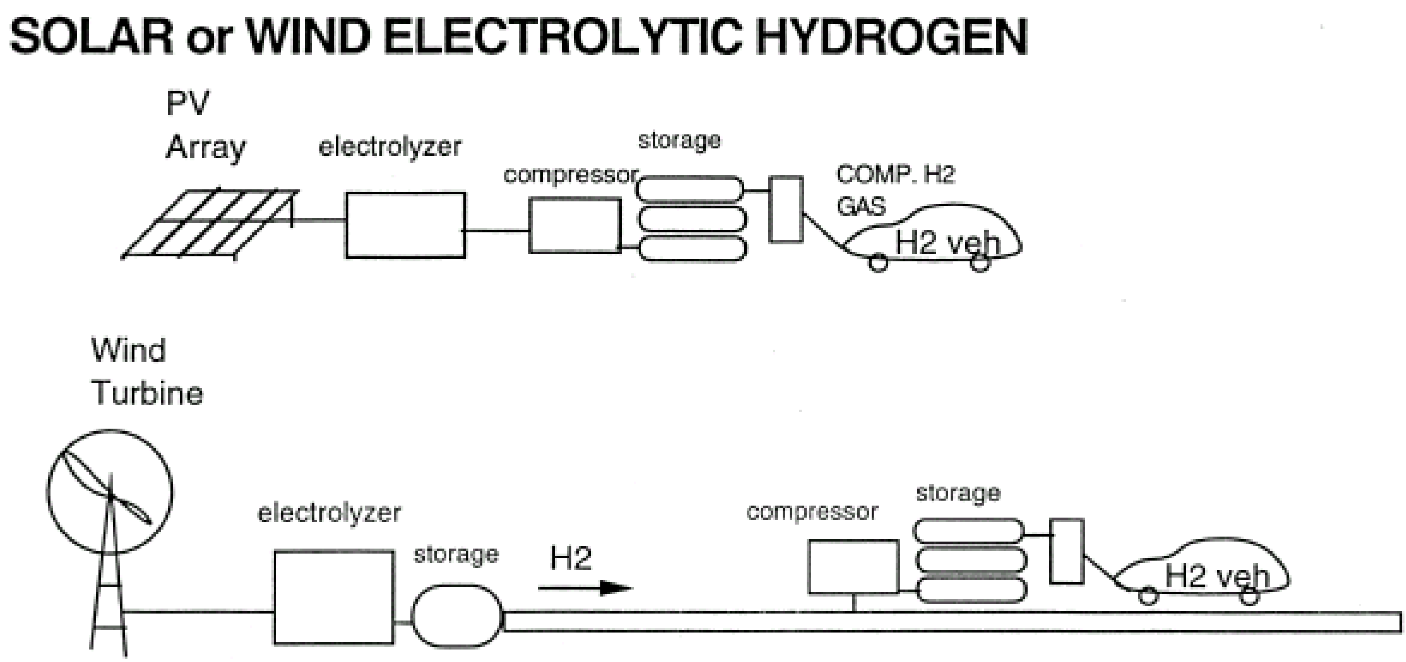
Hydrogen Economy - System Topography



Source :
J.M. Ogden (1999)

Conclusions (1)

- Increased use of hydrogen as an energy carrier could improve greenhouse gas emissions through:
  - sequestration of carbon or CO_2 in large, centralised plants processing fossil fuels,
  - generation of hydrogen using renewable energy sources and its subsequent use as a transport fuel,
  - efficiency improvements from using fuel cell vehicles.
- The net cost of hydrogen to the consumer depends on the production process, the chosen storage, supply and distribution option, as well as the end-use application.

Conclusions (2)

- Optimum method for hydrogen storage and distribution depends on production rate, storage time, and delivery distance.
- Carbon sequestration may be facilitated by increased emphasis and research into pyrolysis as a production route.
- Technical advances and cost reductions are needed in hydrogen storage and distribution.

Ongoing work - Phase 2

- Development of energy and hydrogen futures scenarios
  - further elaborate scenarios selected from the RCEP, PIU Energy Review, and Shell International reports
  - develop additional scenarios within this framework to investigate different possible developments of the hydrogen economy
  - estimate improvements in greenhouse gas emissions at selected penetrations of hydrogen
- Exploring the transition to a hydrogen economy
  - further investigate the lessons to be learned from the development of existing infrastructures (electricity, natural gas, oil, rail transport, media/communications)
  - identify likely technological, market, and policy requirements to achieve a fully integrated hydrogen economy
  - identify desired “end points” and any potential to “lock-out” potentially useful transitions

Ongoing work - Phase 2

- Medium and long term economics and market projections
  - expand on Phase I estimates of the medium and long term costs of hydrogen as a fuel
  - Pinpoint and rank a robust set of needs and opportunities for future technological development
  - Results will help to identify where future development is required, possible bottlenecks, and where research funding in the longer term should be directed
  - Examine relative merits of distributed, small, local hydrogen production compared to larger scale, centralised facilities
- Environmental impact
  - Water vapour effects
  - Materials restrictions (fuel cells, storage materials)