ECN

Energy research Centre of the Netherlands

Hydrogen fuel cells for transportation; realistic solution or distant dream?

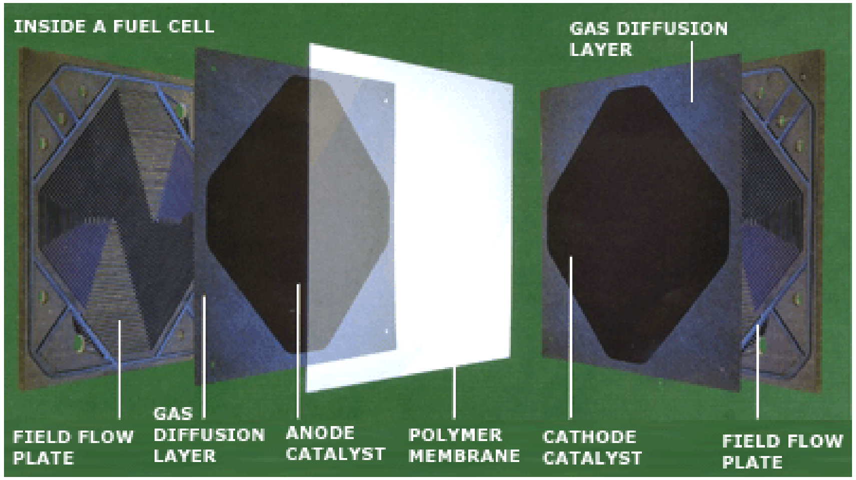
Marcel Weeda, ECN Hydrogen & Clean Fossil Fuels

Symposium 'Transportation in the future', Petten, 27 November 2007

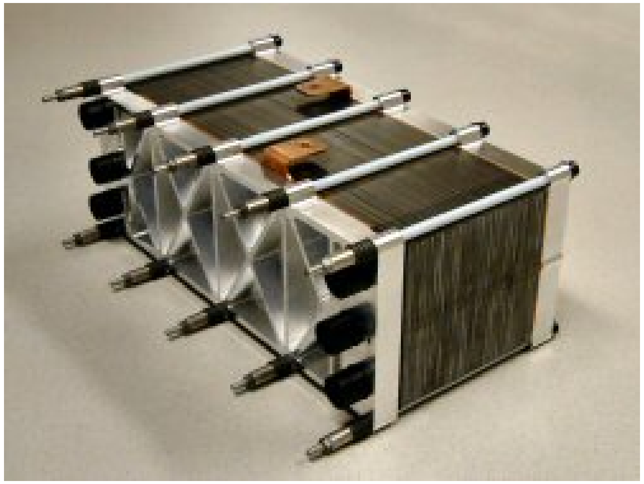
Basics on hydrogen and fuel cells

- Hydrogen is an energy carrier
    - Needs to be produced (from hydrocarbons or water, using heat and/or electricity)
    - Needs to be converted (fuel cell, internal combustion engine, gasturbine, burner)
- Fuel Cell is a conversion technology
    - Needs a fuel (hydrogen, syngas or hydrocarbon)
    - Produces electricity and heat
- Several types of fuel cells exist. Not all fuel cells need hydrogen, and to use hydrogen you do not necessarily need a fuel cell
- Fuel cells: most efficient way to convert hydrogen into electricity at small scale
- Efficiency of fuel cells is indepedant of scale (unlike ICE and gasturbine), and fuel cells have high part load efficiency (unlike ICE and gasturbine)
- The Proton Exchange Membrane Fuel Cell (PEMFC) is the most relevant type for vehicle applications

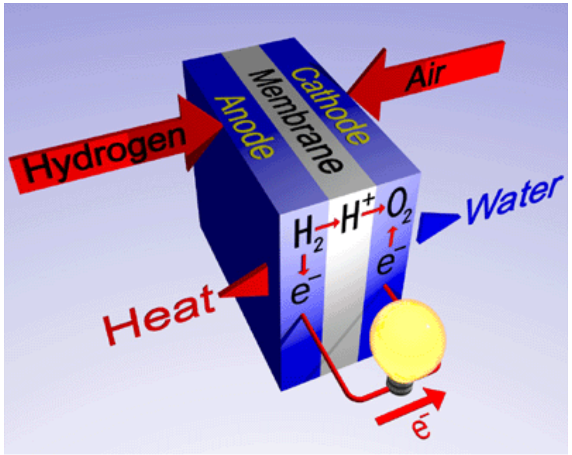
Basics of a (PEM) fuel cell



Fuel cell and flow or separator plates



Stack of fuel cells



Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

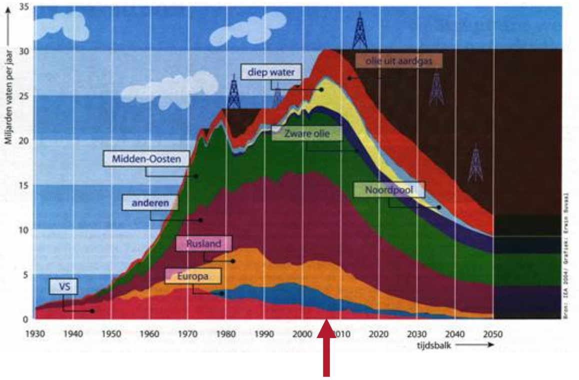
Cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$

$\underline{4H^+ + 2O^{2-} \rightarrow 2H_2O}$

Overall: $2H_2 + O_2 \rightarrow 2H_2O$

Why hydrogen? (1)

- Security of supply; oil addiction is (becoming) a problem
  - Dependency
  - Availability
  - Affordability



- Reduction of CO_2 emissions
  - Additional way to implement renewables
  - Production from fossil sources with CCS
  - Fuel switch and efficiency improvement

Zeeijs rond noordpool verdwijnt razendsnel

Door onze redactie wetenschap

ROTTERDAM, 2 OKT. Het zeeijs rond de noordpool verdwijnt in recordtempo. Nooit eerder sinds het begin van de satellietwaarnemingen in 1979 heeft er in september zo weinig zeeijs gelegen als afgelopen maand. De ijsbedekking lag rond 16 september maar liefst 39 procent onder het gemiddelde van de periode 1979 - 2000. Vooral aan de zijde van de Beringstraat is een enorm zeeoppervlak ijsvrij geworden.

Dat bericht het National Snow and Ice Data Center (NSIDC) van de universiteit van Colorado in Boulder. De gevolgen van het versterkte broeikaseffect worden nu 'luid en duidelijk' waarneembaar. De NSIDC maakt jaarlijks aan het eind van het smeltseizoen de balans op en komt dan in oktober met een persbericht. Het centrum baseert zich op satellietgegevens: voor de periode 1978-1987 van de Nimbus-7 satelliet, daarna van een defensiesatelliet. Het is het meest gezaghebbende instituut voor uitspraken over trends in zeeijsbedekking.

Worden de schaarse vliegtuig- en scheepswaarnemingen uit de jaren voor 1978 als gelijkwaardig meegeteld dan valt te concluderen dat de september-ijsbedekking sinds de jaren vijftig ruwweg is gehalveerd. Twee weken geleden meldde de Europese ruimtevaartorganisatie ESA, zonder noemenswaardige toelichting, dat 'voor het eerst in de geschiedenis' de noordwestelijke doorvaart geheel open lag. Maar voor 1978 zijn daaraan weinig of geen systematische waarnemingen gedaan.

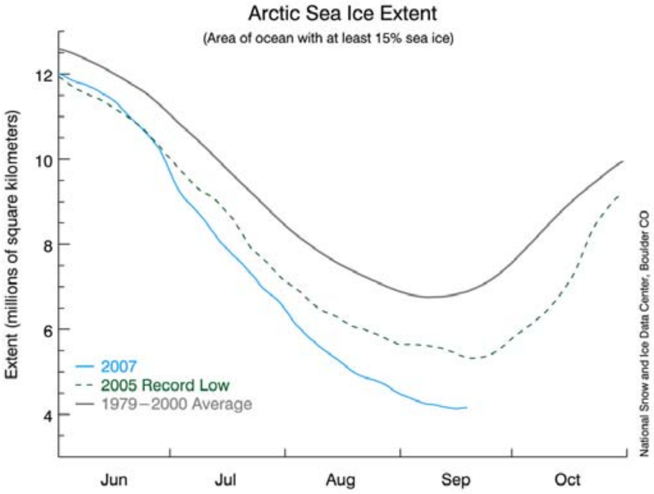
Het wachten was op het ijsbericht van de NSIDC. Dat kwam gisteren, vergezeld van recente satellietopnames. Inmiddels ligt de noordwest passage weer dicht.

De waarnemingen van het NSIDC beperken zich louter tot de ijsbedekking van het zeeoppervlak. Ze houden geen rekening met ijsdikte en de verhouding tussen jong en oud (overjarig) ijs. Maar ook daarin zouden, volgens verspreide metingen, de trends ongunstig zijn. Het NSIDC stelt vast dat het smeltseizoen rond de noordpool steeds langer duurt. De geringste ijsbedekking rond de pool wordt steeds later in september bereikt.

'De ijsbedekking rond de noordpool is in een neerwaartse spiraal geraakt en kan het "point of no return" inmiddels gepasseerd zijn', aldus het persbericht. Daarmee wordt gezinspeeld op een dreigend zelfversterkend effect: als er weinig zeeijs is, kan de zee meer zonnestraling absorberen waardoor de watertemperatuur stijgt.

Afname in zeeijs op noordpool van 2005 tot 2007

NRC Handelsblad 021007 / RB / Bron: NSIDC



Arctic Sea Ice Extent

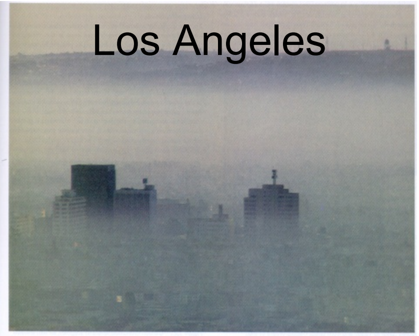
(Area of ocean with at least 15% sea ice)

National Snow and Ice Data Center, Boulder CO

Why hydrogen? (2)

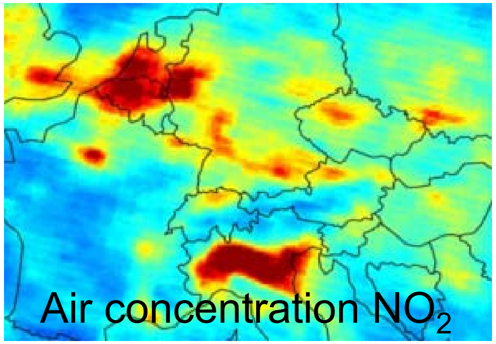
- Reduction of air pollution
  - Clean fuel, no local pollution

Paris



Los Angeles

Figure 2.20 A morning of intense photochemical smog in Los Angeles.



Air concentration NO_2

- Economic competitiveness
  - New products, new markets

Alternatives?

- Hydrogen Economy? Hydrogen is an option in a portfolio of options.

- Biofuels
  - Easy fit into the “system”
  - Sustainability
  - Availability: increase of current 900 million to 2100 milion cars in 2030 (IEA, 2007)
  - Still local emission
  - Aviation, shipping, long distance truck transport
  - Biomass for many other applications

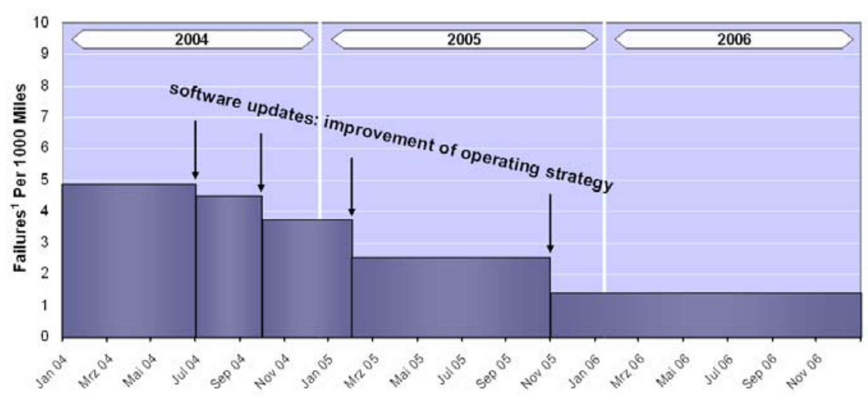
- Electric cars
  - Highest efficiency
  - Limited drive range
  - Charging time
  - Battery life

Tesla Motors:
Range >320 km (claim)
Full charge 3.5 hours
160,000 km (claim)

State-of-the-art hydogen fuel cell vehicles (1)

Vehicle	DC	Mercedes A-Class
Status	Since 2002	> 60 vehicles in operation
Propulsion	Fuel Cell Battery Electric Motor	85 kW 65 kW
Storage	CGH_2	35 MPa (350 bar)
Performance	Range Top speed Acceleration	150 - 170 km 145 km/h

- Currently accumulated mileage >1.5 million km
- Accumulated operation >42,000 h
- January 2007 first F-Cell >100,000 km and 2000 h without significant performance loss
- Overall availability >85%



State-of-the-art hydogen fuel cell vehicles (2)

Vehicle	DC	Mercedes B-Class
Status	**2010**	Small series
Propulsion	Fuel Cell Battery Electric Motor	100 kW (incl. battery) Li-ion 100 kW
Storage	CGH_2	70 MPa (700 bar)
Performance	Range Top speed Acceleration	~400 km 180 km/h

- Market introduction 2015 → ?

State-of-the-art hydrogen fuel cell vehicles (3)

Vehicle	GM	Opel Zafira HydroGen 3
Status		Prototype (version 2004)
Propulsion	Fuel Cell Battery Electric Motor	94 kW 60 kW
Storage	LH_2	Liquid 68 l / 4.6 kg
Performance	Range Top speed Acceleration	400 km 160 km/h 0 – 100 km/h in 16 s

Endurance test

May - June 2004

38 days / 9696 km

State-of-the-art hydogen fuel cell vehicles (4)

Vehicle	GM	Chevrolet Equinox
Status	2007	100 vehicles
Propulsion	Fuel Cell Battery Electric Motor	115 kW 35 kW NiMH
Storage		70 MPa (700 bar, 4.5 kg)
Performance	Range Top speed Acceleration	320 km 145 km/h 0 – 100 km/h in 12 s

- Field test 100 vehicle in Los Angeles, Washington D.C. and New York
- Target: 1000 vehicles by 2010 and 100,000 vehicles by 2015

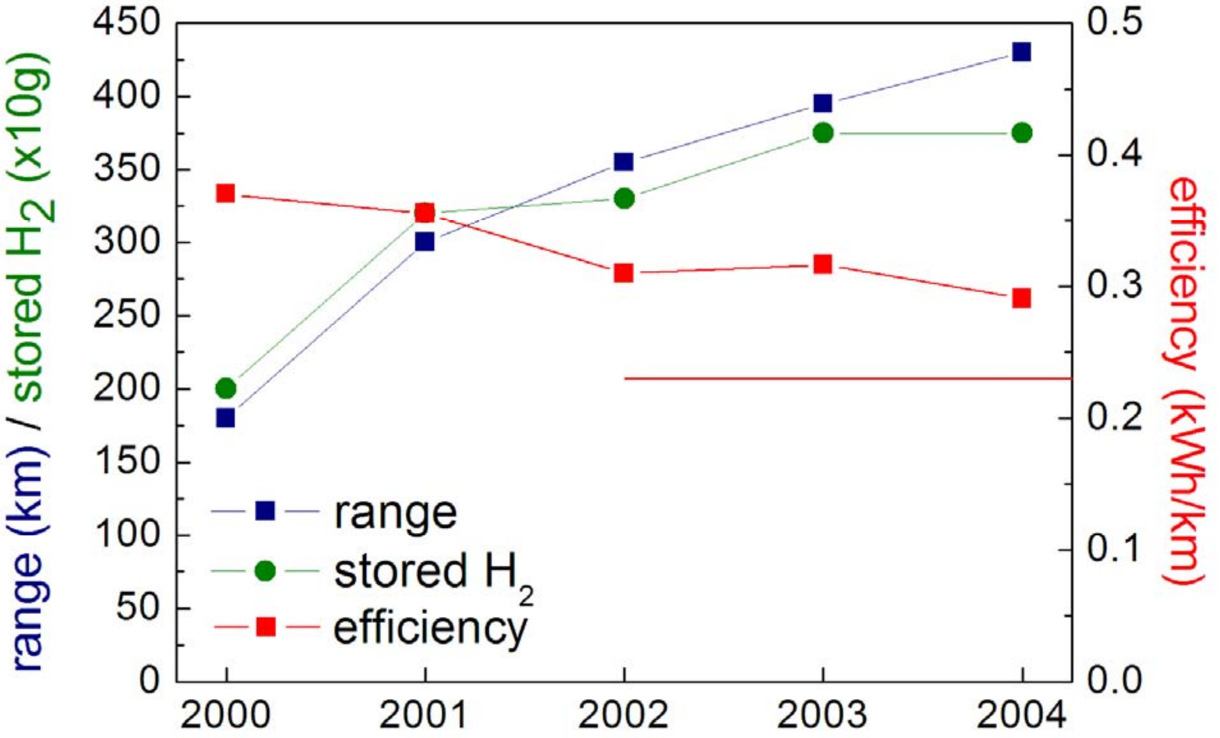
State-of-the-art hydrogen fuel cell vehicles (5)

Vehicle	Toyota	Toyota Highlander
Status	2007	Demonstration
Propulsion	Fuel Cell Battery Electric Motor	90 kW Hybrid with NiMH battery 80 kW (Torque 260 Nm)
Storage	CGH_2	70 MPa (700 bar)
Performance	Range Top speed Acceleration	580 km (real test) 155 km/h

- Long distance road test from Osaka to Tokyo (580 km) on a single fueling of hydrogen
- Toyota FCHV 25% more fuel efficient than earlier version
- 70 MPa hydrogen storage instead of previous 35 MPa

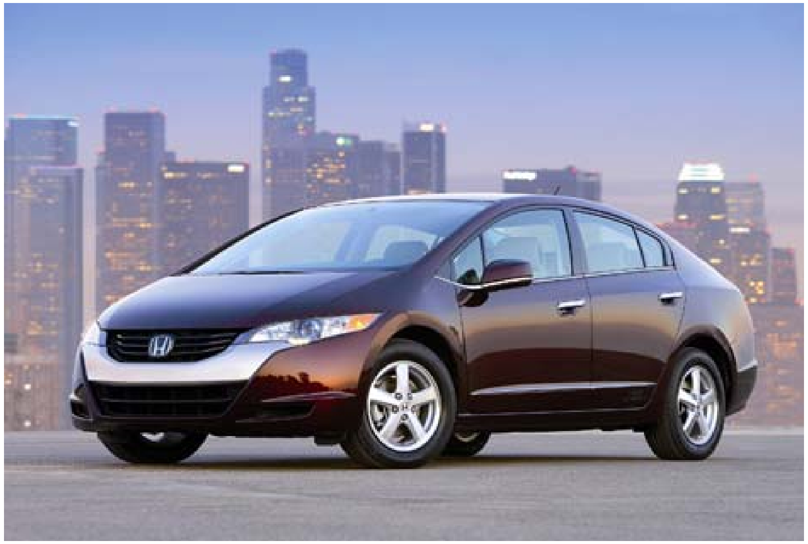
- Range according to 10-15 Japanese test cycle is 780 km

State-of-the-art hydogen fuel cell vehicles (6)



Honda FCX

State-of-the-art hydrogen fuel cell vehicles (7)



Vehicle	Honda	FCX Clarity
Status	2008	Small Series
Propulsion	Fuel Cell Battery Electric Motor	100 kW Li-ion battery 100 kW (torque 256 Nm)
Storage	CGH_2	35 MPa (171 l)
Performance	Range Top speed Acceleration	~430 km 160 km/h (limited)

- 50% increase of output density per volume (67% by mass) compared to previous FCX
- 20% increase of fuel economy (indicative fuel use 26 km/l g.e.)
- Improved low temperature start-up capability: at -30ºC

- Begin of limited retail marketing in summer 2008 in Southern California
- For three years lease term: $600 per month including maintenance and insurance

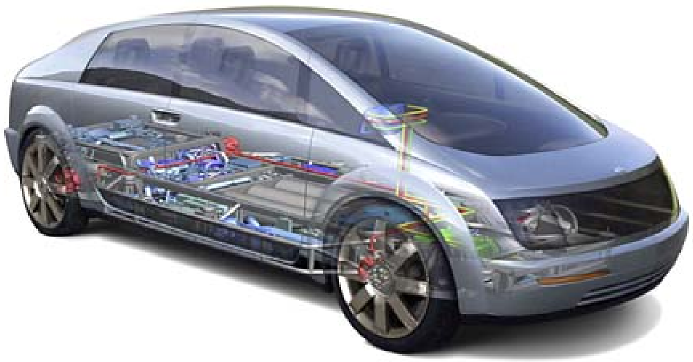
State-of-the-art hydogen fuel cell vehicles (8)

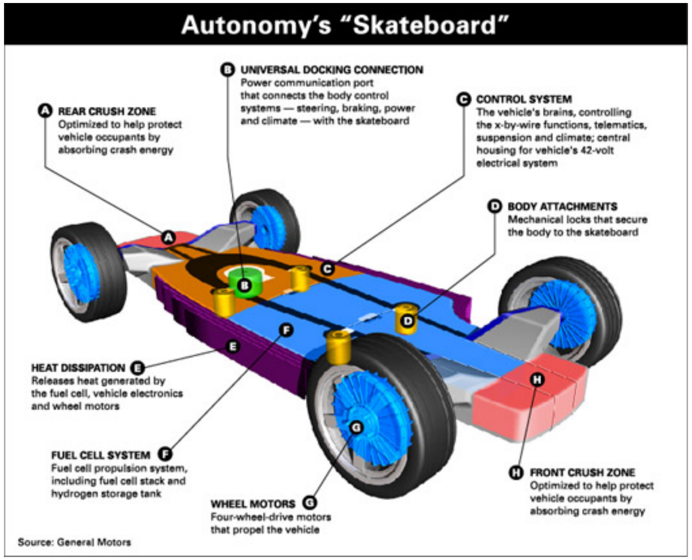
Fuel cell vehicle outlook

- **High Temperature PEM** Fuel Cell battery hybrid
- **Plug-in capability (range 100 km battery only)**

- *150 W Photovoltaic panel (roof mounted)*
  ~2 h @ nominal capacity required for 1 km

Fuel cell vehicle outlook





Autonomy's "Skateboard"

A REAR CRUSH ZONE
Optimized to help protect vehicle occupants by absorbing crash energy

B UNIVERSAL DOCKING CONNECTION
Power communication port that connects the body control systems — steering, braking, power and climate — with the skateboard

C CONTROL SYSTEM
The vehicle's brains, controlling the x-by-wire functions, telematics, suspension and climate; central housing for vehicle's 42-volt electrical system

D BODY ATTACHMENTS
Mechanical locks that secure the body to the skateboard

HEAT DISSIPATION E
Releases heat generated by the fuel cell, vehicle electronics and wheel motors

FUEL CELL SYSTEM F
Fuel cell propulsion system, including fuel cell stack and hydrogen storage tank

WHEEL MOTORS G
Four-wheel-drive motors that propel the vehicle

H FRONT CRUSH ZONE
Optimized to help protect vehicle occupants by absorbing crash energy

Source: General Motors

Fuel cell drive train issues

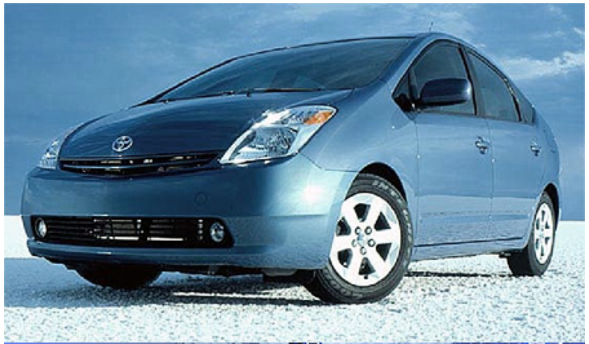
- Drive train cost
  - Cost of the fuel cell
    - Cheaper materials fuel cell
    - Less components fuel cell system
    - Mass production
  - Hydrogen storage

- Improve fuel cell life

- Improve operational window
  - Operation under wider range of climate conditions (e.g. High Temperature PEM)
  - Robustness; tolerance towards under off spec conditions

- Reduction of volume and weight

Other hydrogen vehicles; transition options?

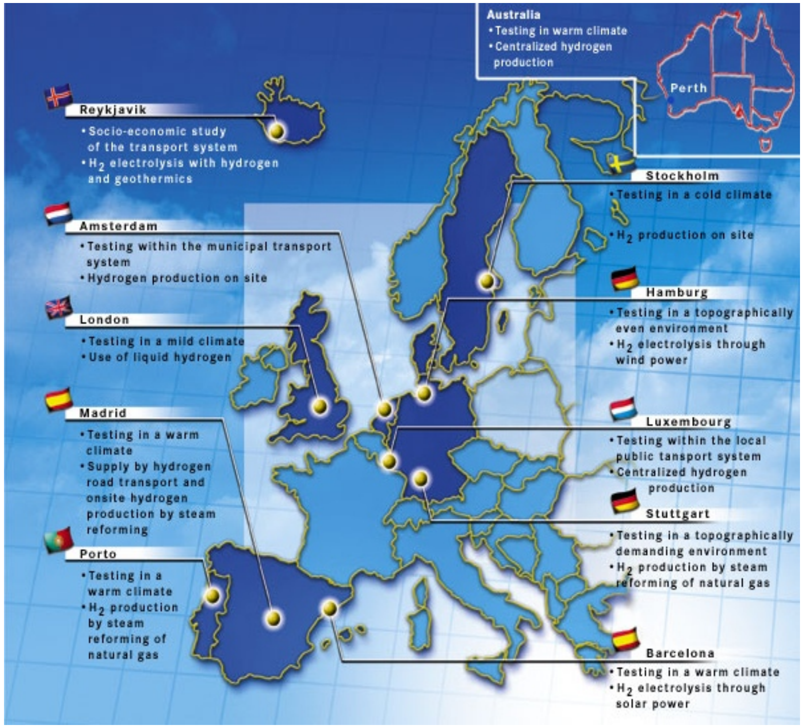


- H_2 Internal Combustion Engine (ICE) Hybrid
- Quantum Technologies based on Toyota Prius
- Currently 10 in Norway and 10 in Iceland
- Comparable power to gasoline version
- Increased fuel efficiency

- H_2 ICE
- Mainly Ford, although also active in fuel cells

- H_2/gasoline bivalent ICE
- BMW 760 V12, but other models should follow
- Mazda RX8 and Mazda Premacy (hybrid bivalent ICE)
- Fiat Panda

Hydrogen busses (1)



- EU CUTE project: 27 busses in 9 EU cities
- 9 busses in 3 related projects; Iceland, Australia (Perth) and China (Beijing)
- Different climatic / topographic conditions
- Results 2003 – 2005
  - Accumulated mileage 840,000 km
  - Accumulated operation 62,500 h
  - Availability >81% (up to >99% in Stuttgart)
  - Passenger carried >4 million
  - No major safety incidents

Hydrogen busses (2)

- CUTE followed by HyFLEET:CUTE
- Continued operation of CUTE busses (in Amsterdam and Hamburg until 2008)
  - >1.8 million km and >116,000 h of operation by all Citaro busses by end February 2007
- Operation fleet of 14 H_2-ICE busses in Berlin
- Design new H_2 FC-Hybrid bus: 20% better fuel economy than a comparable diesel bus
- Demonstration of new bus in 2009
- In CUTE and HyFLEET:CUTE also testing of H_2 production options and infrastructure
  - On-site NG-reforming; electrolysis; delivery
  - New technologies; dispensers, compressors
  - New concepts; LPG reforming and synergy with stationary fuel cell
- Education; Training; Develop and deliver data facts and recommendations

Hydrogen scooters and motor bikes

Suzuki 125 cc class motor

Yamaha

Asia Pacific Fuel Cell Technologies: 4th generation zero emission scooter

Honda 125 cc class

Vectrix, USA

Piaggio

Hydrogen filling stations

Reykjavik, Iceland

- Worldwide about 150 H_2 filling stations
- About 20% publicly accessible
- In Europe about 40 stations in operation of which13 stations with public access:
  - 6 in Germany
  - 2 in Norway and Italy
  - 1 in Iceland, Sweden and Switzerland
- In Germany as many public H_2 filling stations as biodiesel filling stations in NL
- In the Netherlands currently 2 filling stations
  - GVB Amsterdam (CUTE)
  - ECN Petten

Examples of H_2 filling stations with public access

Berlin

Washington DC

Mantova, Italy

Singapore

München

Where does the hydrogen come from?

Natural gas

Coal

Nuclear energy

Biomass

Wind energy

Geothermal heat

Solar energy

How to get the H_2 energy to the customer? (1)

as electricity

for on-site electrolysis

as natural gas for on-site SMR

liquefaction

as LH_2 by truck

How to get the H_2 energy to the customer? (2)

compression

as CGH_2

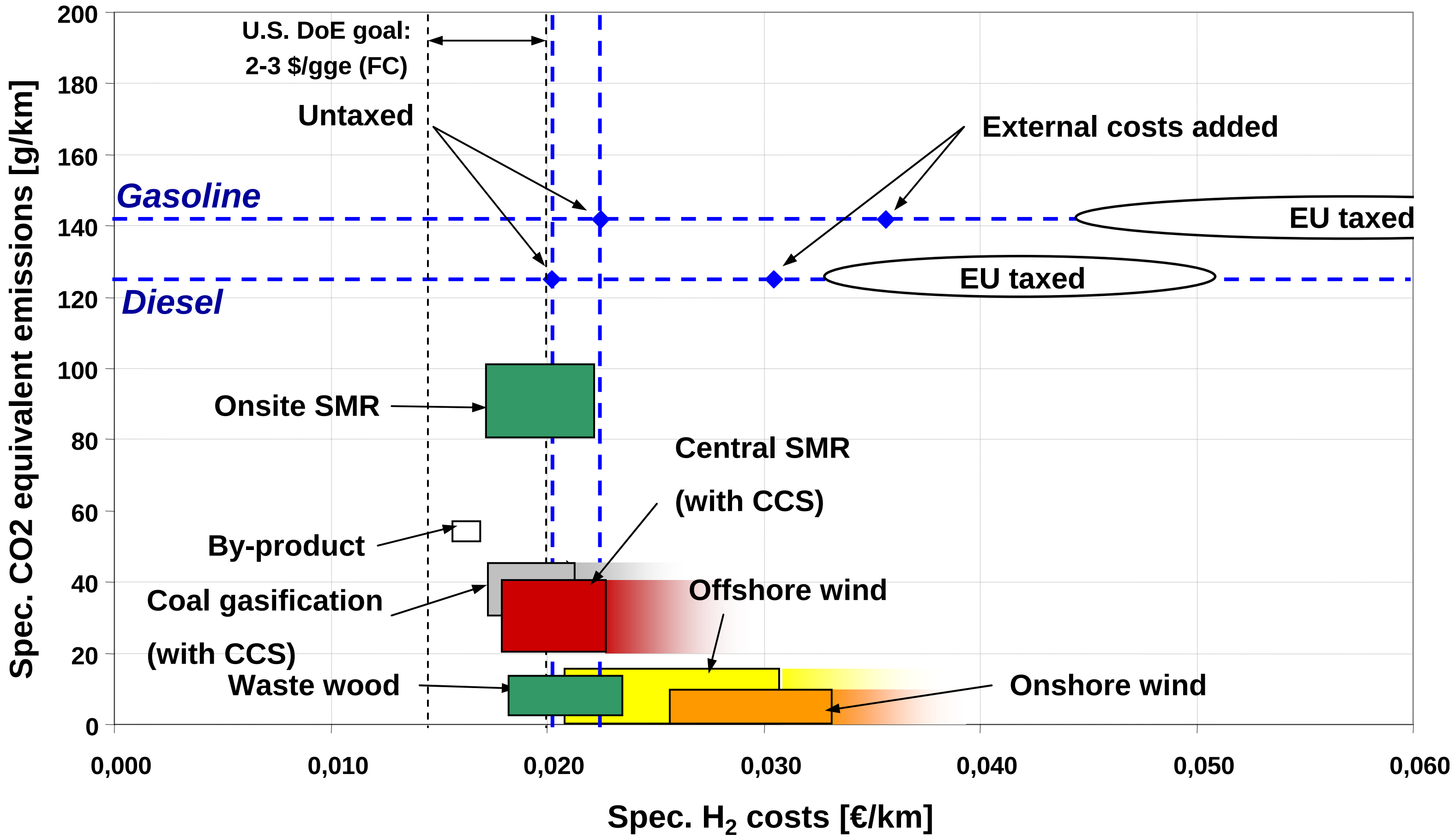
by truck

30 bar H_2 pipeline

as CGH_2

by pipeline

Hydrogen perspective; energy chain analysis



Hydrogen production and infrastructure issues

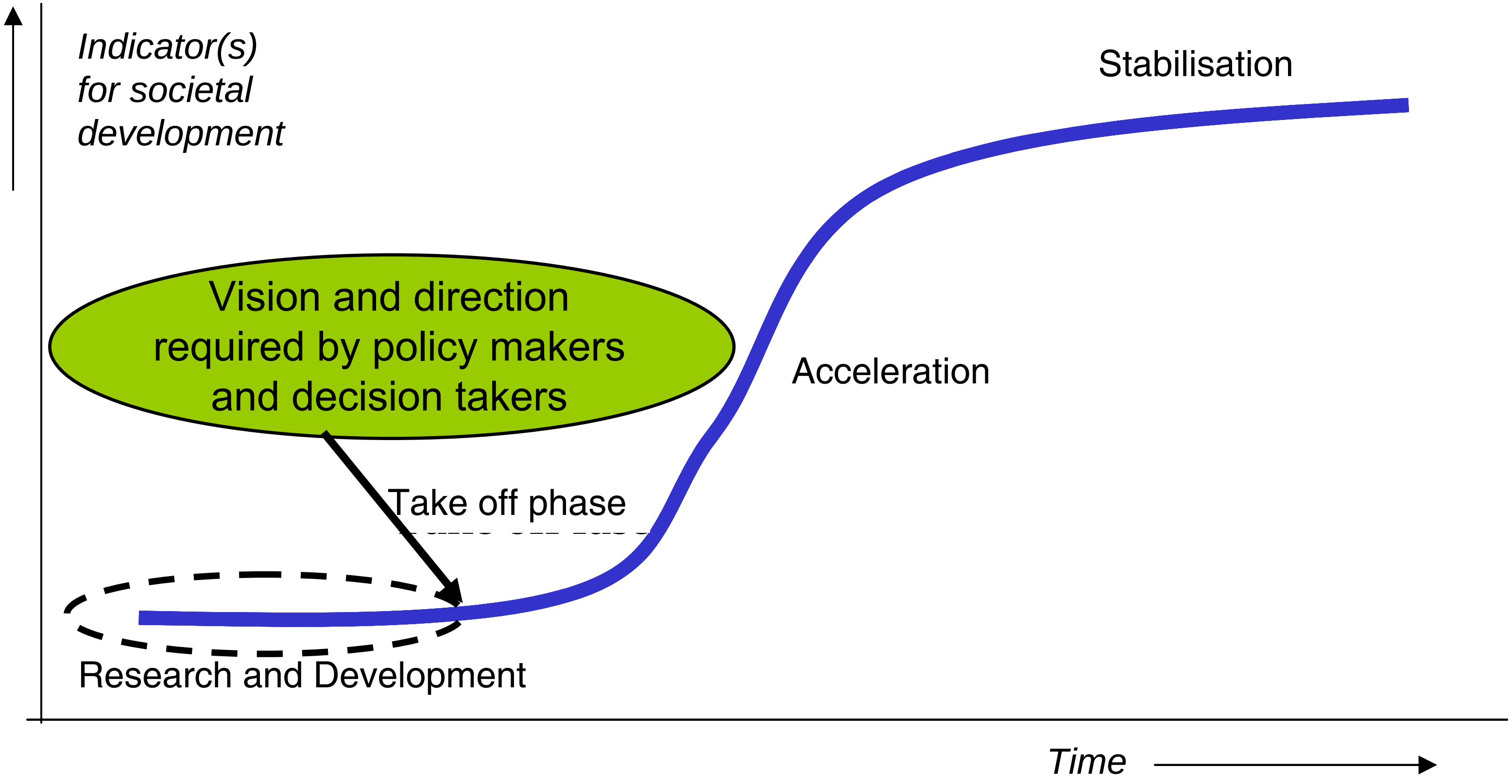
- The hydrogen infrastructure does not yet exist
  - Industrial production, but only few merchant hydrogen
  - Some industrial hydrogen pipelines (NL, BE, FR and GE)
  - Renewable hydrogen or fossil hydrogen (for the time being)

- No infrastructure without cars - no cars without infrastructure

- No consensus on concepts for hydrogen fuelling infrastructure
  - On-site production
  - Trucked in compressed or liquified hydrogen
  - Pipeline
  - Hydrogen specifications, build-up capacity, external safety issues, spatial planning

- No consensus on likely evolution of hydrogen fuelling infrastructure
  - How to deal with initial underutilization; balancing investment vs. unit size
  - Concentrated users: high demand per fuelling station (preference fuel providers)
  - Distributed users: large market for vehicle sales (preference car manufacturers)
  - How many fuelling stations required to satisfy/convince customers

Where are we in the transition?



Indicator(s)
for societal
development

Stabilisation

Vision and direction
required by policy makers
and decision takers

Acceleration

Take off phase

Research and Development

Time

Still R&D and demo-project policy. No real deployment policy yet.

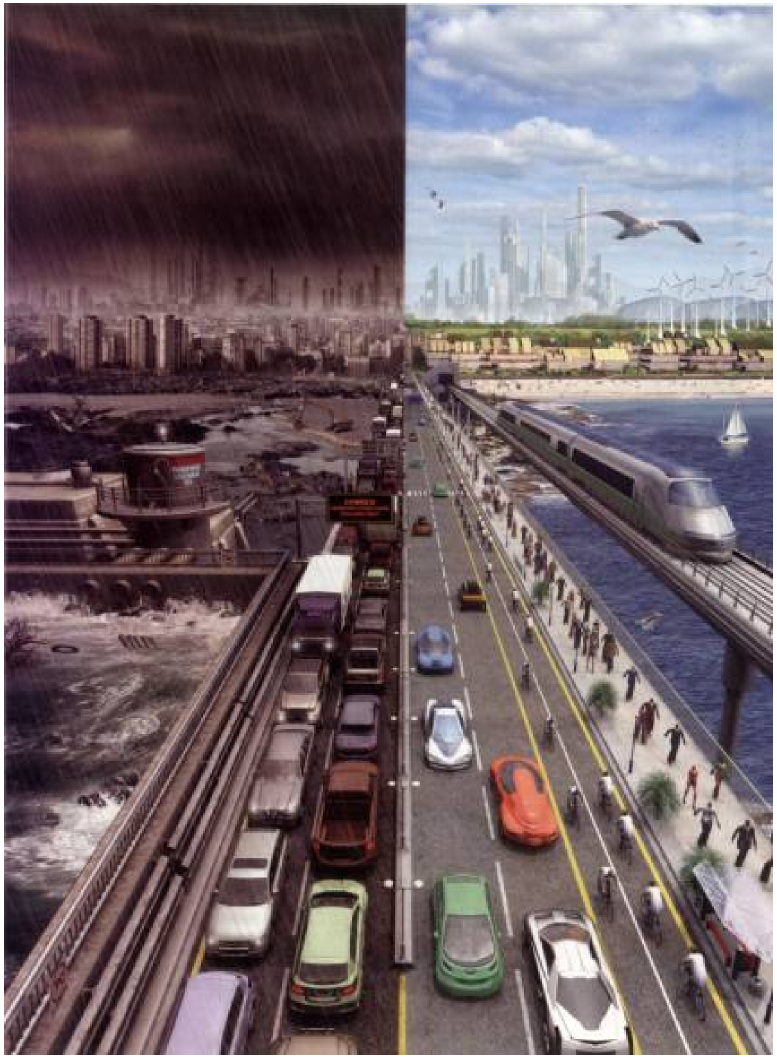
Summary / Conclusions

- Hydrogen has the required characteristics for an energy carrier in a sustainable energy system
- Clear role for hydrogen in transport applications
- Long term outlook hydrogen fuel cost and hydrogen vehicle cost are OK, also for WTW GHG-emissions and primary energy use
- Current development and performance very promising

- Hydrogen fuel cells for transportation is a realistic solution

- H_2 and FC still in R&D phase: cost reduction, cost reduction, ….
- Further R&D needed into infrastructure dilemmas
- Start real market introduction 2015-2020
- Significant short term investments needed for long term benefits
- As number in series increase real deployment policies should be developed both for hydrogen cars and for hydrogen infrastructure: policy framework, early markets, incentives

Business as usual



Action

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Thank you for your attention

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