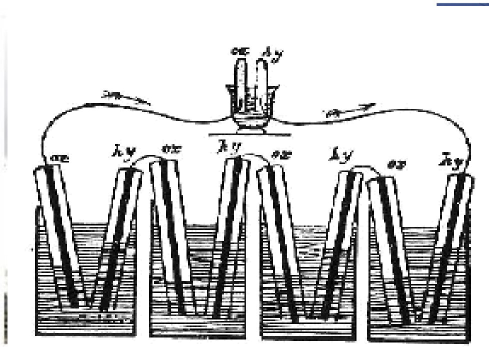
Hogeschool van Arnhem en Nijmegen

Energy storage in hydrogen



Mascha Smit

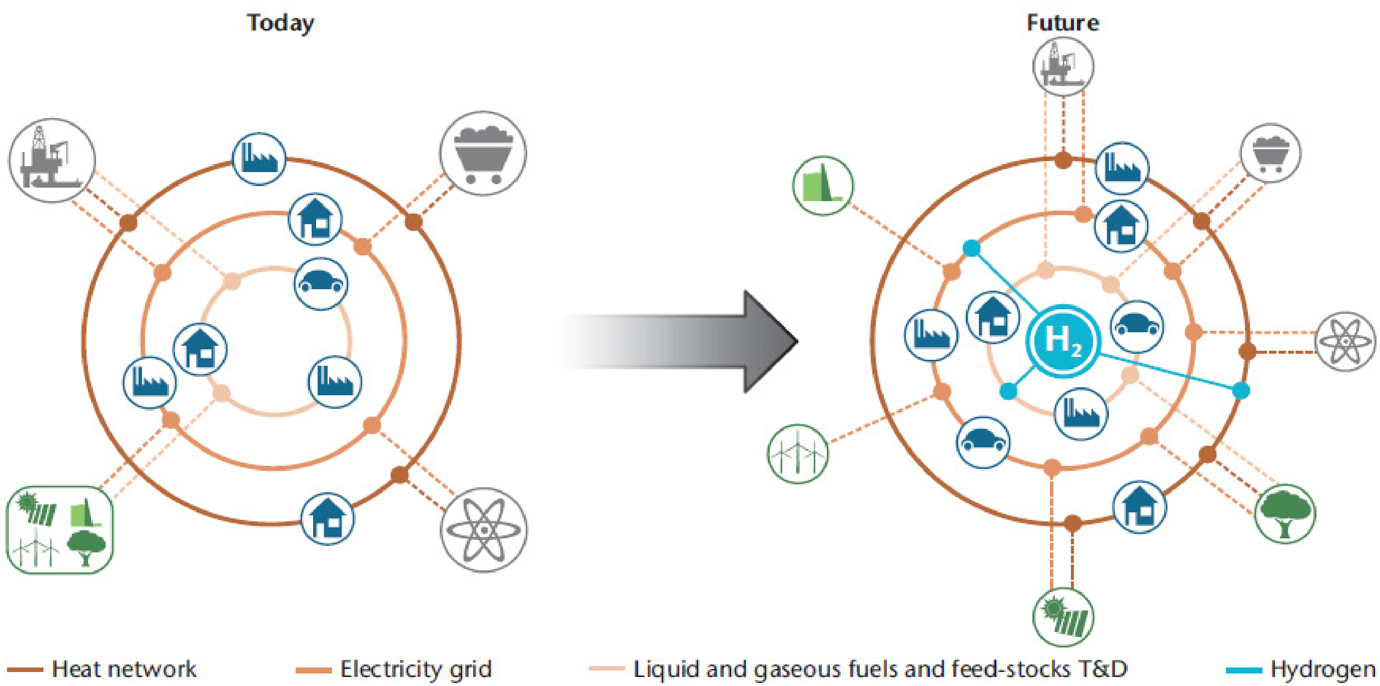
KIvI symposium

Energieopslag

12 april 2017

Changing energy system

- today: lineair system from producer to consumer, seperated 'lines' for different carriers
- future: complex interconnected system of different energy carriers with producers, prosumers and consumers
- Hydrogen part of energy system



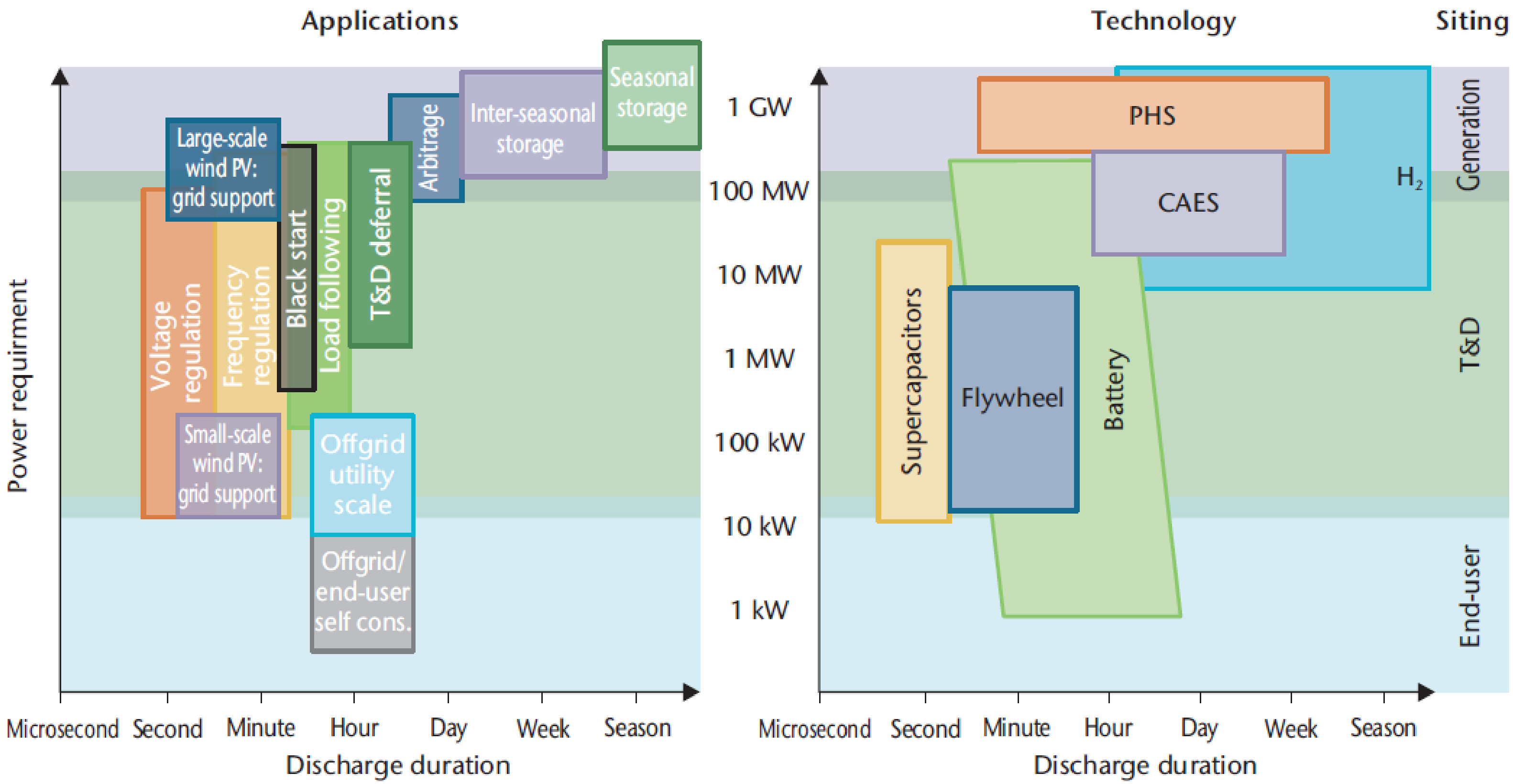
Technology Roadmap –
Hydrogen and Fuel cells; IEA, 2015

Need for seasonal energy storage

- **gasless future?**
- **electrical heating or heating network**
- **heating with heatpump will increase electricity consumption during winter ~4 times**
- **monthly RE production capacity NL more or less constant:**
  - summer: less wind
  - winter: less sun
- **electrical heating requires more windturbines and seasonal storage**

Energy storage

- only hydrogen suited for large scale seasonal storage



Note: CAES = compressed air energy storage; PHS = pumped hydro energy storage.

Technology Roadmap – Hydrogen and Fuel cells; IEA, 2015

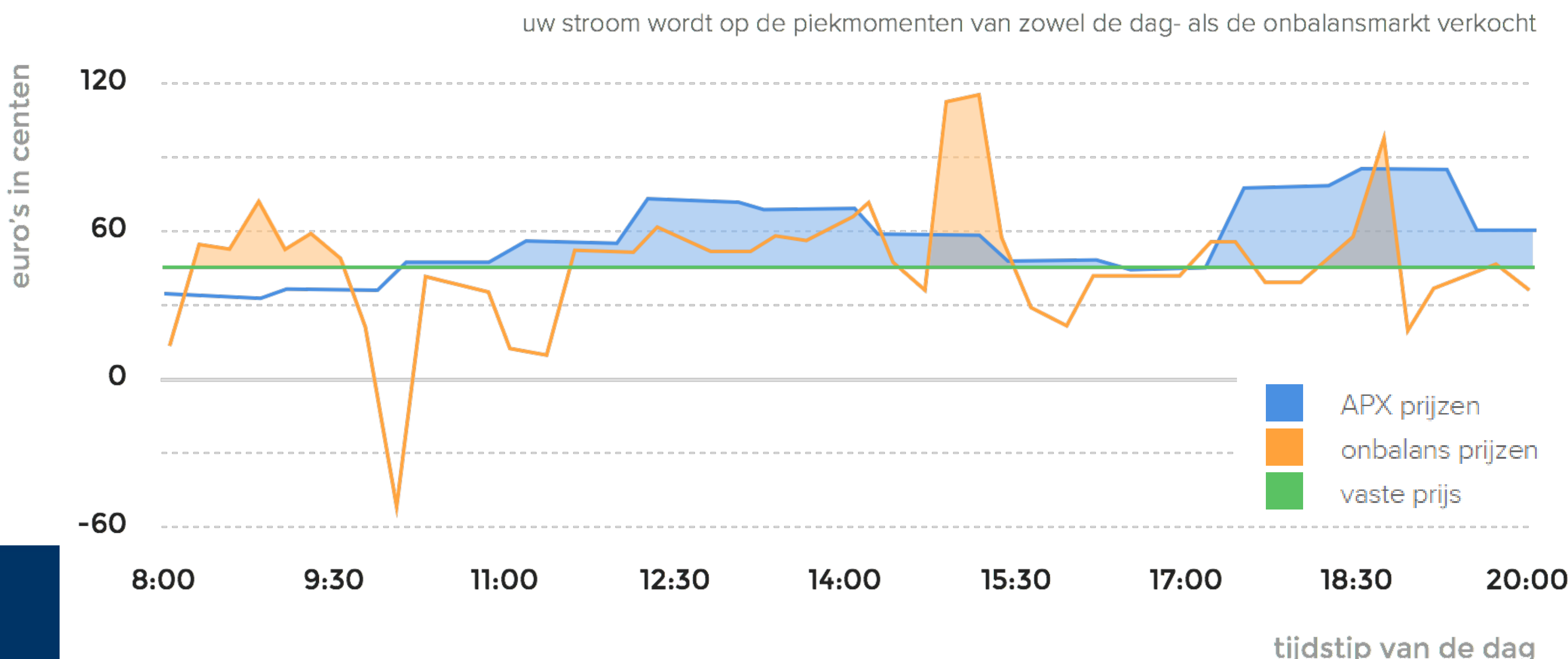
Hydrogen for energy storage

- **Use excess renewable energy**
  - offshore wind GW-scale
  - low tot negative price
  - add to energy balance!
- **Produce H2 in large quantities**
  - cheaper due to large scale installation
  - use oilrig facilities?
  - store, ship, transport
- **Use when needed**
  - electricity
  - heating (winter only)
  - transport
  - industry

→ wind and H2

‘smart grid’

- smart use of flexible energy pricing



http://julesenergy.nl/

Dutch fuel vision

Dutch report ’Energieakkoord voor duurzame groei’ (2013) includes targets for sustainable transport:

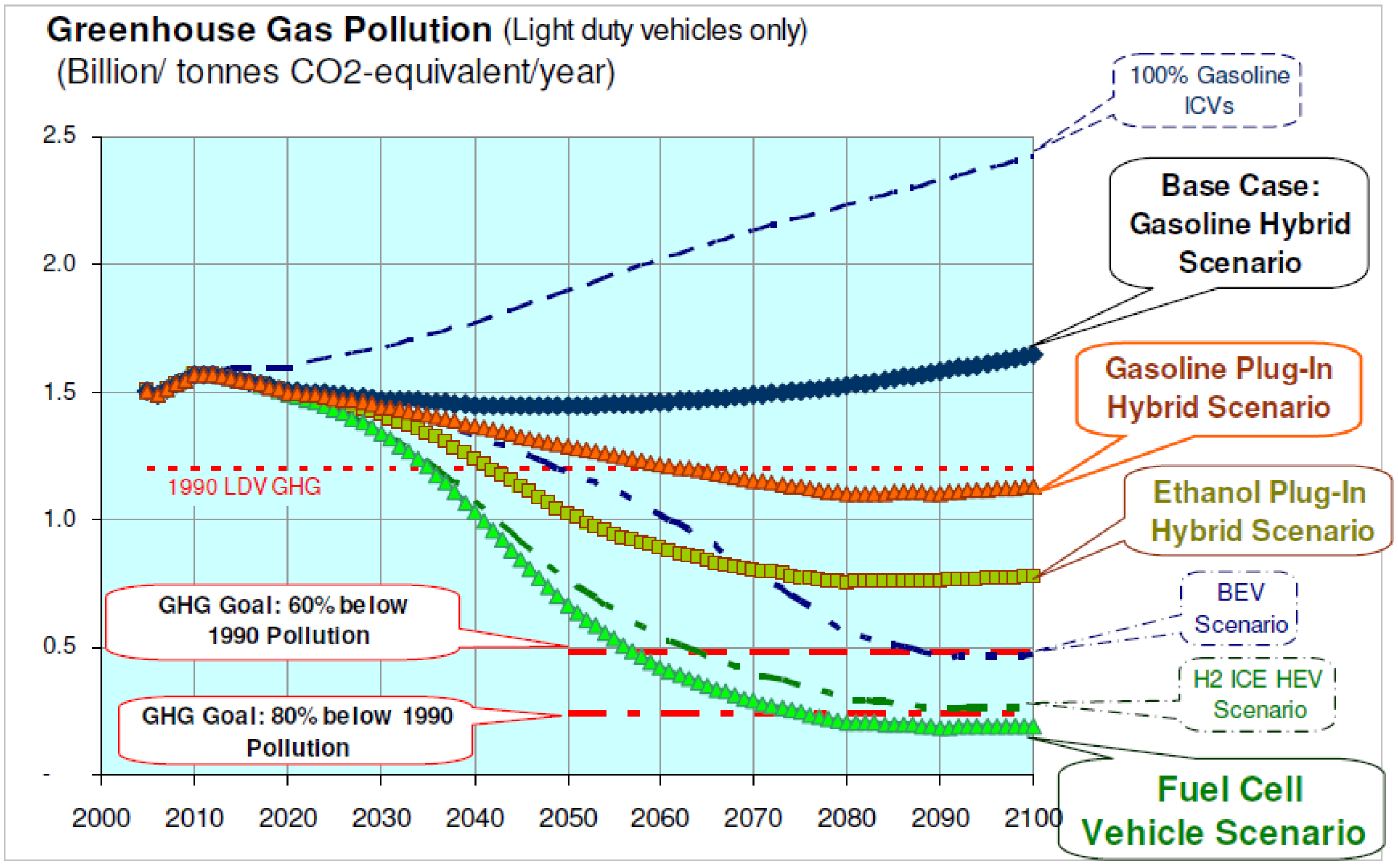
- 2030 max. 25 Mton CO_2 from transport (17% less than 1990)
- From 2035 on all new vehicles for personal use emission-free.
- cumply with EU target 2050: 60% less CO_2 than 1990

Four simultaneous routes for transport in report ‘Brandstofvisie’ (2013) en Agenda (2015):

- Electric vehicles
- Hydrogen technology
- Renewable gas
- Increased efficiency

Emission scenario transport

- **FCEV's will lead to reduces GHG emissions**



http://www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/thomas_fcev_vs_battery_evs.pdf

Why hydrogen?

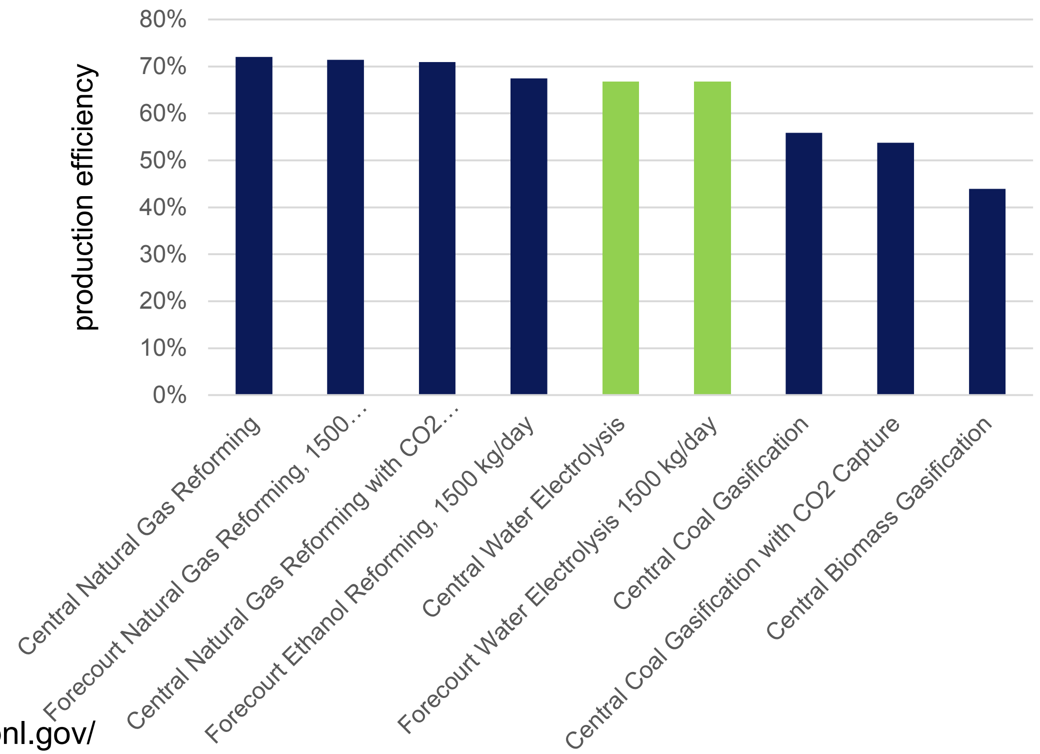
- **energy carrier**
- **NO emissions!**
  - from renewable sources
- **availability**
  - H2 production locally or centralized from multiple sources
- **non-toxic, non-carcinogenic**
- **high efficiency**
  - electrical: ~50%
  - cogen: >90%
- **can be 100% renewable**

Hydrogen technology requires….

- **H2 production**
- **H2 storage**
- **H2 transport & distribution**
- **conversion of H2 to energy**
  - fuel cells
  - electricity and heat
- **suitable applications**
- **laws, standards, education, etc.**

H2 Production

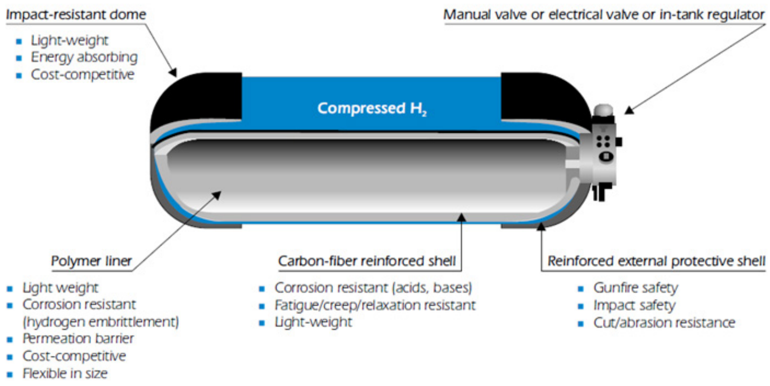
- **Steam Methane Reforming**
  - natural gas
- **Alkaline electrolyzer**
- **PEM electrolyzer**
- **bio-processes**
- **others**



DoE Hydrogen Analysis Resource Center; http://hydrogen.pnl.gov/

Storage & transport

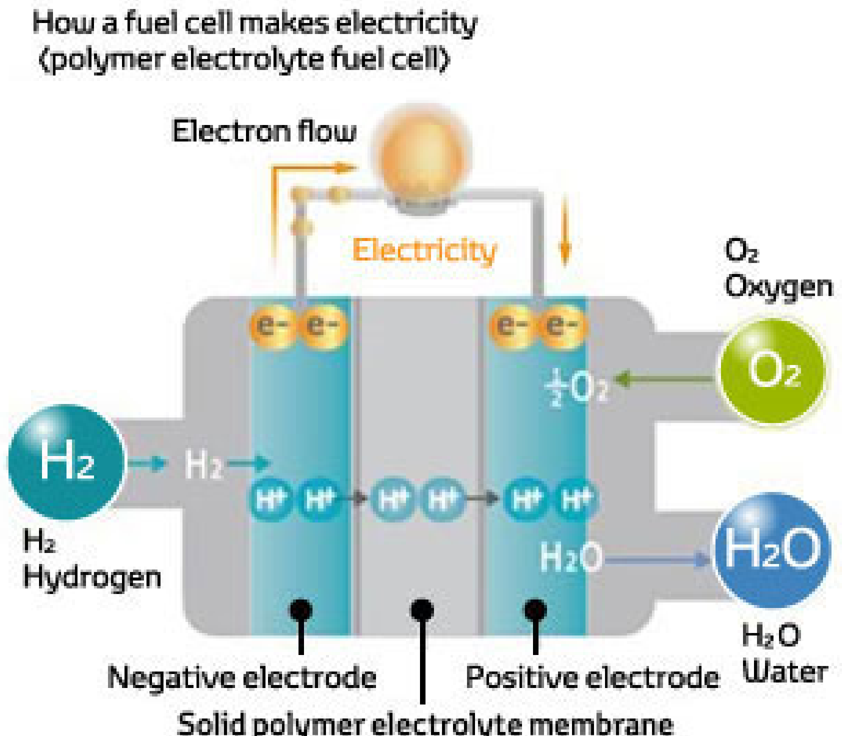
- small and light = specialized techniques and materials
- compressed
- cryogenic
- in solids
- underground?
- convert to other carrier?
  - methanation
- pipelines (nat. gas network)
- ships/trailers

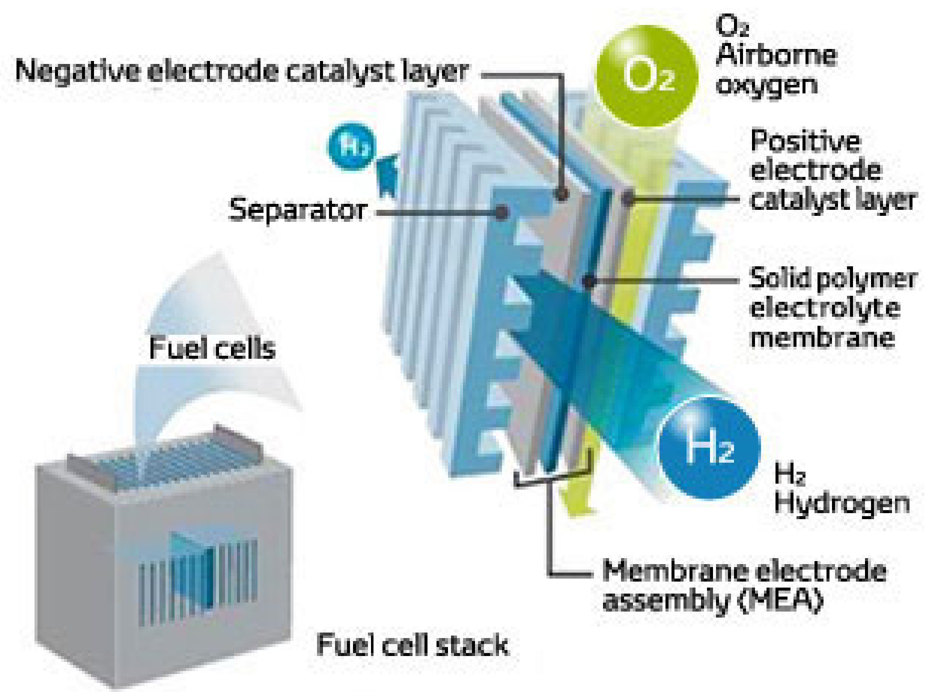


Conversion to electricity in fuel cell

- **different fuel cell types for different applications**

$$2H_2 + O_2 \rightarrow 2H_2O + \textit{energy}$$





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Current status and cost of H2 technology

Application	Power or capacity	Efficiency *	Initial investment cost	Life time	Maturity
Alkaline FC	Up to 250 kW	~50% (HHV)	USD 200-700/kW	5 000-8 000 hours	Early market
PEMFC stationary	0.5-400 kW	32%-49% (HHV)	USD 3 000-4 000/kW	~60 000 hours	Early market
PEMFC mobile	80-100 kW	Up to 60% (HHV)	USD ~500/kW	<5 000 hours	Early market
SOFC	Up to 200 kW	50%-70% (HHV)	USD 3 000-4 000/kW	Up to 90 000 hours	Demon-stration
PAFC	Up to 11 MW	30%-40% (HHV)	USD 4 000-5 000/kW	30 000-60 000 hours	Mature
MCFC	KW to several MW	More than 60% (HHV)	USD 4 000-6 000/kW	20 000-30 000 hours	Early market
Compressor, 18 MPa	-	88%-95%	USD ~70 /kWH$_2$	20 years	Mature
Compressor, 70 MPa	-	80%-91%	USD 200-400/kWH$_2$	20 years	Early market
Liquefier	15-80 MW	~70%	USD 900-2 000/kW	30 years	Mature
FCEV on-board storage tank, 70 MPa	5 to 6 kg H$_2$	Almost 100% (without compression)	USD 33-17/kWh (10 000 and 500 000 units produced per year)	15 years	Early market
Pressurised tank	0.1-10 MWh	Almost 100% (without compression)	USD 6 000-10 000/MWh	20 years	Mature
Liquid storage	0.1-100 GWh	Boil-off stream: 0.3% loss per day	USD 800-10 000/MWh	20 years	Mature
Pipeline	-	95%, incl. compression	Rural: USD 300 000-1.2 million/km Urban: USD 700 000-1.5 million /km (dependent on diameter)	40 years	Mature

Technology Roadmap – Hydrogen and Fuel cells; IEA, 2015

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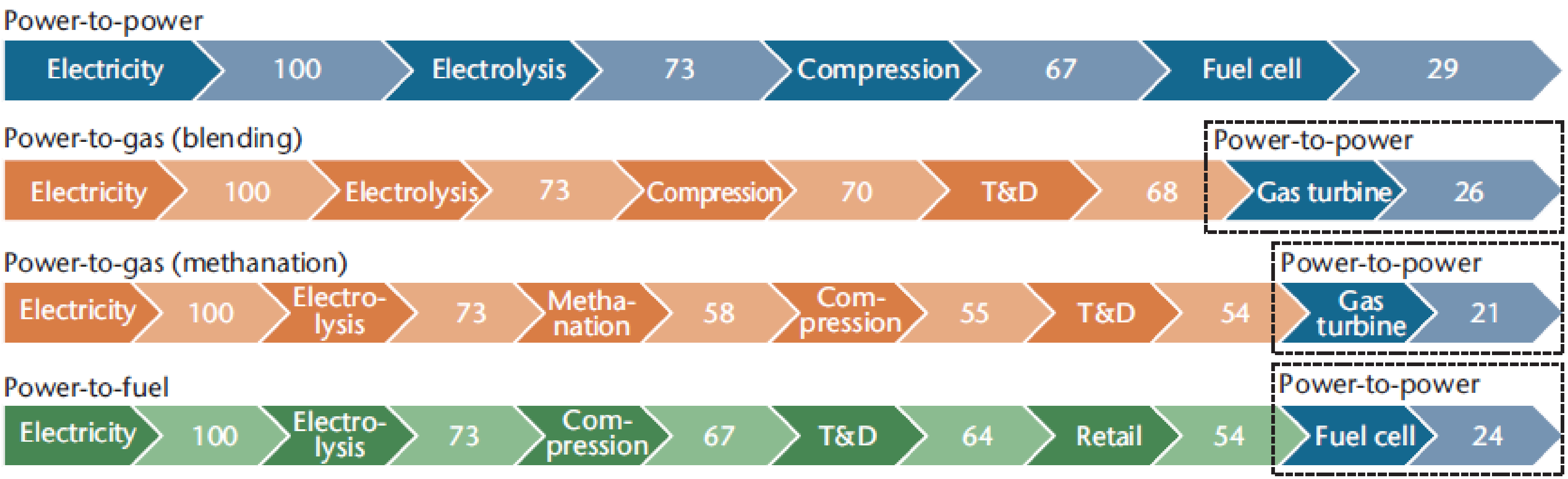
Performance of systems for lage scale H2 storage

Application	Power or energy capacity	Energy efficiency*	Investment cost**	Lifetime	Maturity
Power-to-power (including underground storage)	GWh to TWh	29% (HHV, with alkaline EL) - 33% (HHV, with PEM EL)	1 900 (with alkaline EL) - 6 300 USD/kW (with PEM EL) plus ~8 USD/kWh for storage	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration
Underground storage	GWh to TWh	90-95%, incl. com-pression	~8 USD/kWh	30 years	Demonstration
Power-to-gas (hydrogen-enriched natural gas, HENG)	GWh to TWh	~73% excl. gas turbine (HHV) ~26% incl. gas turbine (PtP)	1 500 (with alkaline EL) - 3 000 USD/kW (with PEM EL), excl. gas turbine 2 400 (with alkaline EL) - 4 000 USD/kW (with PEM EL), incl. gas turbine (PtP)	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration
Power-to-gas (methanation)	GWh to TWh	~58% excl. gas turbine (HHV) ~21% incl. gas turbine (PtP)	2 600 (with alkaline EL) - 4 100 USD/kW (with PEM EL), excl. gas turbine 3 500 (with alkaline EL) - 5 000 USD/kW (with PEM EL), incl. gas turbine (PtP)	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration

Technology Roadmap – Hydrogen and Fuel cells; IEA, 2015

Conversion efficiency of H2 bases RE pathways



Note: The numbers denote useful energy; except for gas turbines, efficiencies are based on HHV; the conversion efficiency of gas turbines is based on LHV.

Technology Roadmap – Hydrogen and Fuel cells; IEA, 2015

Large scale storage: H_2 system vs Tesla Powerpack

	H_2 system 1: *electrolyzer, storage, fuel cell system*	H_2 system 2: *electrolyzer, storage, fuel cell system*	Tesla Powerpack *(only short time storage)*
conditions	free electricity, 6 hr/day	electricity 0.06 €/kWh 12 hr/day	free electricity when needed
size (MW)	20	20	20
capacity (hr/day)	4	4	4
investment (MEuro)*	77	59	32
maintenance, replacement and operation (MEuro/yr)*	1,9	1,3	2.7
COE 20yr (Euro/kWh)	**0.20**	**0.36**	**0.20**

* Based on current reported commercial prices

Simulation residential storage system

Part of RVO project ‘energy system integration studies’

Energy-autarchic home with RE en H2-FC storage in NL

Energy from wind (10kW turbines) and PV.

Climate from KNMI (2013).

Electrolyzer, compressor, PEM fuel cell and storage tank.

FCEV or EV (100km/day) or none.

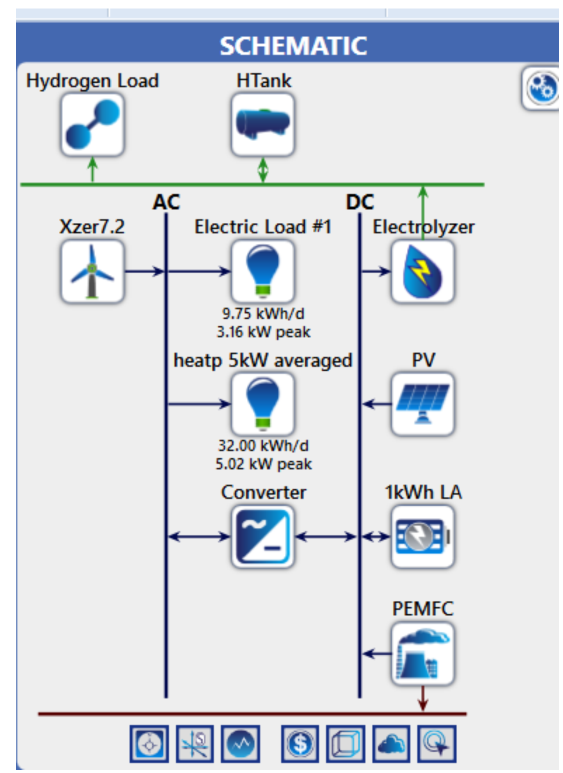
Electric load as for 5p home plus induction cooking.

With/without electrical heating (heatpump).

Warm water from FC (plus solar thermal installation not included in model).

With/without batteries.

Current costs.



Cost RE home with H2 storage

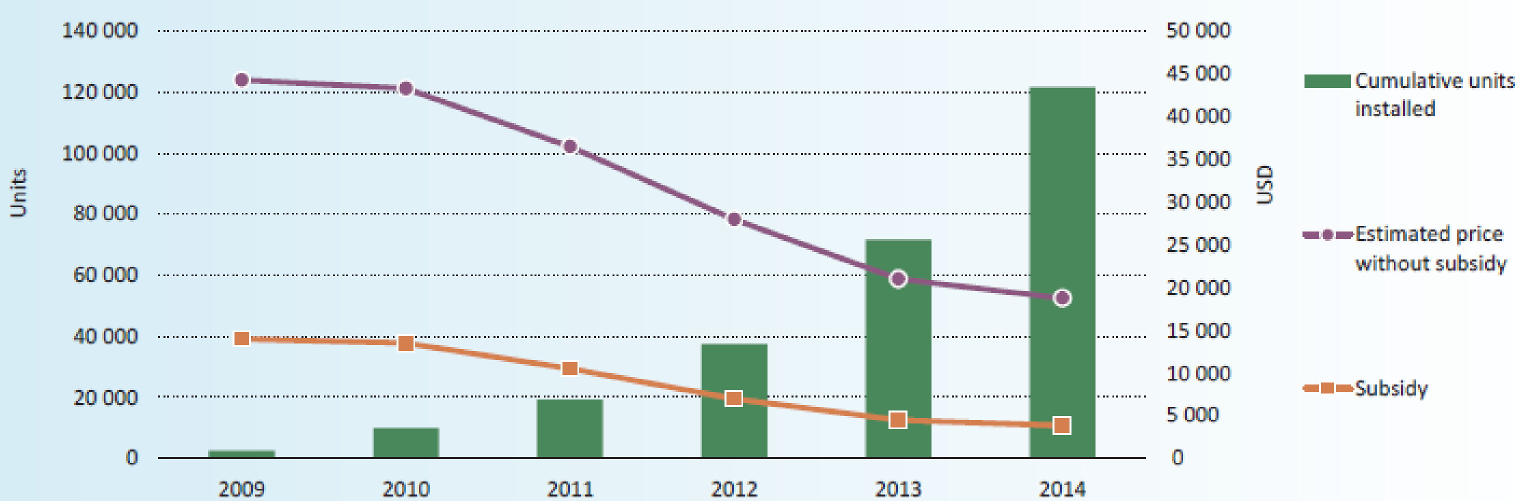
- el. heating requires large hydrogen system for seasonal storage
- hydrogen car requires larger electrolyzer
- larger system equals lower price
- cost including RE

-> cost of small scale H_2 storage today > 1 €/kWh >> electricity price

Case	FCEV	EV	Heatpump	System/component size	COE (% of lowest)
1	0	0	0	**1**	**166**
2	0	X	0	**2**	**107**
3	X	0	0	**3**	**312**
4	0	0	X	**4**	**105**
5	0	X	X	**5**	**100**
6	X	0	X	**6**	**146**

Cost example: Enefarm Japan

- **120.000 systems for residential microCHP installed**
  - heating and electricity
  - mainly from methane not H_2
- **large cost reduction due to increased production**

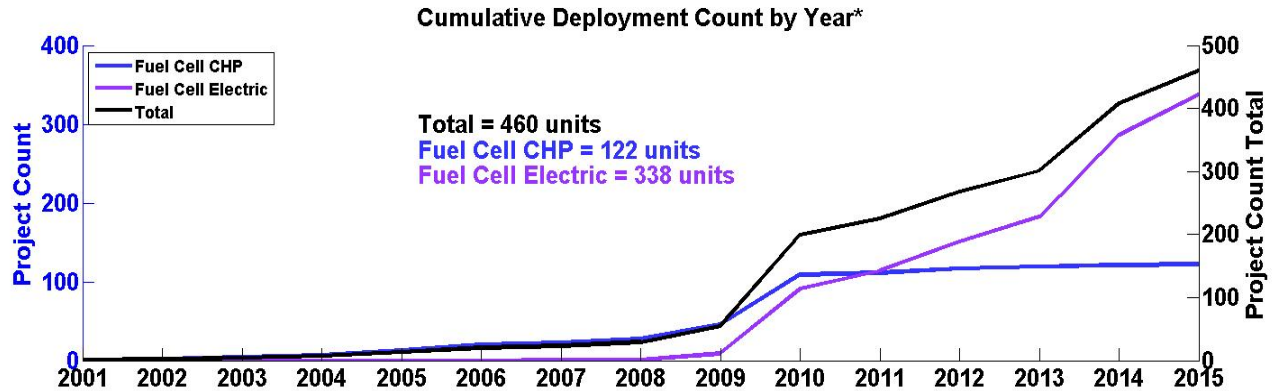


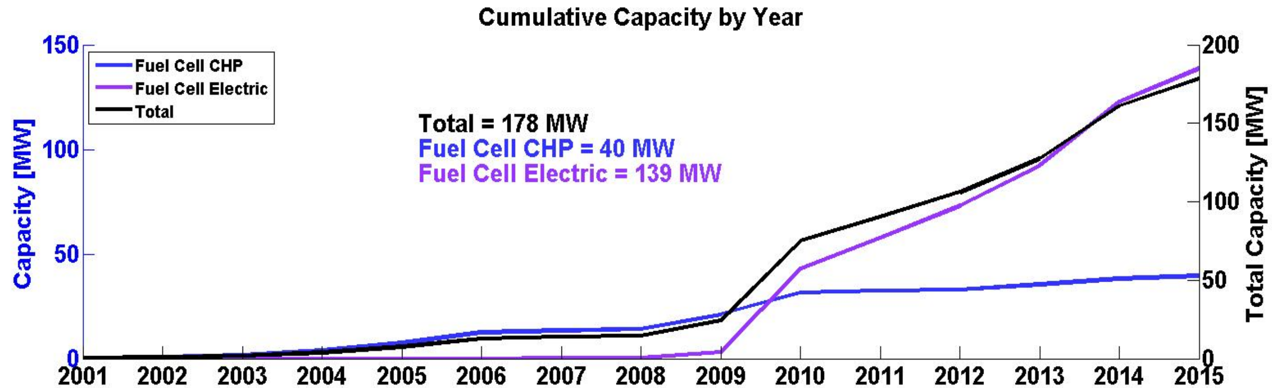
Sources: Hydrogen and Fuel Cell Strategy Council (2014), *Strategic Roadmap for Hydrogen Fuel Cells*; IEA AFC IA (2014), IEA AFC IA Annex Meeting 25.

Technology Roadmap – Hydrogen and Fuel cells; IEA, 2015

Increasing installed capacity

- stationary power plants US





NREL cdp_stat_01
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*Data from the CA SGIP.

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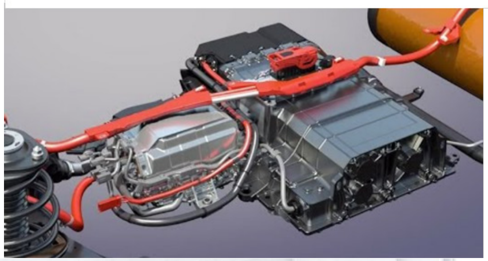
Current FC's in transport

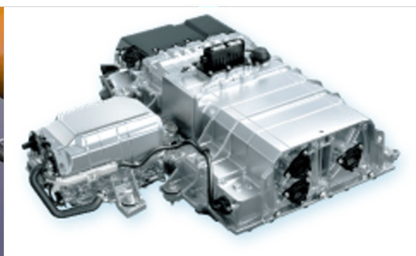
30-9-2016: USA	30-9-2016: rest of world
1,015 active vehicles	**1212 active vehicles**
• 983 passenger vehicles - including:	• 896 passenger vehicles - including:
• 714 Toyota Mirai	• 406 Toyota Mirai
• 126 Hyundai ix35 Tucson FCEV	• 318 Hyundai ix35 Tucson FCEV
• 47 Mercedes-Benz B-Class F-Cell	• 100 Mercedes-Benz B-Class F-Cell
• 62 Toyota Highlander FCHV-adv	• 5 Toyota Highlander FCHV-adv
• 17 Honda FCX Clarity	• 3 Honda FCX Clarity
• 27 buses	• 87 buses and shuttle buses
• 4 shuttle buses	• 101 scooters
• 1 dump truck	• 36 light commercial vehicles
+ 76 planned vehicles	**+ 856 planned**

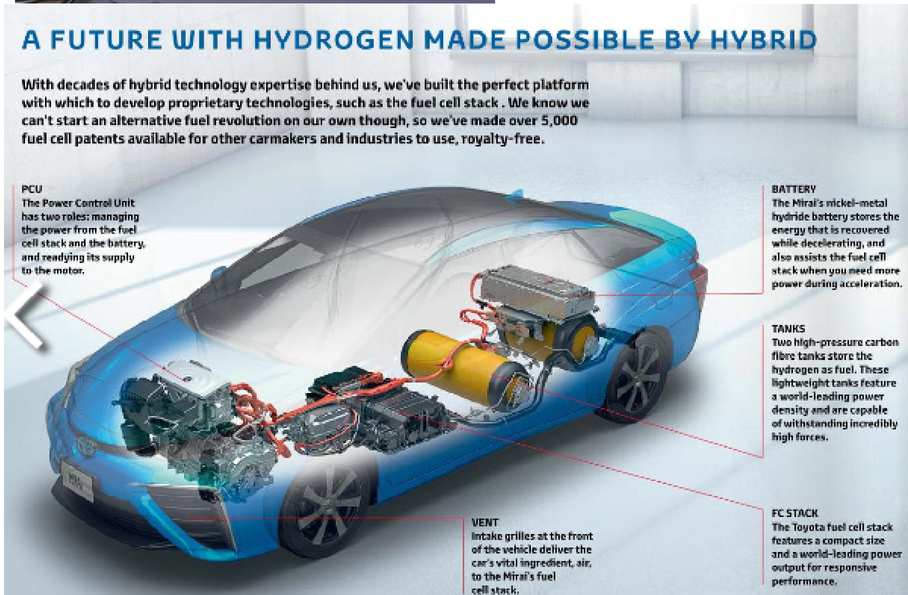
DoE Hydrogen Analysis resource center; http://hydrogen.pnl.gov/

Toyota Mirai

500 km range
3 min refuel
5 kg H2 @ 700 bar
+ battery = hybrid!







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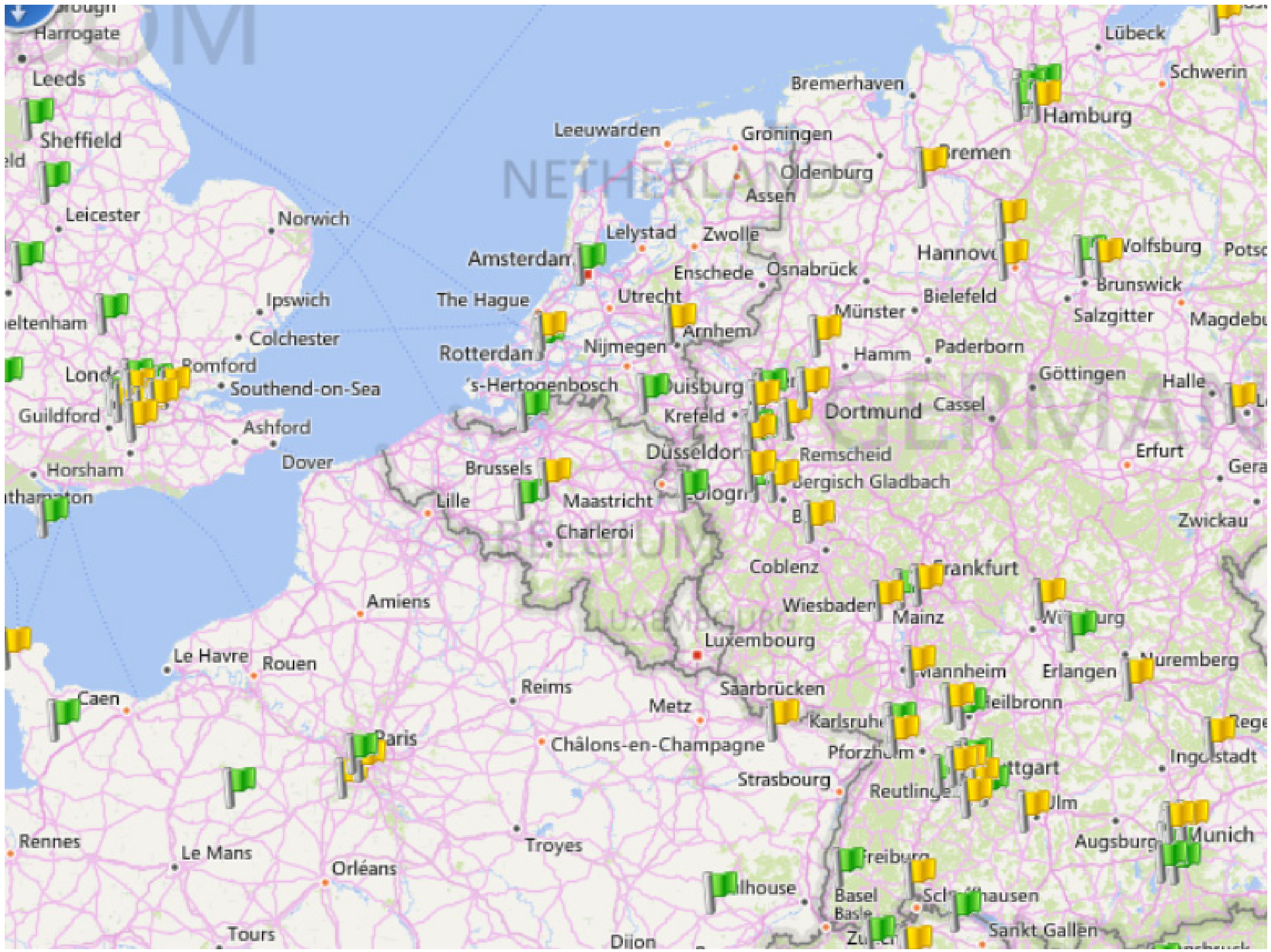
Fuel cell vehicles are leading innovation in two key areas.

Depending on how we embrace fuel cell vehicles and hydrogen as an energy source,
the potential results could change the world and bring about innovations that far exceed even those of the Prius.

Toyota sees great potential in hydrogen and fuel cell vehicles.

H2 fueling stations - planned



Hydrogen production capacities

- **Most hydrogen now produced from fossil fuels**
  - steam reforming or partial oxidation of methane
  - coal gasification
- **For oil refining (50%), ammonia and methanol production**
- **H2 production capacity (Netherlands):**
  - 659 million kg/yr
  - average 20,000 km/yr/car and 8,3 million vehicles
  - enough fuel for 3,3 million vehicles
- **If all current H2 available then 40% of required km's!**
- **Means knowledge on handling and safety no problem**

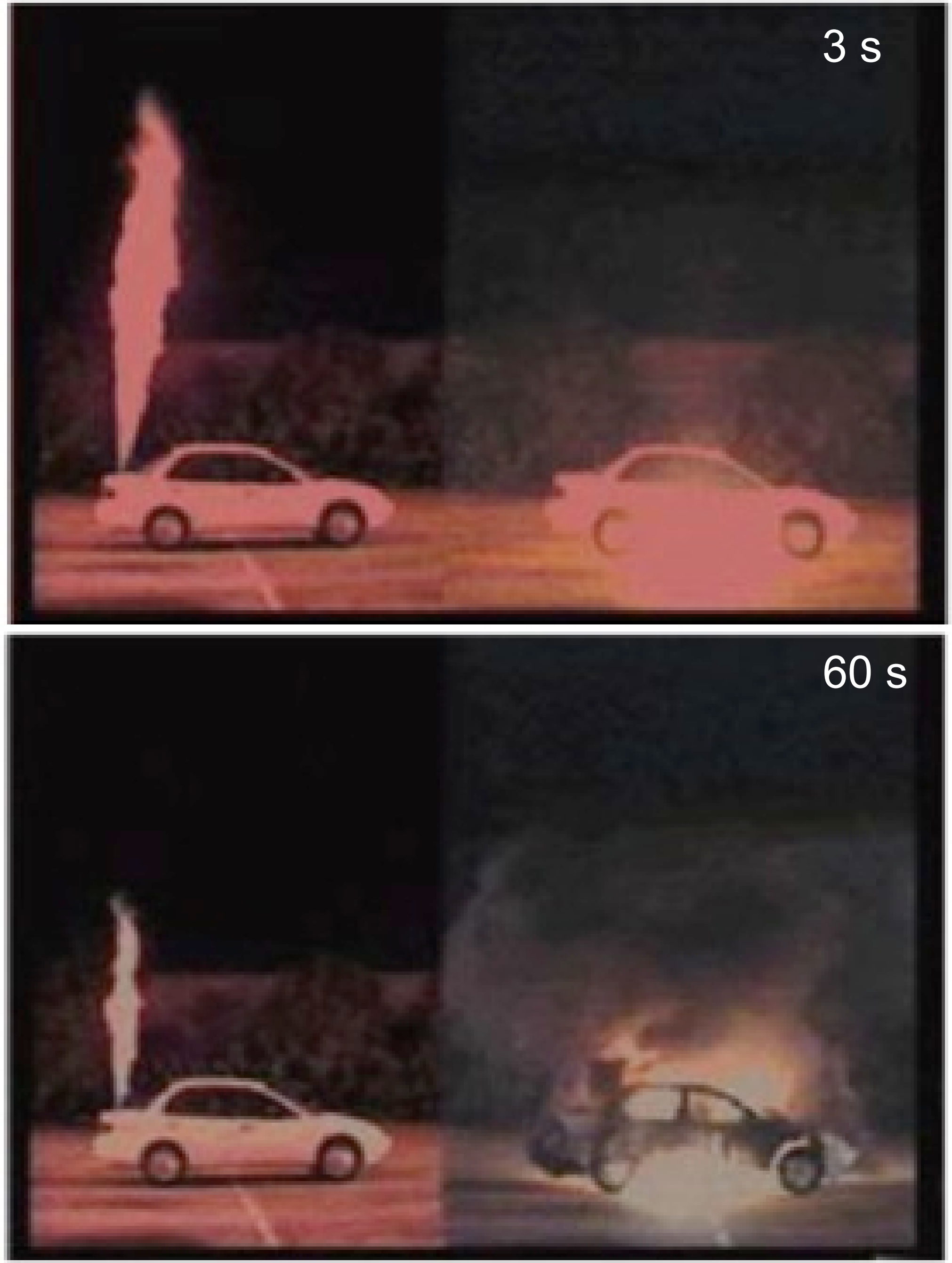
DoE Hydrogen Analysis resource center; http://hydrogen.pnl.gov/

Safety

- **it is a FUEL!**
  - requires proper handling
  - like any other fuel
- **odorless, colourless**
  - requires sensors/detection
- **ignition energy varies**
  - high <10%
  - very low at 29% stoich mix
- **lighter than air, rapid upwards diffusion**
  - ventilated space
- **combustion only at concentrations >> than gasoline**
- **flames have low radiant heat**

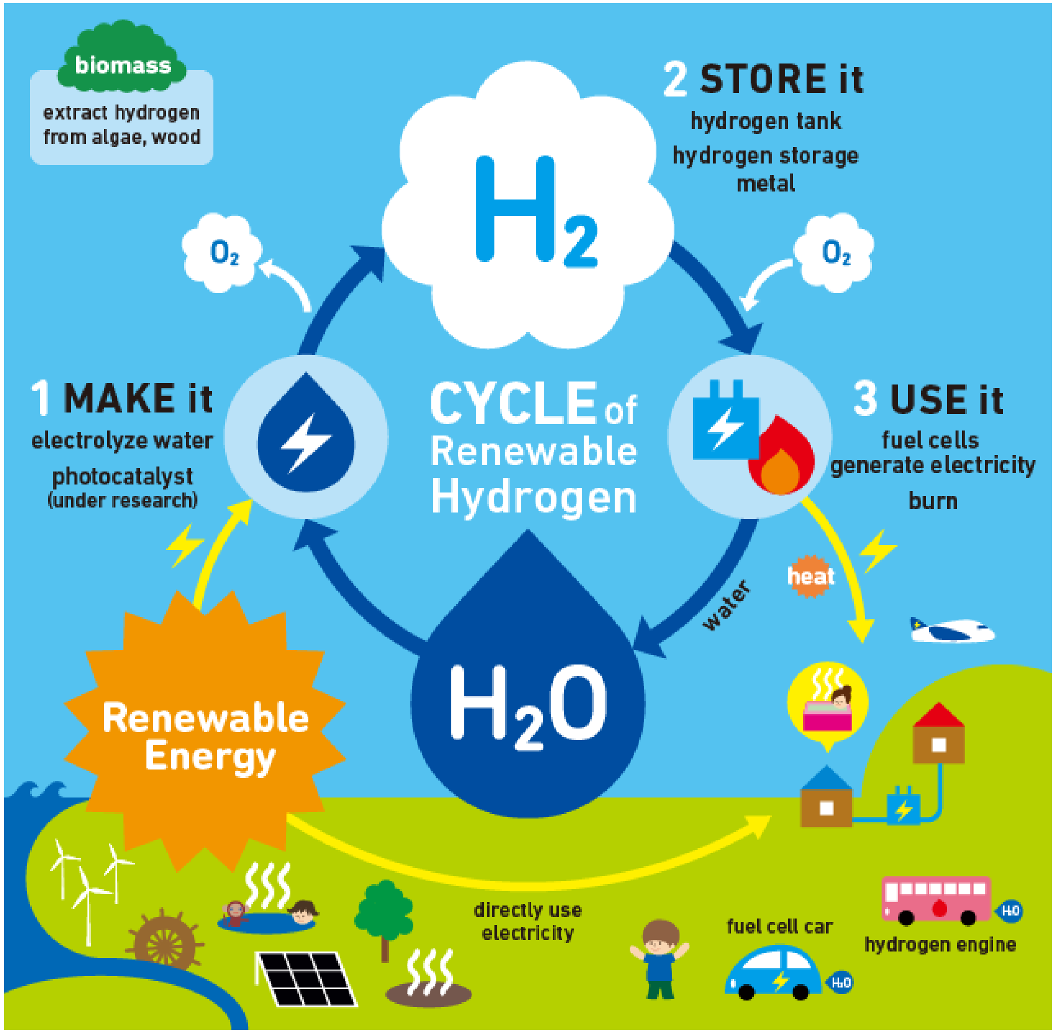
	Hydrogen	Gasoline Vapor	Natural Gas
Flammability Limits (in air)	4-74%	1.4-7.6%	5.3-15%
Explosion Limits (in air)	18.3-59.0%	1.1-3.3%	5.7-14%
Ignition Energy (mJ)	0.02	0.20	0.29
Flame Temp. in air (°C)	2045	2197	1875
Stoichiometric Mixture (most easily ignited in air)	29%	2%	9%

http://www.arhab.org/pdfs/h2_safety_fsheet.pdf



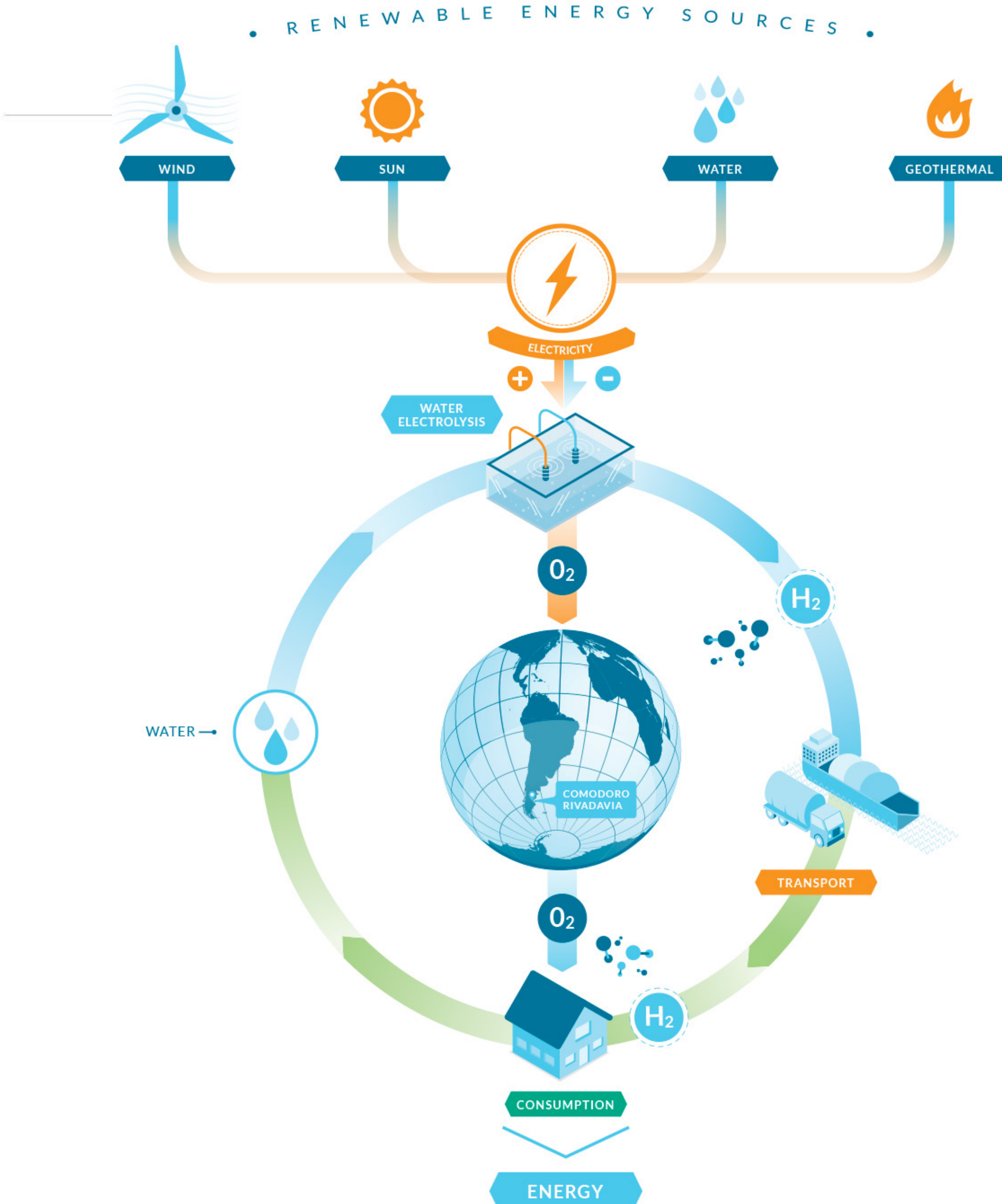
Fuel leak simulation, M.R. Swain, Univ. Miami (2003)

Part of circular economy?



http://en.rh2.org/rh2_info/chapter2/

van Arnhem en Nijmegen



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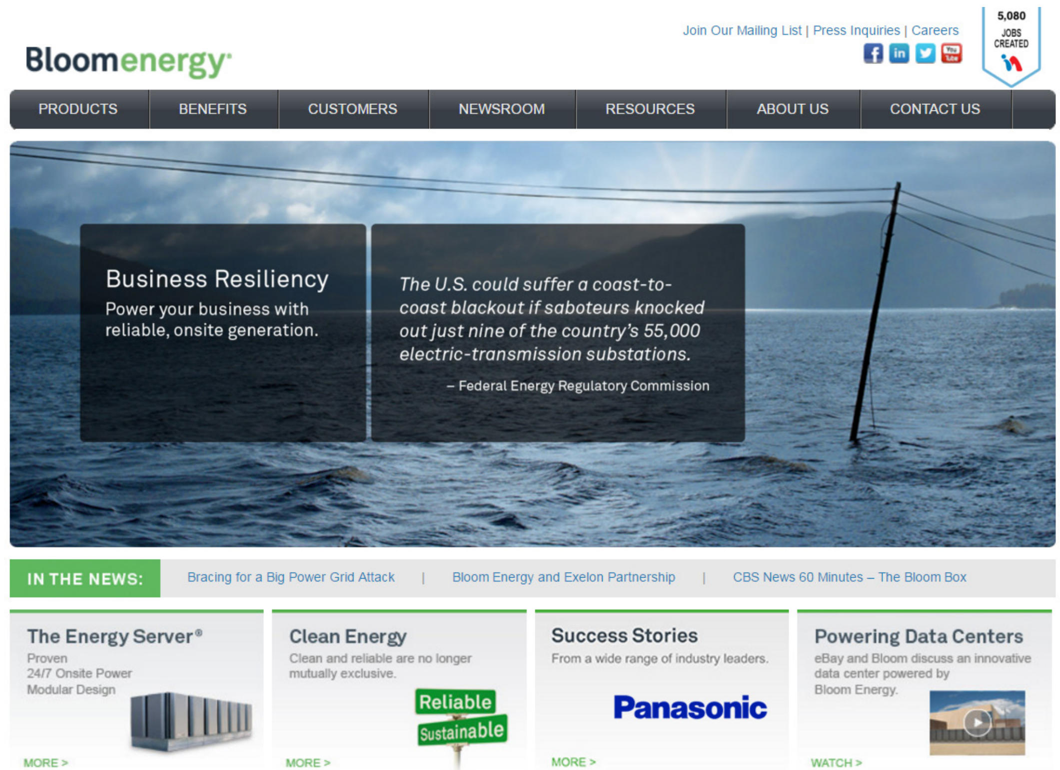
http://www.hychico.com/as
sets/img/renewable-
energy-sources.png

voorbeeld diensten ipv producten FC's

- **Bloom Energy**
- **200kW HT fuel cell units (SOFC)**



klanten: http://www.bloomenergy.com/customer-fuel-cell/

circular economy – services?

- sell service, not product!
- Bloom energy sells kWh's not fuel cells
- data centers etc.

Bloom Energy Purchase and Financing Options

Bloom Energy offers customers multiple purchase and financing options to best meet their business objectives. Bloom Energy has partnered with banks, utilities and other institutional investors to offer tailored financing options to customers.

Capital Purchase

Customers who want to maximize their return on investment can purchase and install Bloom Energy Servers at their facilities and capture all of the economic benefits of producing their own power for significantly less than the price of electricity purchased from the grid.

Bloom Electrons®

The Bloom Electrons service allows customers to lock in electricity costs for 15 years, delivering predictable costs and significant savings without the upfront capital purchase and ownership of the equipment. Bloom Energy manages and maintains the energy systems; customers only pay for the electricity that is produced.

Click to Download the Bloom Electrons One-Pager

Operating Lease

The Bloom Energy operating lease, available through Bank of America Merrill Lynch and other similar banks, allows companies to conserve Capex and reduce Opex with a fixed energy cost and predictable payment for 10 years.

Click to Download the Non-NDA BALC Lease One-Pager

Service Agreements

Regardless of which pricing option customers choose, Bloom Energy is committed to providing customers with operating and maintenance support to ensure the performance of our Energy Servers. Bloom Energy's Remote Monitoring and Control Center constantly monitors each energy system to optimize performance and dispatch certified service technicians for required maintenance.

Contact us today at sales@bloomenergy.com to learn more about the service agreement options available.

Concluding

- hydrogen will be part of future energy system
- adds to energy balance
- fits within circular economy
- most suitable for seasonal energy storage and transport
- commercialization has taken off
- further cost reduction required, expected
- infrastructure required

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