Fuel Cells with Hydrogen Technology

Introduction

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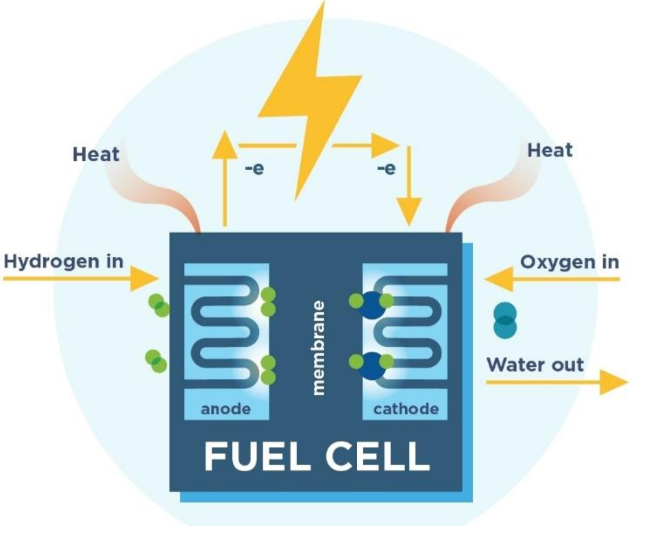
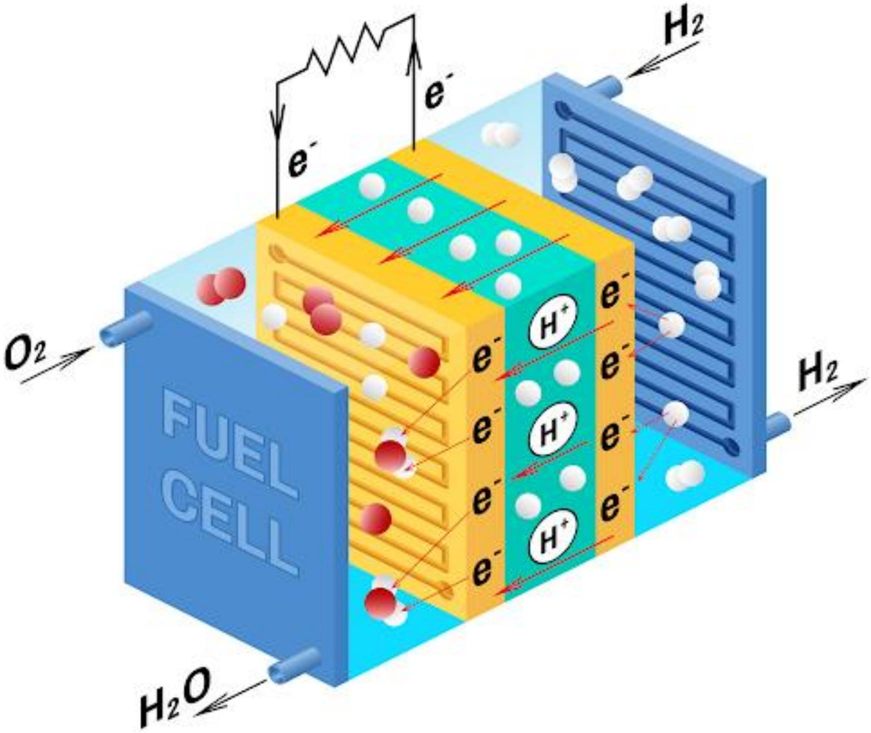
Content

- Hydrogen boom
- Fuel cell steps in Finland (and beyond)
- Fuel cells – structure, operation principle
- Application areas
- Conclusions



Motivation



Why just now?

I. HYDROGEN BOOM

Asian ’technology giants’ are developing fuel cells in energy production, trafic and domestic use

SOUTH-KOREA

Until 2040

- Domestic production of 6.2 milj. fuel cell vehicles
- 40 000 buses, 80 000 taxis, 30 000 trucks
- 1 200 refuelling stations
- 15 GW fuel cells in energy production

JAPAN

Until 2030

- 5,3 miljon fuel cells in domestic use
- 800 000 vehicles
- 900 hydrogen refulling stations
- 1200 fuel cell buses
- R&D fuel cells in marine use

AUSTRALIA

- Goal to be the leading country in in green hydrogen export in 2030
- Partner agreements for example with Japan, China and Singapore
- Regioanal hydrogen strategies and developing programs

Source: AFRY

Fuel cells & hydrogen – the boom has started?

Hydrogen strategy 2020
The essential role of hydrogen in energy use and export

Generic hydrogen vision 2002.
Industrial orientated roadmap 2019 based on 100 % domestic hydrogen

5 GW electrolysers in 2025
Goal to be the most cost effective hydrogen producer in the world in 2030

The export of coal neutral hydrogen to Europe and Asia based on natural gas, renewables and nuclear power

Aims to be the leading country in hydrogen production.
Wind, solar and wave power

1 miljon fuel cell vehicles and 1000 refulling stations 2030
Strong focus in trafic develoment
37 regional policies for hydrogen from 2020

Aims to be the biggest hydrogen producer
5 mrd € solar- and wind power project Hellos Green Fuels for Hydrogen production in 2025
To Neomi city

Source : AFRY

In EU hydrogen strategy the primary goal is green hydrogen – produced mainly via wind and solar energy

450 Mrd € investments

2020-2024

- Decarbonisation in industry
- Development the infrastructure in trafic
- The 'low carbon' hydrogen has also a role

2025-2030

- Part of the integrated energy system
- New role in energy and trafic
- Local transmission

2030-2050

- The technology of green hydrogen has attained its maturiry
- 25 % of renewable electricity perhaps allocated to hydrogen production
- Transmisson developes

Source: AFRY

Nordic and Baltic countries

The hydrogen stategy in Norway was bublished in 2020 based on that the hydrogen road map will be developed

Energimyndighet prepared the hydrogen startegy at end of 2021

The Danish hydrogen strategy was ready 2021. The Hydrogen Association published the hydrogen roadmap in 2021

The hydrogen roadmap in Estonia was ready in 2021

Lithuania is preparing its own hydrogen strategy

Source: AFRY

Finland

Finland doesn’t have a detailed hydrogen strategy. Finland has looked up hydrogen ’in the same line’ than other low carbon technolgies in energy productuion

One driver for utilising hydrogen in order to achieve climate goals is seen in areas where the electrification is not possible

What is the need of hydrogen in different application areas in Finalnd

THE NEED OF A CLEAR STRATEGY IS VITAL

Source: AFRY

Kuva 29. Esimerkkejä kotimaisista vetyprojekteista vuonna 2021

PtGtP
Uusiutuvan vedyn tuotanto**
Sijainti: Vaasa
Vaihe: Demonstraatio
Yritykset: EPV Energia, Vaasan Sähkö, Wärtsilä, Vaasan kaupunki

Prizztech
Synteettisen metaanin tuotanto
Sijainti: Meri-Pori
Kapasiteetti: Soveltuvuusselvitys (20MW)

P2X Solutions
Vihreän vedyn tuotanto**
Sijainti: Harjavalta
Vaihe: Suunnitteluvaihe 20MW
Yritykset: P2X Solutions

Green H2UB Green NorthH2 Energy
Vetypolttoaineiden tuotanto
Sijainti: Naantali
Vaihe: Aiesopimus
Yritykset: Green H2UB (Elomaticin kehitysyhtiö),Turun Seudun Energiantuotanto; Green NorthH2 Energy (Elomaticin tytäryhtiö), Flexens

Ren-Gas
Uusituvan metaanin ja vihreän vedyn tuotanto
Sijainti: Lahti
Vaihe: Toteutettavuusanalyysi
Yritykset: Lahti Energia

Wärtsilä
Synteettinen metaani**
Sijainti: Vantaa
Vaihe: Demonstraatio
Yritykset: Vantaan Energia, Wärtsilä

Flexens
Vedyn käyttö ja tuotanto meriteollisuudessa
Sijainti: Ahvenanmaa
Vaihe: Pilotti
Yritykset: Flexens

Both2nia
Vetylaakso
Sijainti: Perämeren rannikko FI-SE
Yritykset: Konsortio

Ren-Gas
Uusituvan metaanin ja vihreän vedyn tuotanto
Sijainti: Mikkeli
Vaihe: Toteutettavuusanalyysi
Yritykset: Etelä-Savon Energia

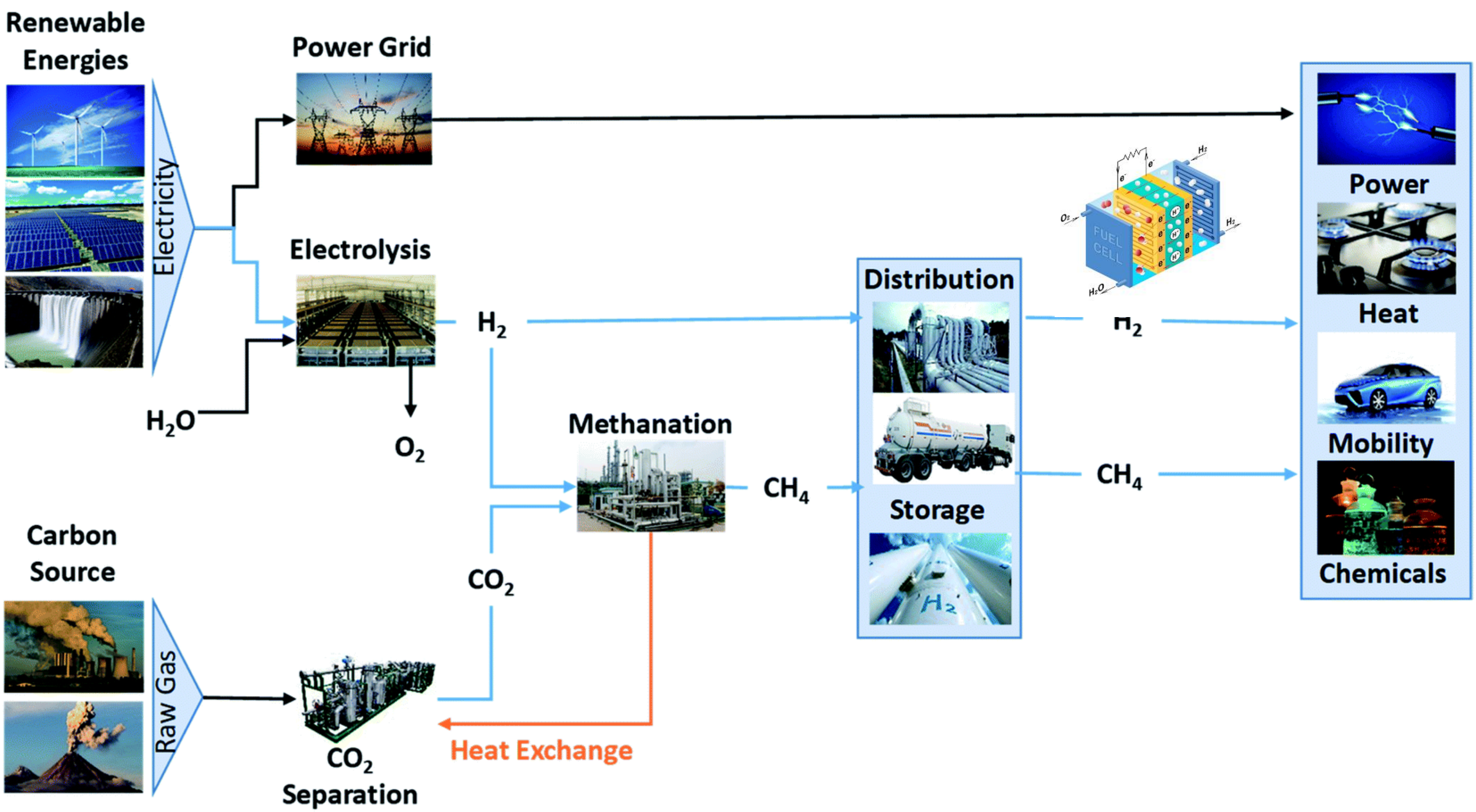
Konsortio
Synteettinen metanoli
Sijainti: Joutseno
Vaihe: Demonstraatio
Yritykset: Finnsementti, Kemira, Neste, St1, Wärtsilä, Finnair, Shell

Soletair
Synteettisten polttoaineiden tuotanto + CO2 talteenotto
Sijainti: Joutseno
Vaihe: Demonstraatio
Yritykset: Soletair, LUT-yliopisto

Q Power
Synteettisen kaasun tuotanto
Sijainti: Kerava
Vaihe: Demonstraatio
Yritykset: Q Power, Keravan Energia

Neste
Puhdas ja vähähiilinen vety*
Sijainti: Porvoo
Vaihe: Demonstraatio

Green Hydrogen



Gulf of Bothnia – the hydrogen society of the Persian Gulf

Green hydrogen has a sgnificant meaning

Hydrogen usage is estimated to cover 25 % of EU's energy need in 2050.

The potential of green hydrogen lies in replacement of today's grey hydrogen, in synthetic fuels, fuel cells and in heavy (eg. steel) industry.

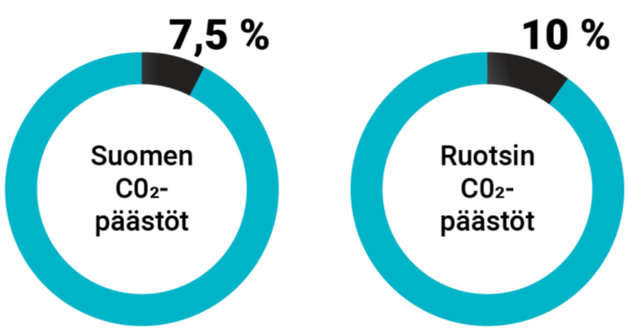
Significant locations in the arc of the Bothnia Gulf are for example Kokkola, Kalajoki, Pyhäjoki, Raahe, Oulu, Kemi, Tornio, Boden, Luleå, Skellefteå ja Umeå.

YLE 19.10.2021

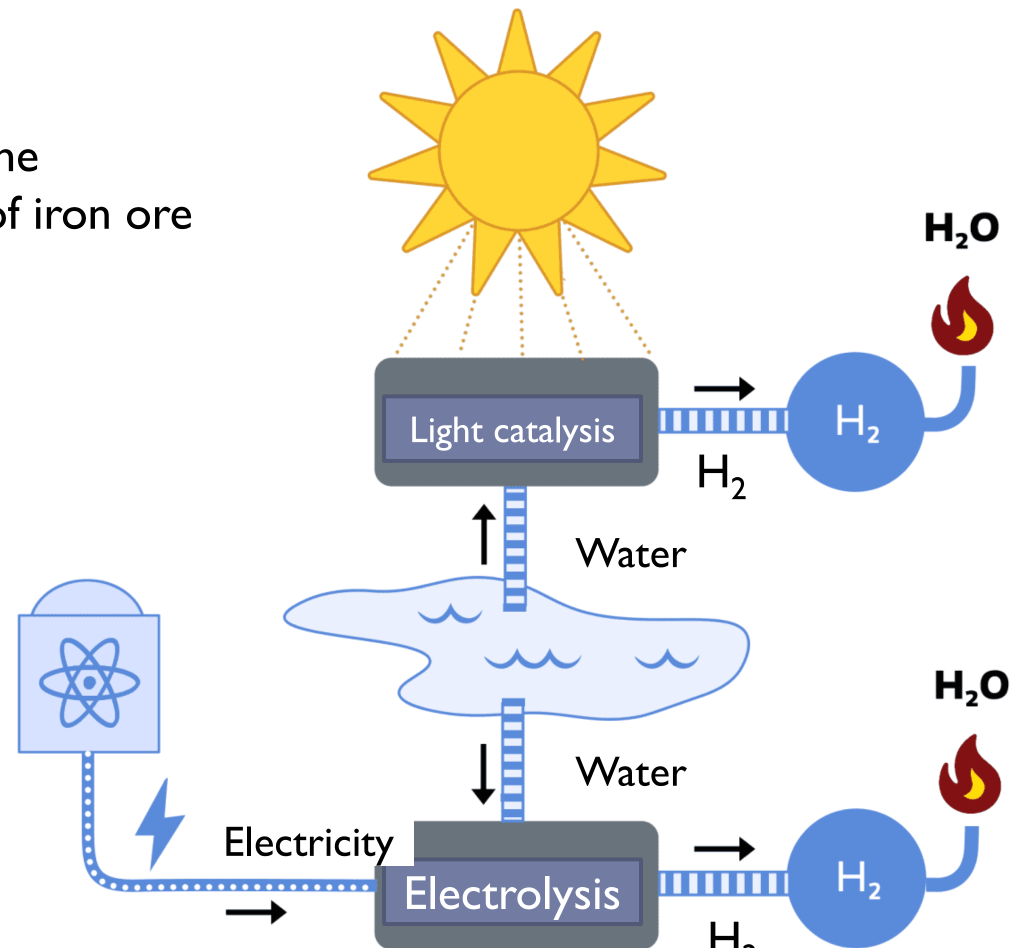
Hydrogen via Solar light

Univeristy of Oulu has investigated the utilisation of hydrogen in reduction of iron ore via light catalysis.

SSAB: Steel production



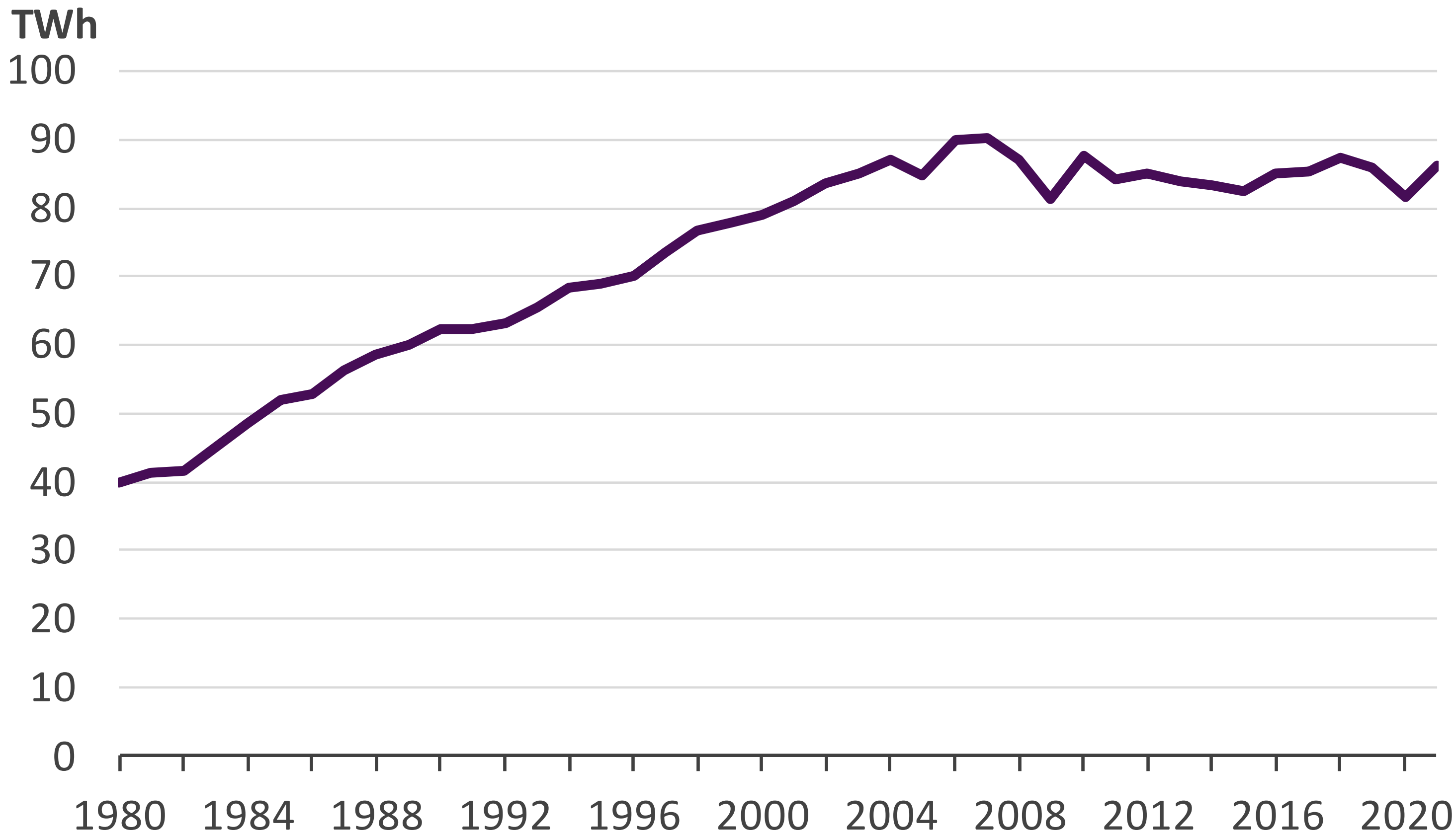
Lähde: SSAB



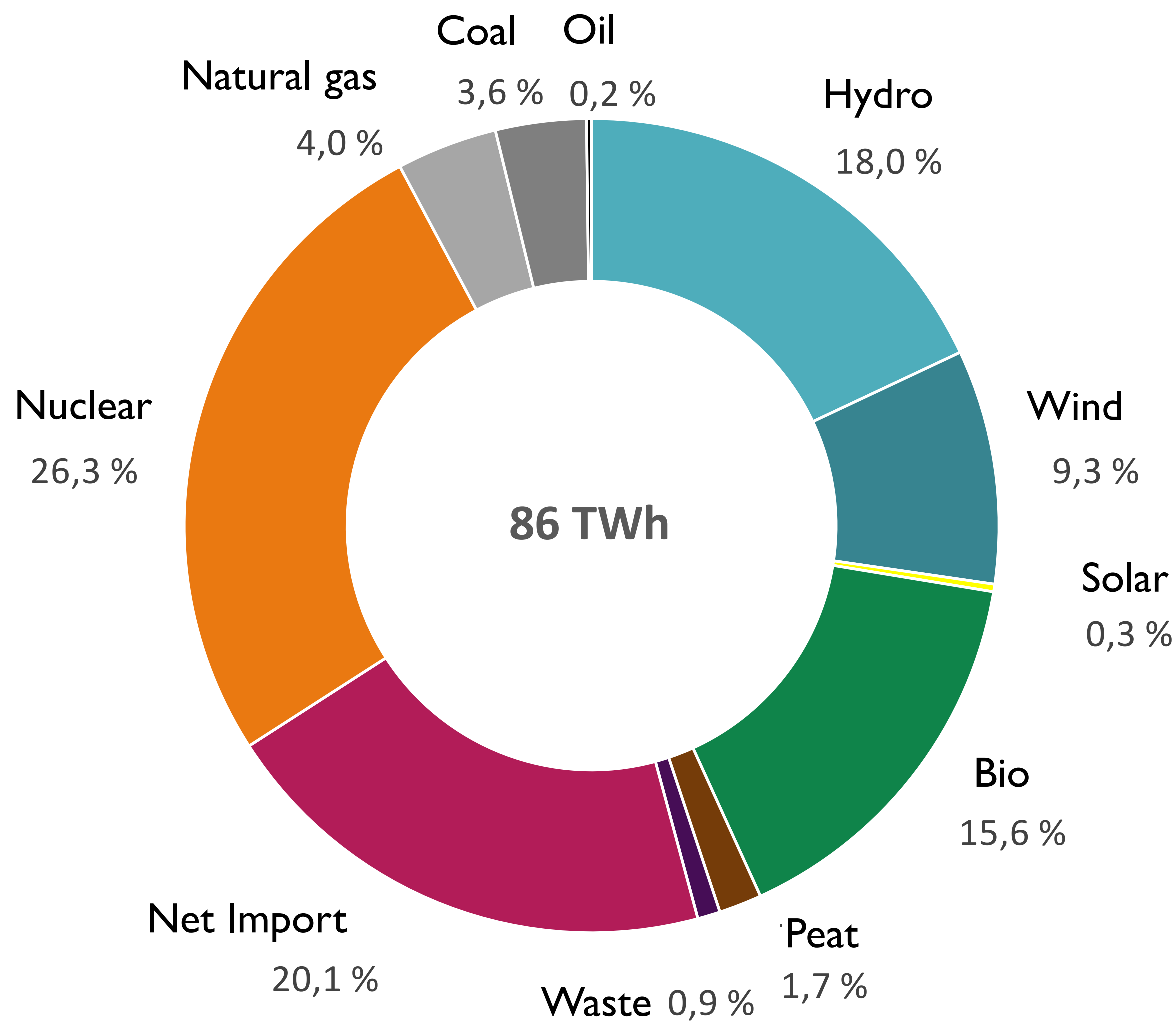
YLE 19.10.2021

Electricty in Finland …

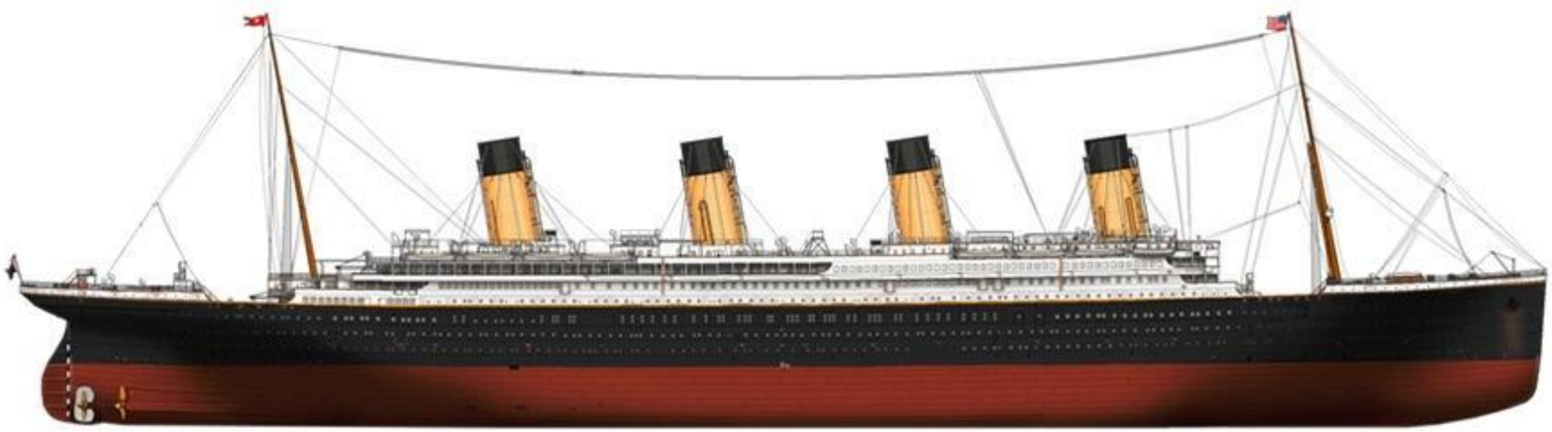
Consumption of electricity in Finland 2021, 86 TWh (+ 6 %)



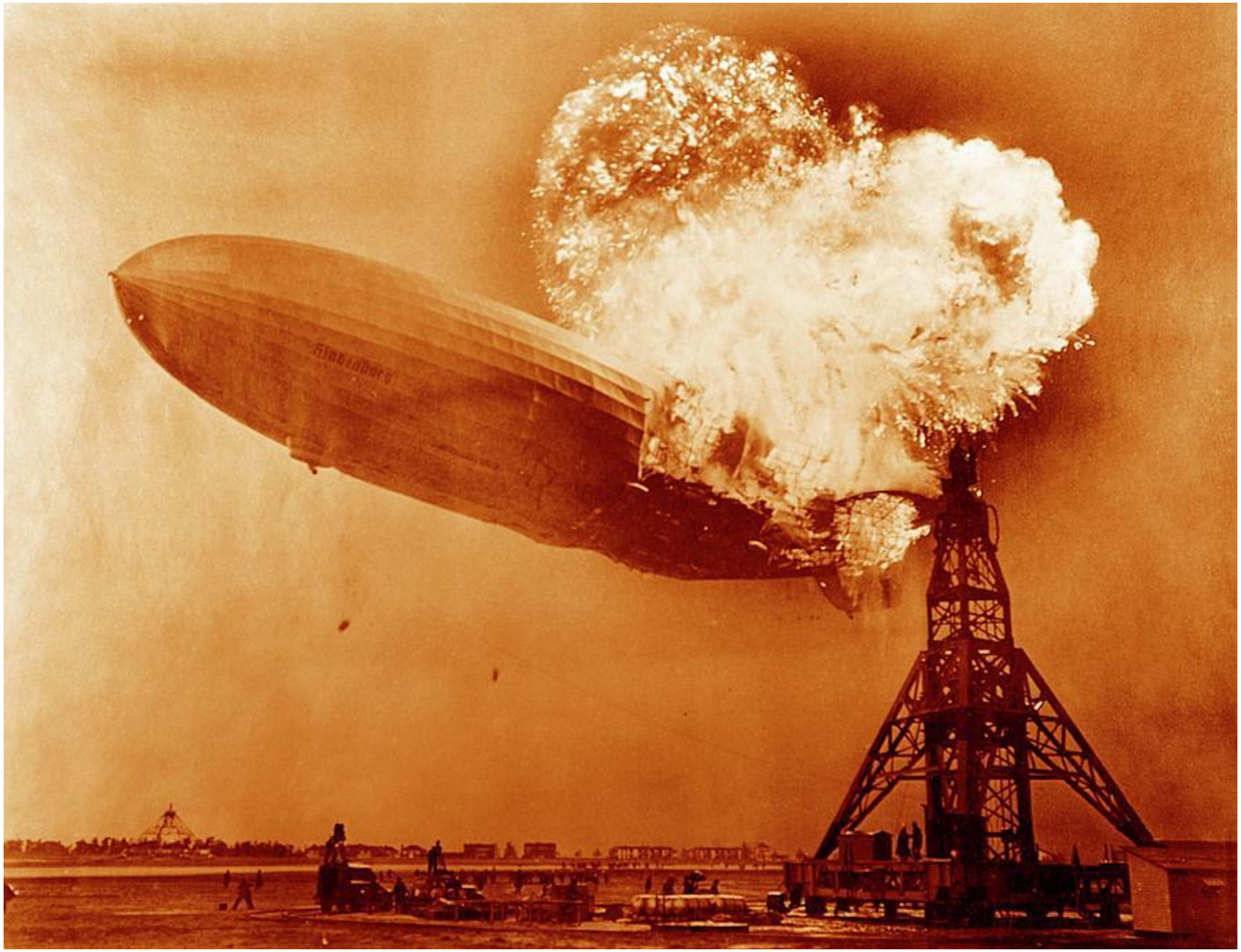
Electricity supply from different energy sources 2021



Prologue



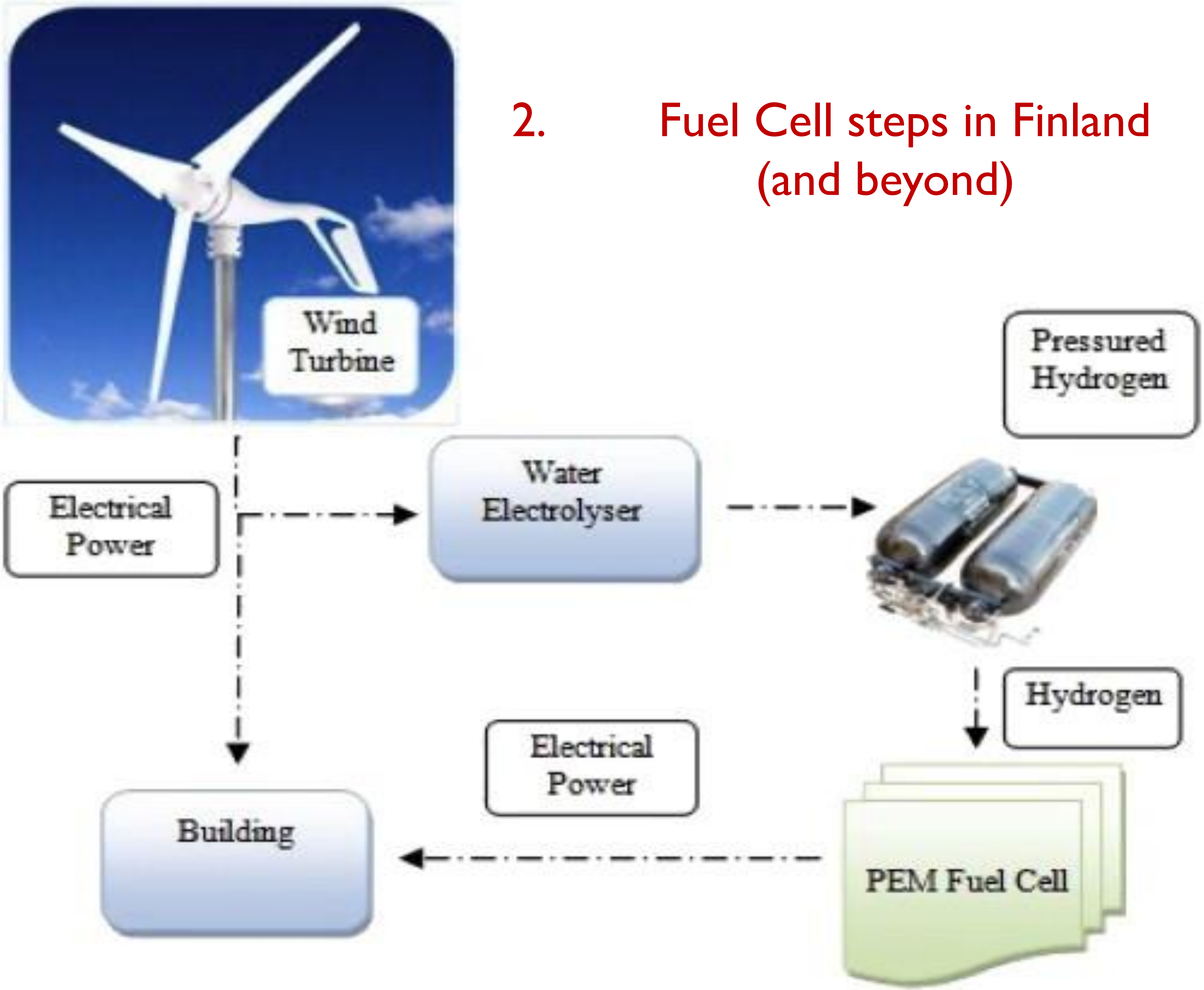
Prologue (Cont.)



Lakehurst, New Jersey

6.5.1937

2. Fuel Cell steps in Finland (and beyond)



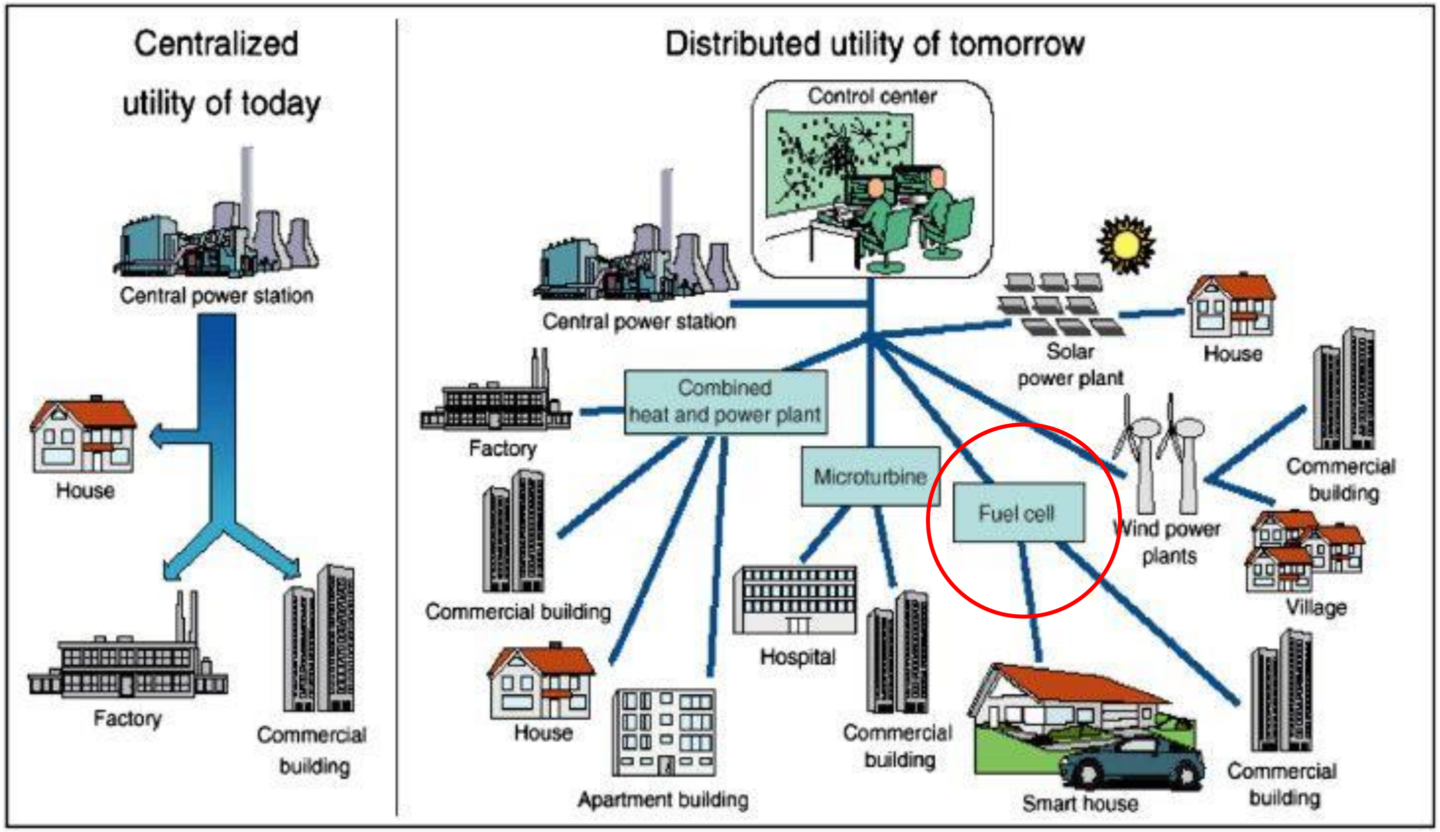
Tekes (Business Finland) – programs 1

DENSY program (Distributed Energy Systems, 2003 – 2007) promoted the knowhow of distributed energy technologies in Finland. During the program awakening of the climate change occured extensivly. Fuel cell technology was a part of the program.

Total budget 47 M€, Tekes 31 M€.

DENSY

Distributed Energy Systems - characteristics

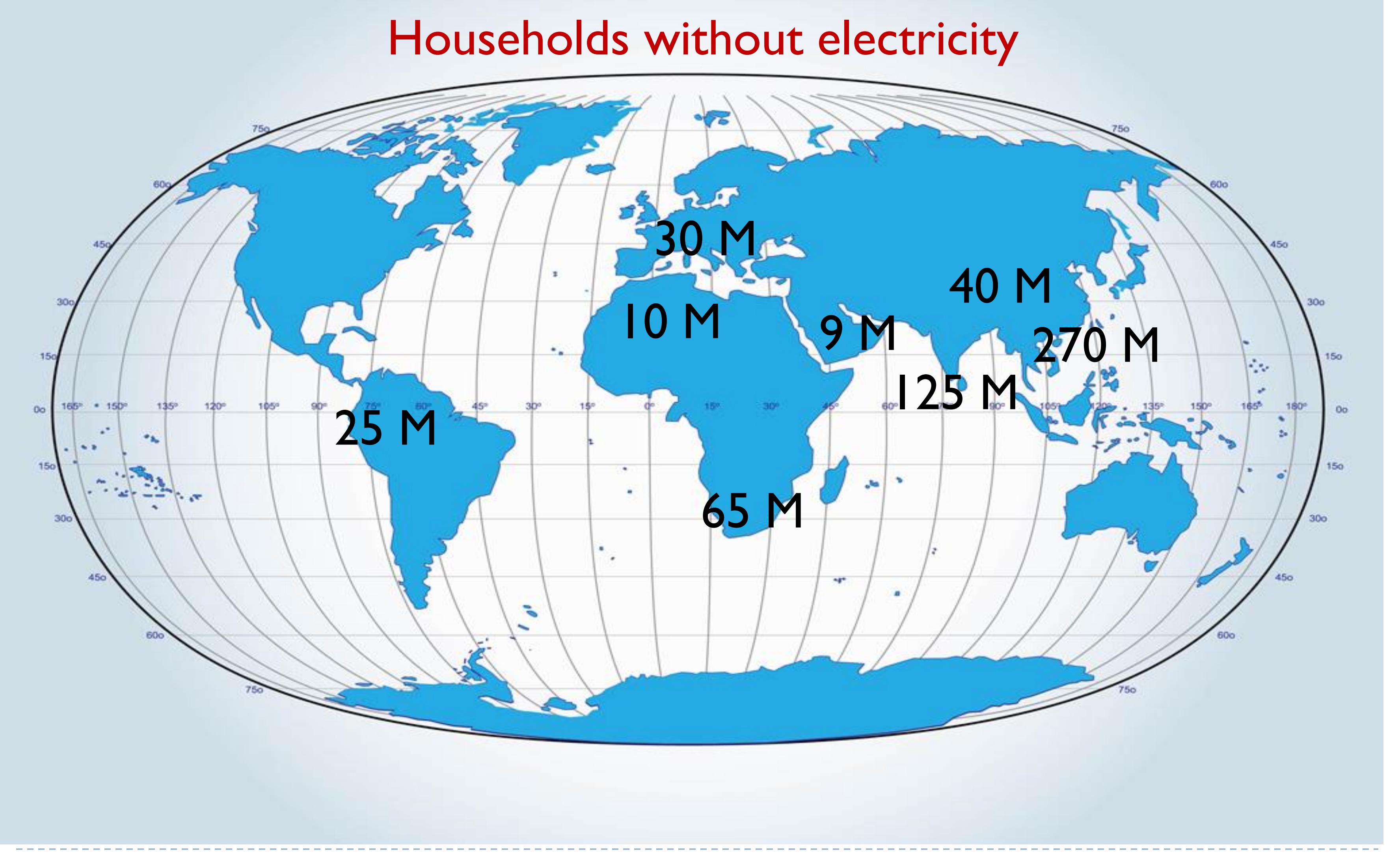


Production near consumption

Not connected to a high voltage transmission line

Moderate unit size, < 10 MW (< 50 MW)

Global markets – high potential



Tekes (Business Finland) programs 2

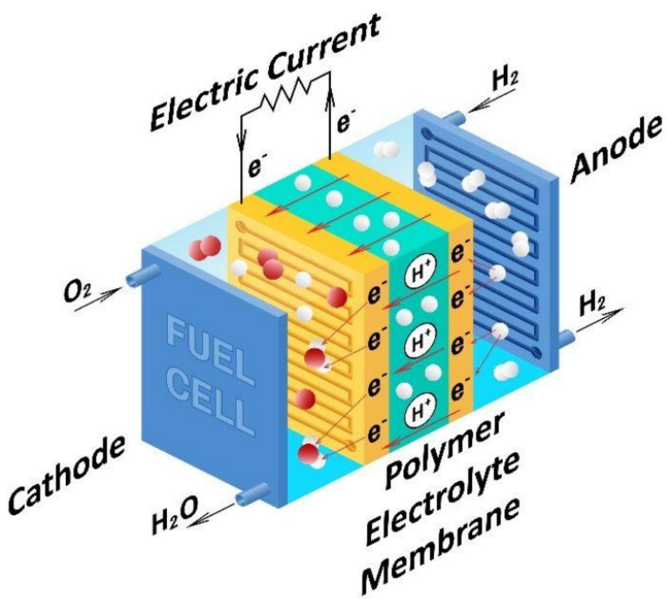
Climbus (2004-2009) Business prospects via the restraint of the climate change. The program created an intensive climate cluster in Finland. Totally 167 companies took part to the program.

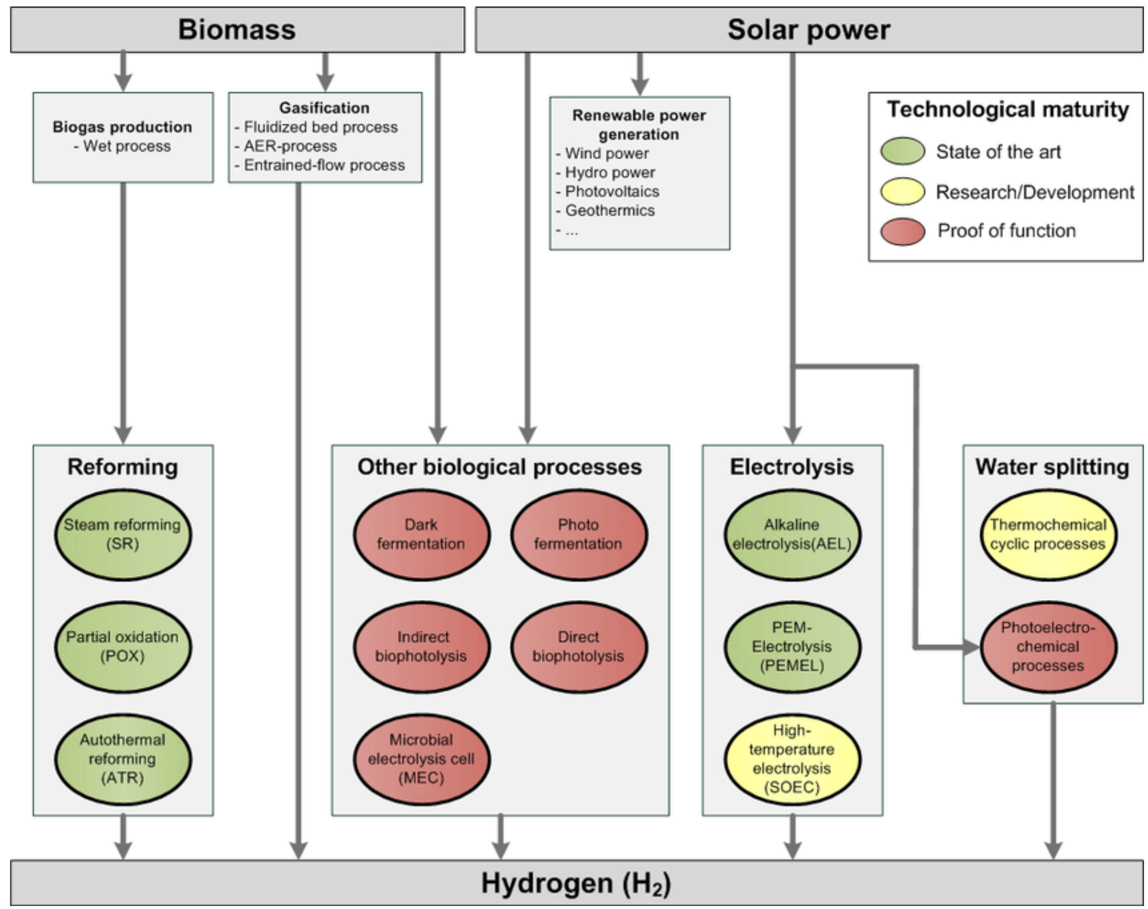
Total budget 90,5 M€,

Tekes 43,6 M€

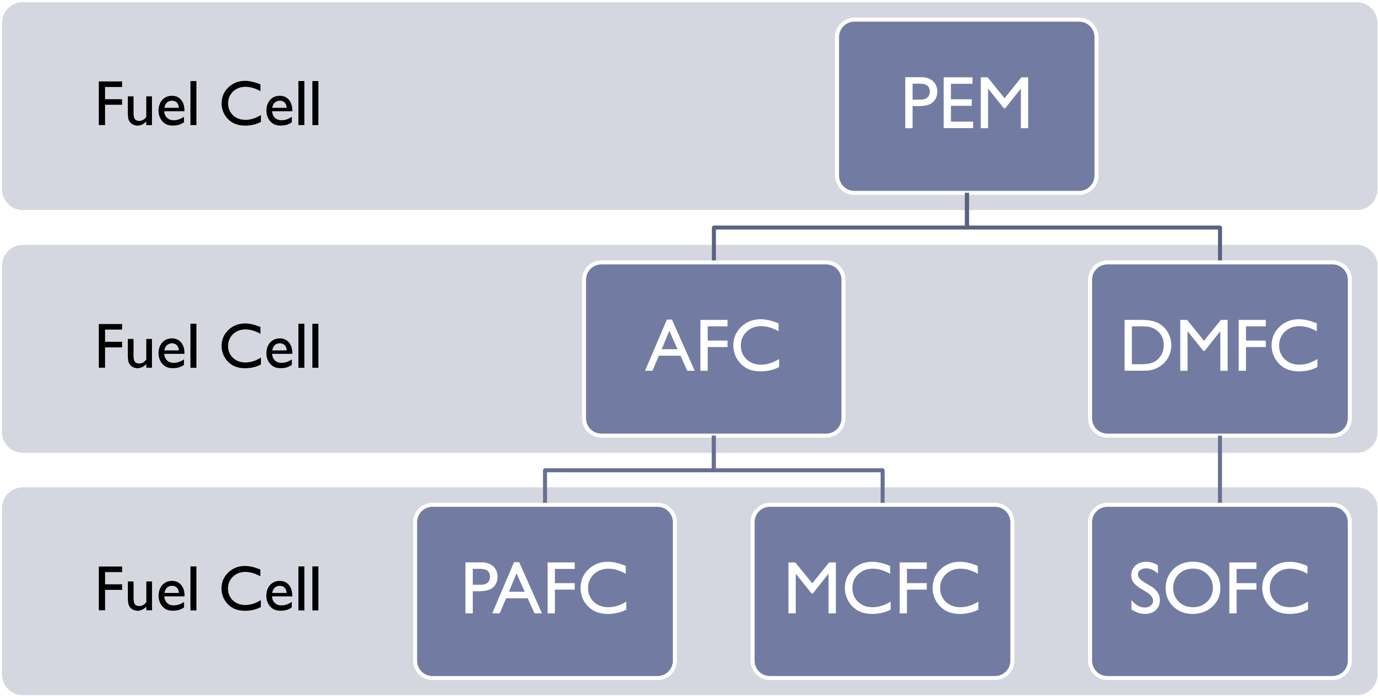
Tekes (Business Finland) programs 3

Fuel Cells 2007 – 2013, 90 M€

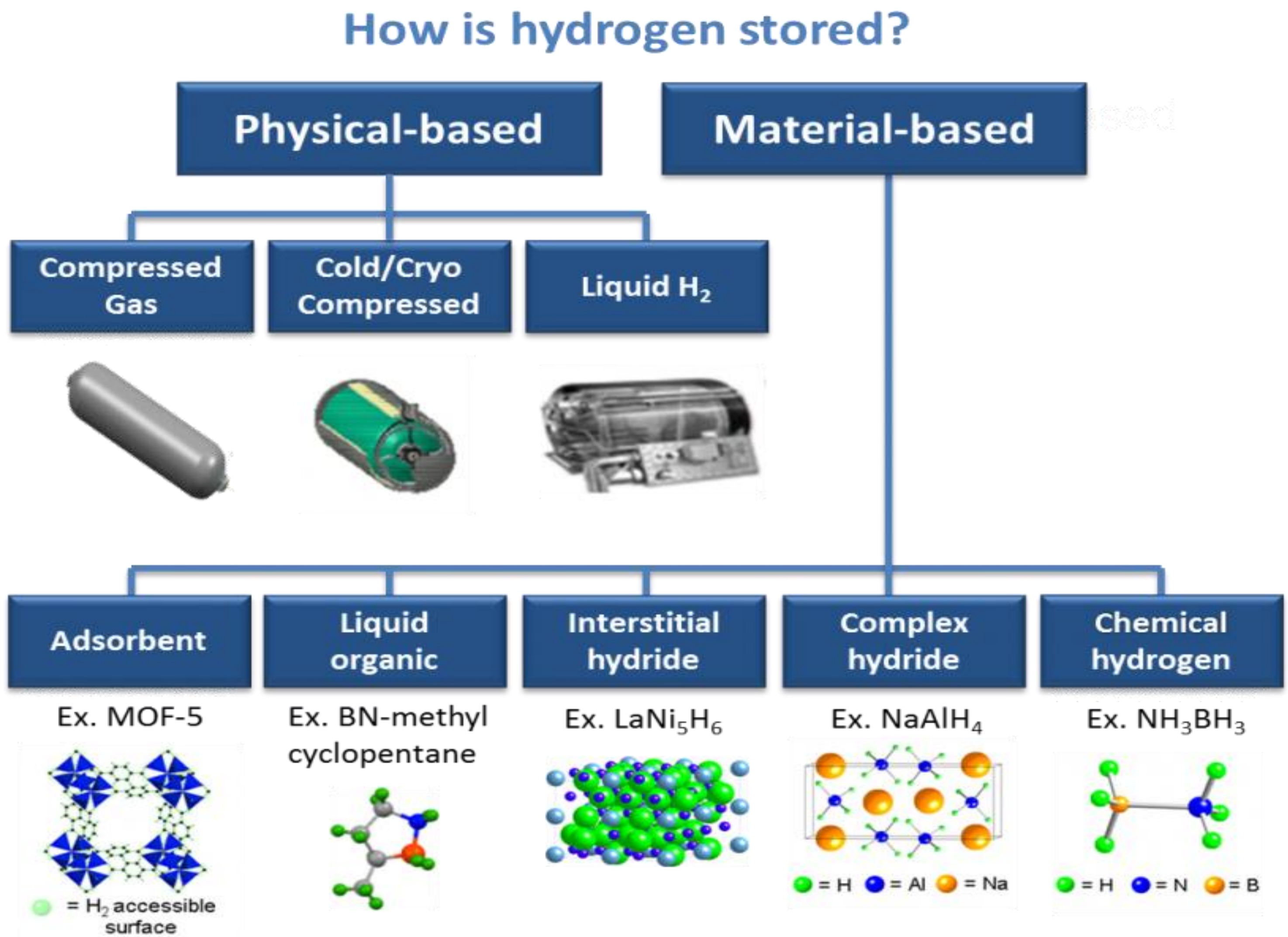




Fuel Cells, 2007- 2013



Fuel Cells, 2007- 2013



Fuel Cells, 2007 - 2013

Trafic	Stationary loacations, CHP	Niche-markets
On road	Households	Mobile ja micro FC's
On sea	Hotels	Special vehicles
In air	Hospitals	Portable generators, UPS
On rail	Industry	H_2 –power plants

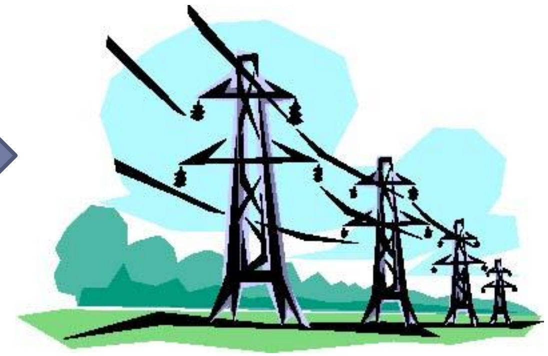
Program results in Vuosaari harbor area 2014

- Special vehicles – forklifts, harbor cranes
- Personal trafic – aim in buses
- Telecommunication, basestation, remote control, UPS
- CHP systems for harbor area
- Fuel cells utilising biogas
- Hydrogen refilling station

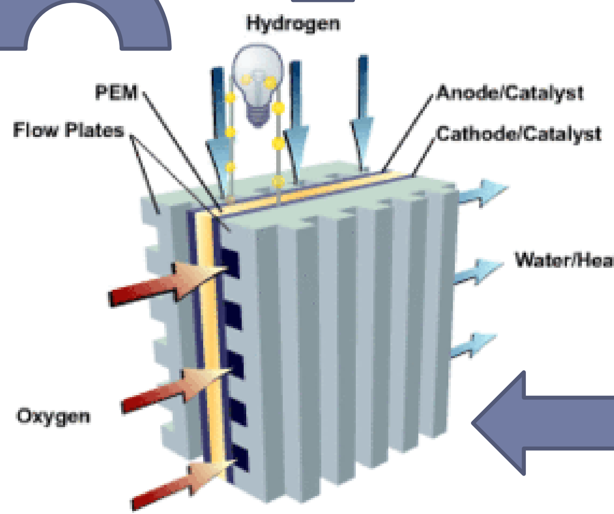
Hydrogen village in Äetsä

Kemira (Finnish) Chemicals factory, Äetsä

’House of hydrogen’ in Äetsä



Electricity
Heat



Hydrogen

Finnish Chemicals

Solar power plant in Lempäälä Marjamäki

maps4news.com/©HERE

SOFC (24 x 3 kW) x 2 = 144 kW (Convion)

2020 presents hydrogen olympics and fuel cells – Japani wants to spread hydrogen message to whole world

100 fuel cell buses and 35 refillig stations during olympics .

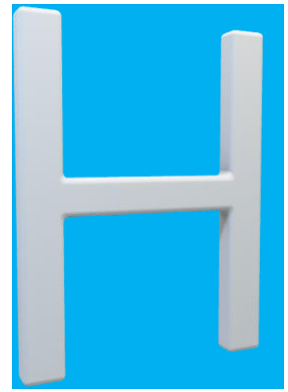
Japan government aims to 100 000 fuel cell vehicles in Tokyo in 2025. The country has now over 100 refilling stations.

BUT … Covid-19

Different colors of hydrogen

Grey hydrogen:

Hydrogen produced from fossil fuels

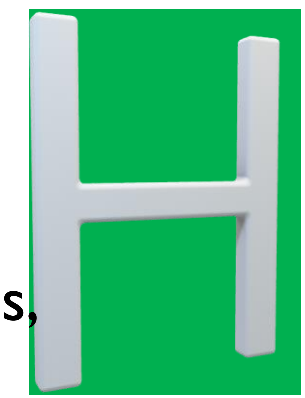


Blue hydrogen:

Hydrogen produced without emission, nuclear

Turquoise hydrogen:

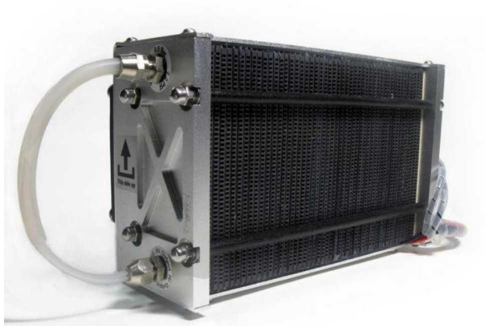
Hydrogen via pyrolysis, Coal as a by-product



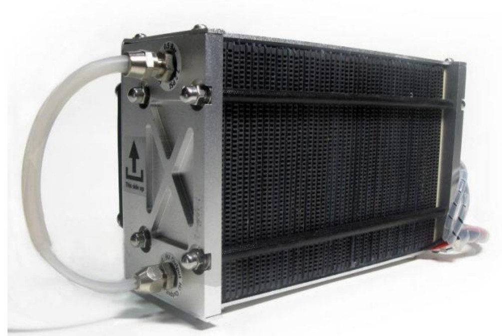
Green hydrogen:

Hydrogen via electrolysis utilising renewables

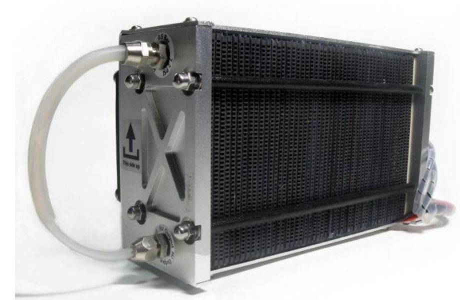
Fuel Cells – price trends



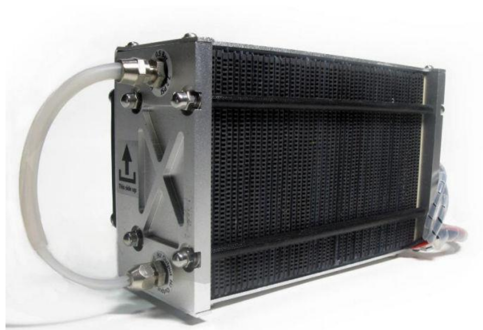
1970's
600 000 $/kW
(space)



1990's
4500 $/kW
(stationary)



2010's
1000 $/kW
(stationary)

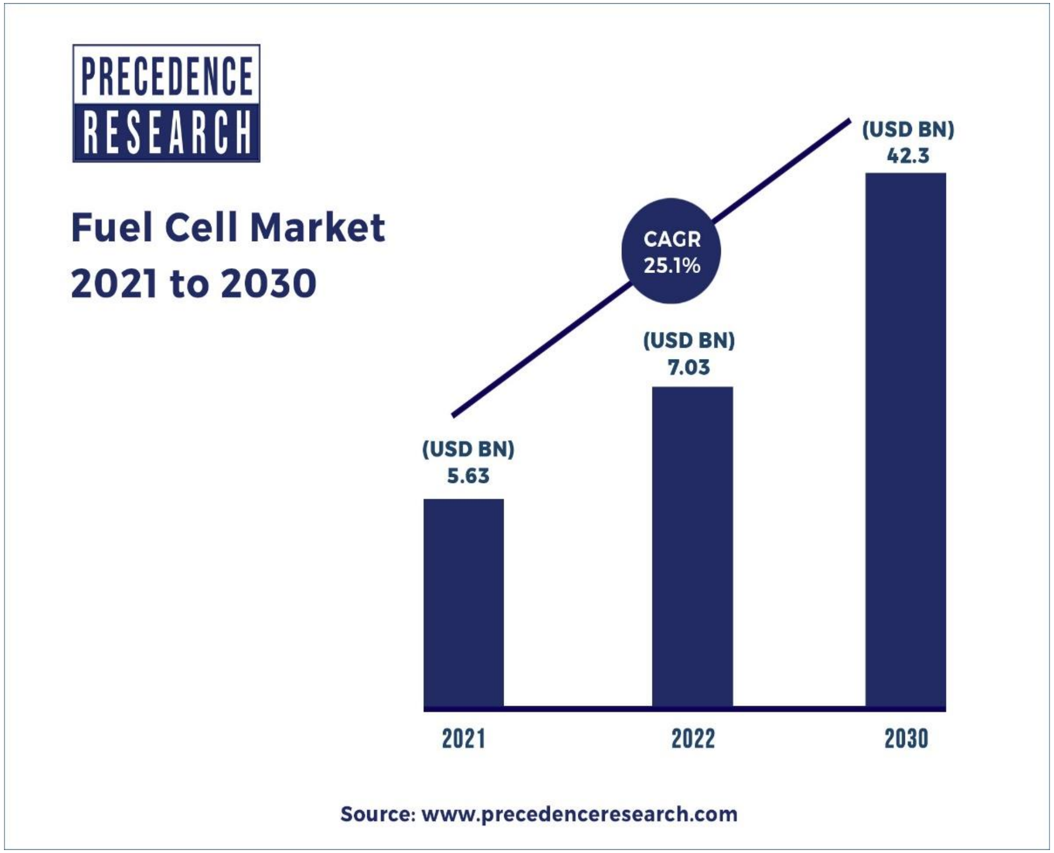


2020's

1000 → 500 → 300 $ / kW

Fuel Cell markets

2330 MW in 2021



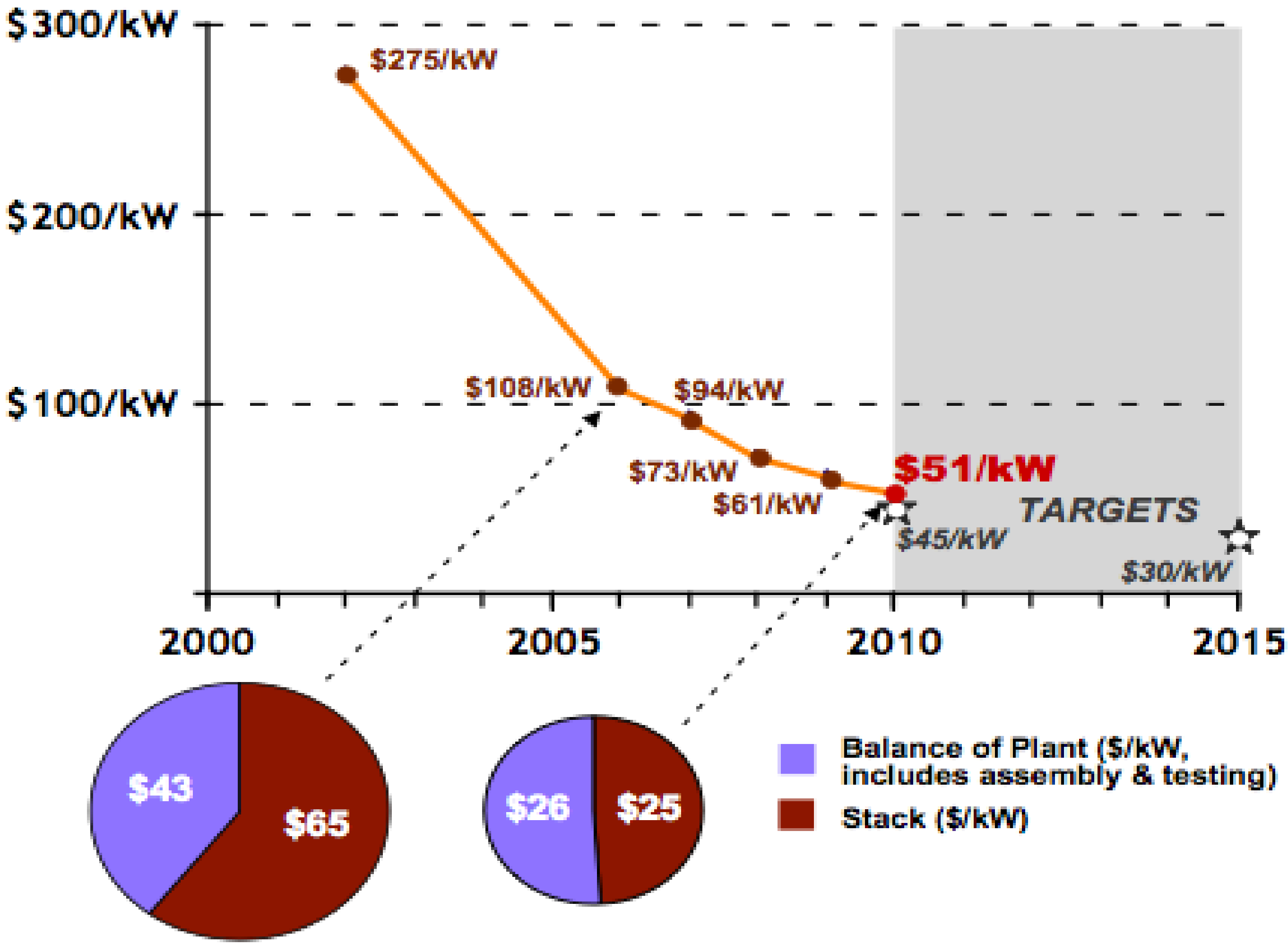
Global MWs shipped by application

MW	2016	2020
Portable	0.3	0.4
Stationary	209	325
Transport	307	994
Total	516.3	1319.4

Global units shipped by application

1000 unit	2016	2020
Portable	4.2	4.1
Stationary	51.8	57.8
Transport	7.2	20.5
Total	63.2	82.4

Fuel Cell; price - automobile



Toyota Mirai 2020

$ 53 / kW

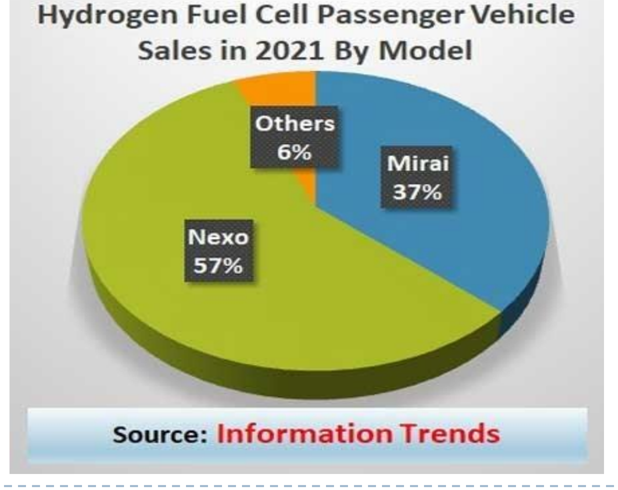
44 000 Fuel Cell vehicles in 2021 (growth 42 %)

+ 5000 buses and 5000 trucks

- 2001 - Hyundai Santa Fe FCEV
- 2013 - Hyundai Tucson/iX35 FCEV
- 2008 - Honda FCX Clarity
- 2015 - Toyota Mirai
- 2016 - Riversimple Rasa
- 2016 - Honda Clarity Fuel Cell
- 2018 - Hyundai Nexo

	Toyota Mirai	Hyundai ix35 Fuel Cell	Honda Clarity Fuel Cell
			
Acceleration 0-60 mph	9.6 s	12.5 s	11 s
Fuel Cell power	113 kW	100 kW	103 kW
Engine power	113 kW	100 kW	130 kW
Top speed	179 km/h	161 km/h	200 km/h
Range	ca. 550 km (NEDC test)	594 km	482 km
H_2 storage	70 MPa	70 MPa	70 MPa

44 000 Fuel Cell vehicles in 2021



Toyota Mirai: ~ 50 000 € (FC ~ 5 000 €)

FC system	57 kg
Hydrogen	5 kg
Hydrogen tanks	83 kg

145 kg / 650 km

Tesla Model 3: ~ 50 000 €

Battery Pack	540 kg

540 kg / 430 km

Infrastructure of refilling …

Toyota Mirai 2022

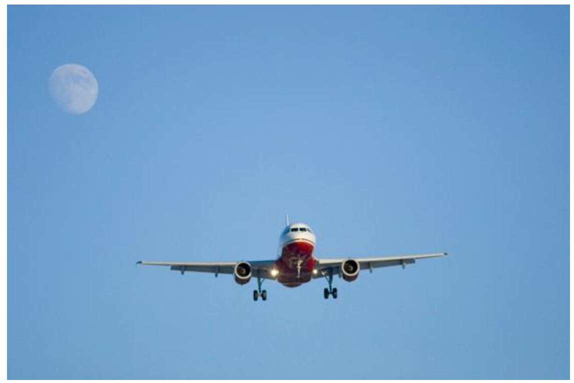
Industrial Manufacturing

Space technology

1 M€/kg

- New materials
- New technology
- New IT

Aircraft technology



10 k€/kg

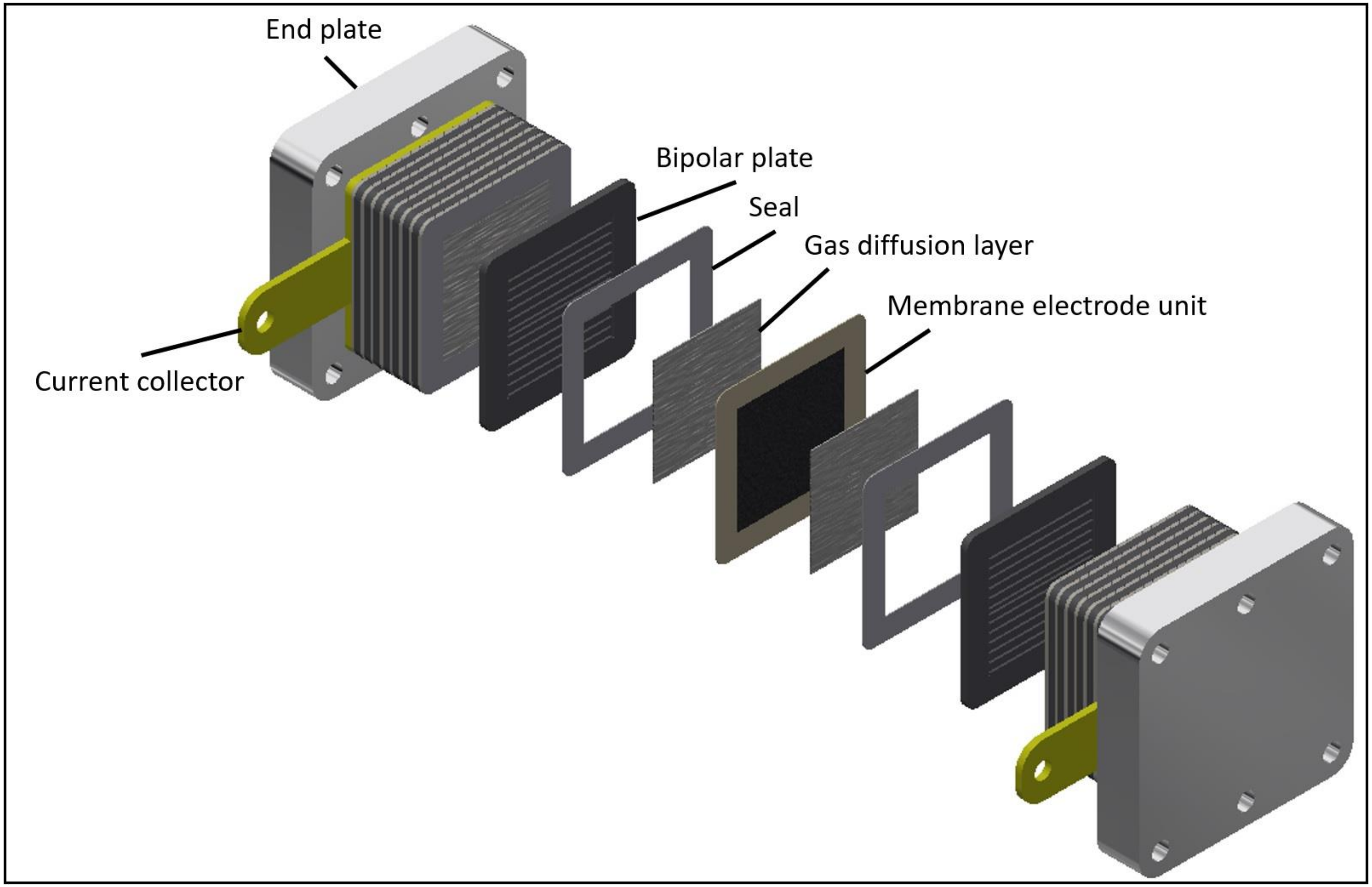
- New materials
- Industrial scale
- Tested IT

Automobile technology

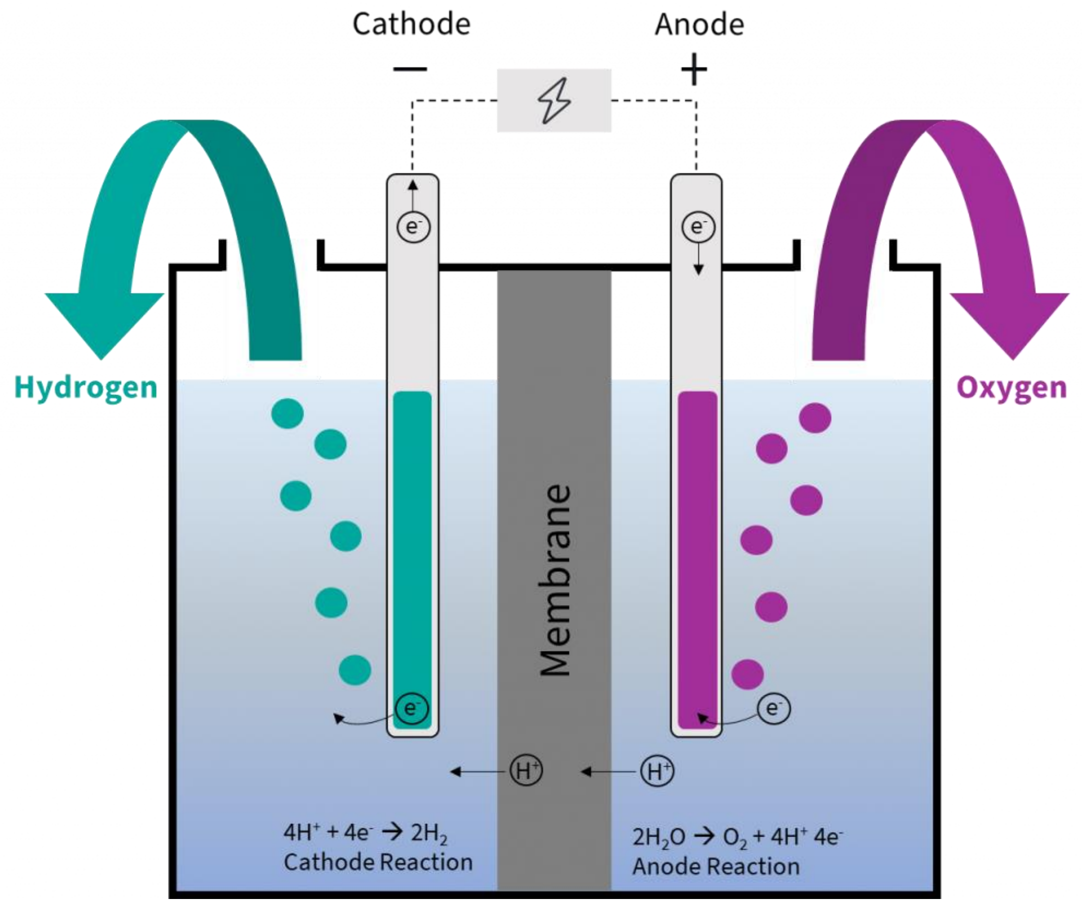
5 €/kg

- Low costs
- Well-established technology
- Massproduction

3. Fuel cells – structure, operation principle



What is it all about?



Water electrolysis … *Reversed*

Where did it all started?

William Grove (1811-1896)

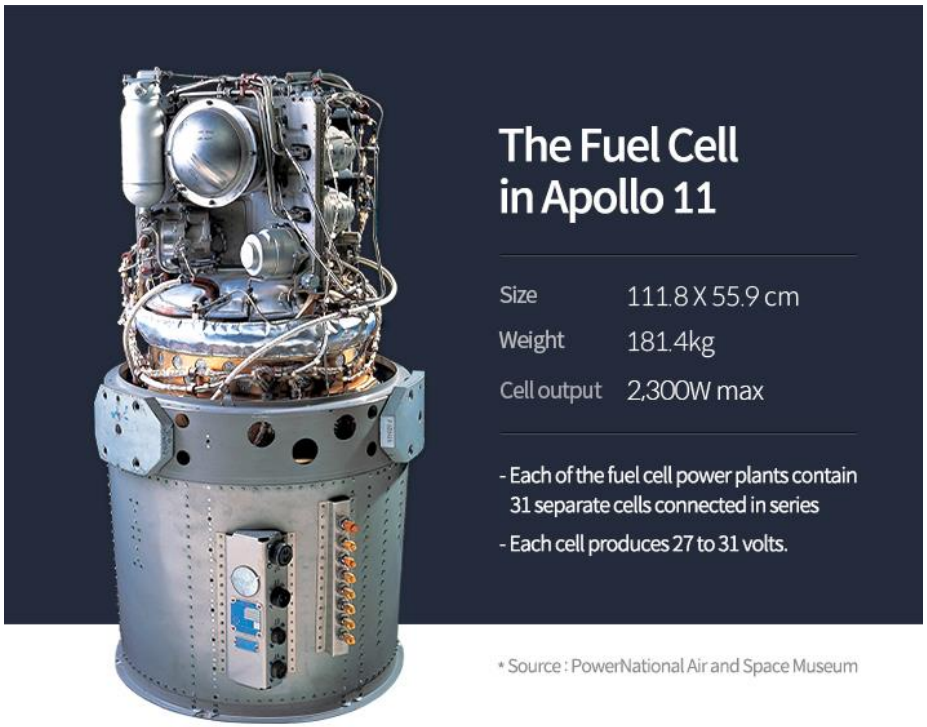
- Measured and published the phenomenon of fuel cells (reversed water electrolysis), 1839.
- *'Grove's experiment clarifies well the theory, but concerning practical applications, it is quite useless*

Fuel Cells - history

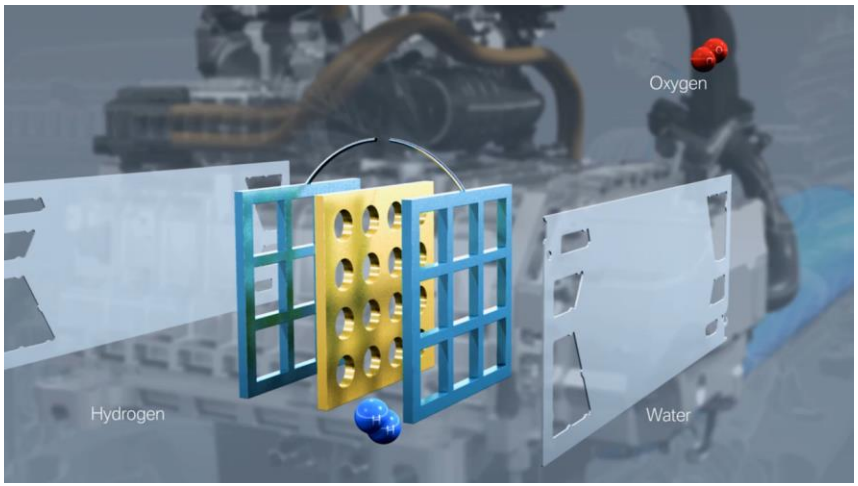
Concept: William Grove, 1839

Demo: Thomas Bacon, 1952

First applications: Gemini ja Apollo – space ships

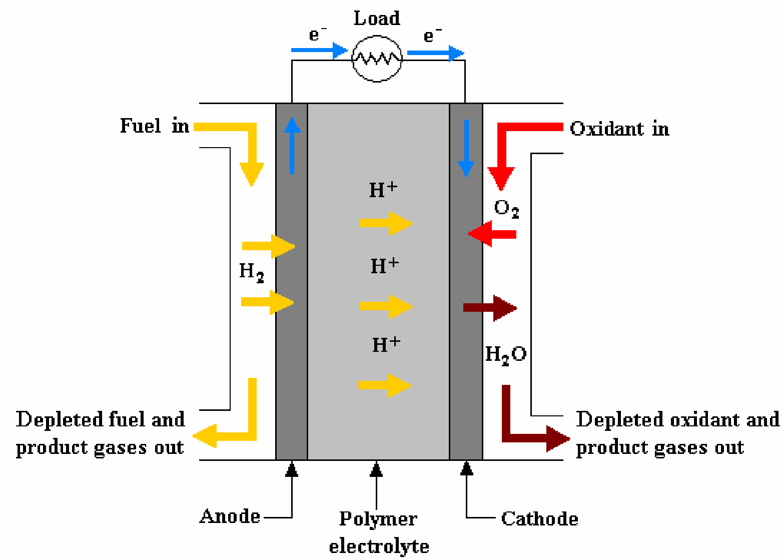


Fuel Cell – basic principle



- CASE
- The main principle of PEM (Proton-Exchange Membrane Fuel Cell)

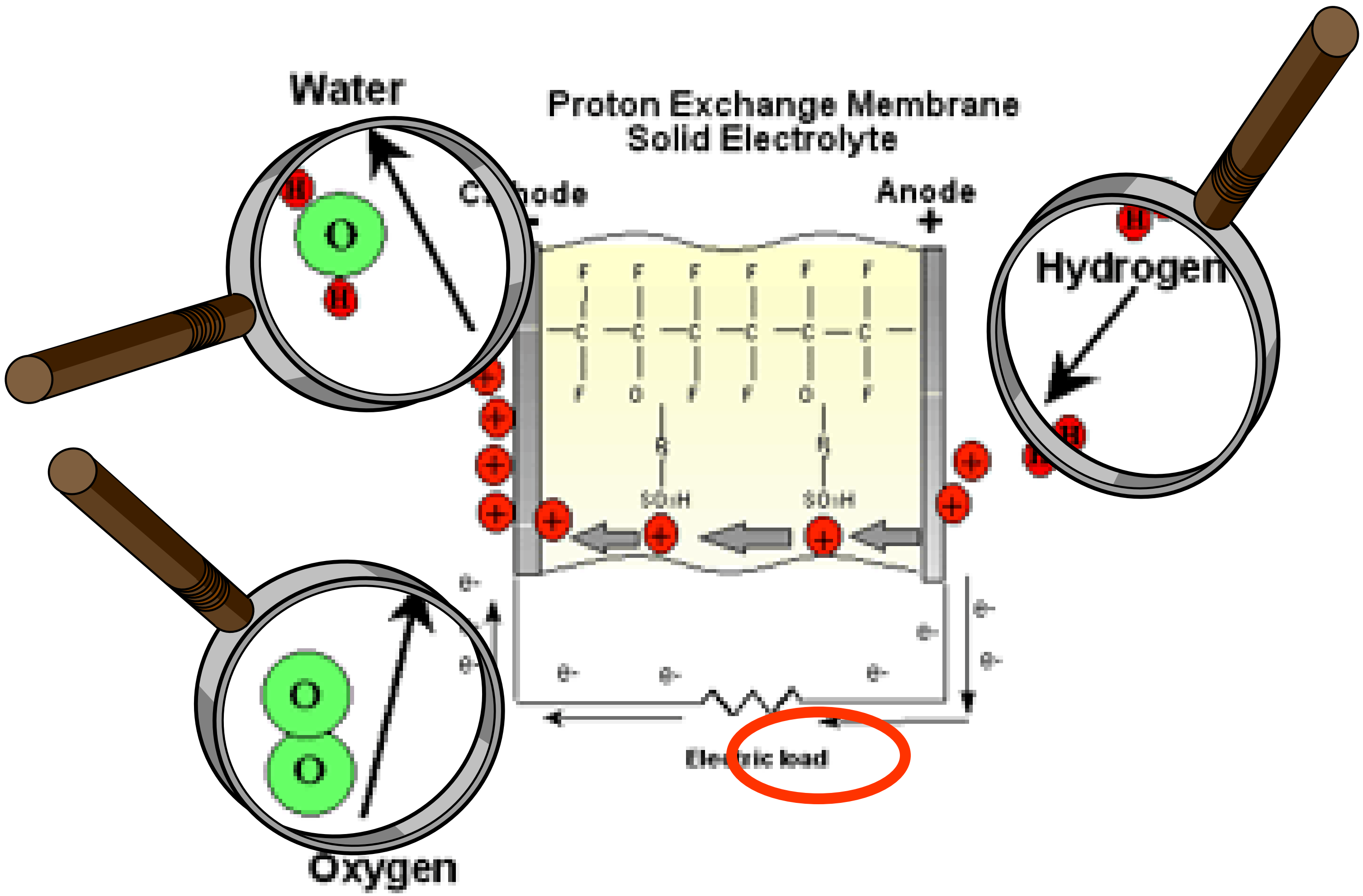
Fuel Cell – basic principle



Operation of a PEM Fuel Cell

Hydrogen and oxygen are fed to the anode and cathode, respectively of a solid polymer cell, or PEM cell, whereby the reactions of electrodes are: Anode: $2H_2 \rightarrow 4H^+ + 4e^-$ and cathode: $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$. In other words, on the anode hydrogen gas is ionized, releasing electrons and H+ ions (protons) that pass through the electrolyte from the anode to the cathode. In the reaction, two electrons are transported through an external circuit connected between the electrodes from the anode to the cathode for one anode to the hydrogen molecule. In addition to the electrical energy generated, clean water is the reaction product.

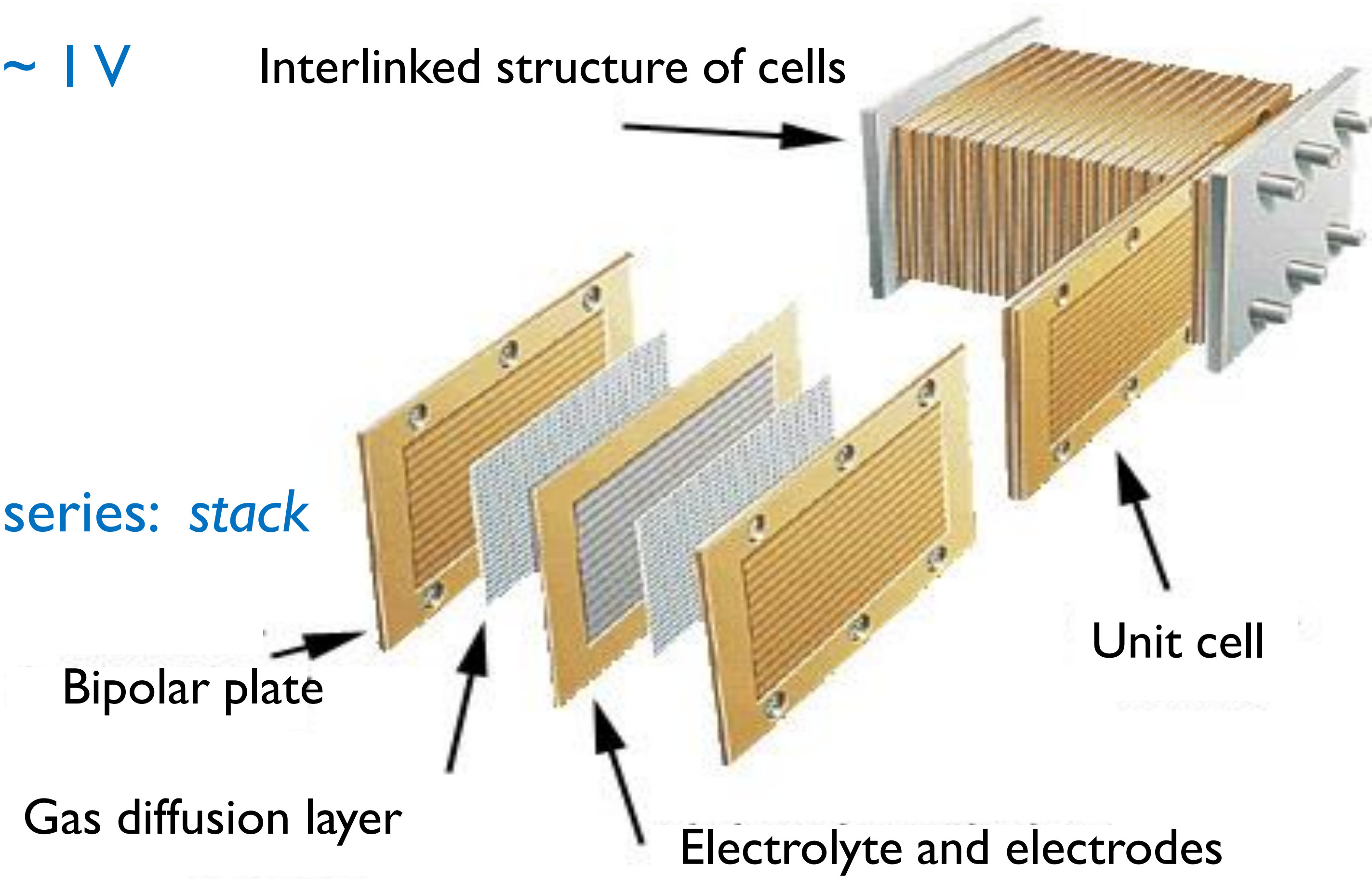
Hydrogen + oxygen (air) >> electric current



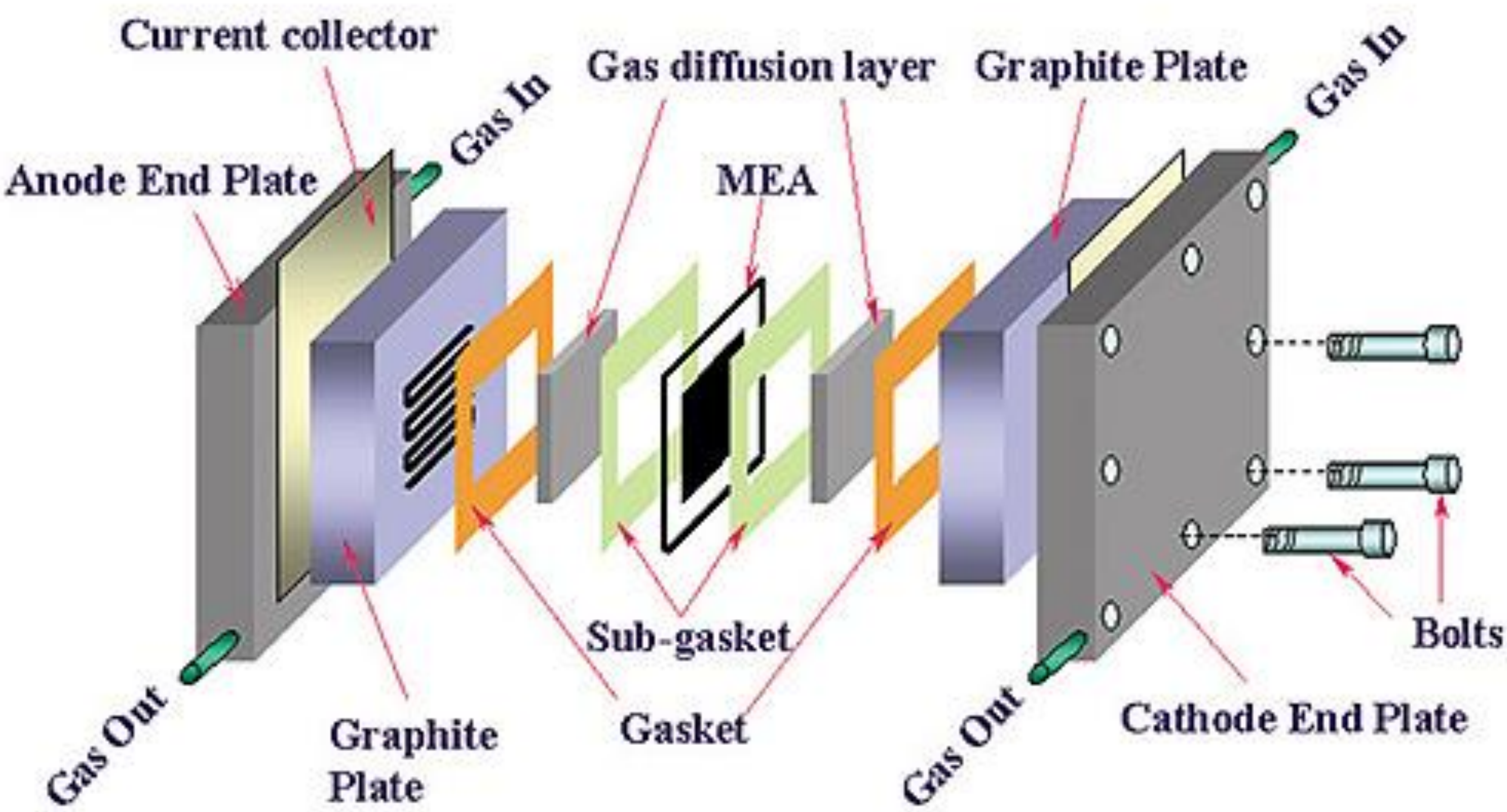
Fuel Cell – basic structure

Cell voltage ~ 1 V

Unit cells in series: *stack*



Fuel Cell - structure



Fuel Cell – open circuit voltage

The operation of the fuel cell is based on Gibbs' free energy change

$$E = \frac{-\Delta g}{z\,F}$$

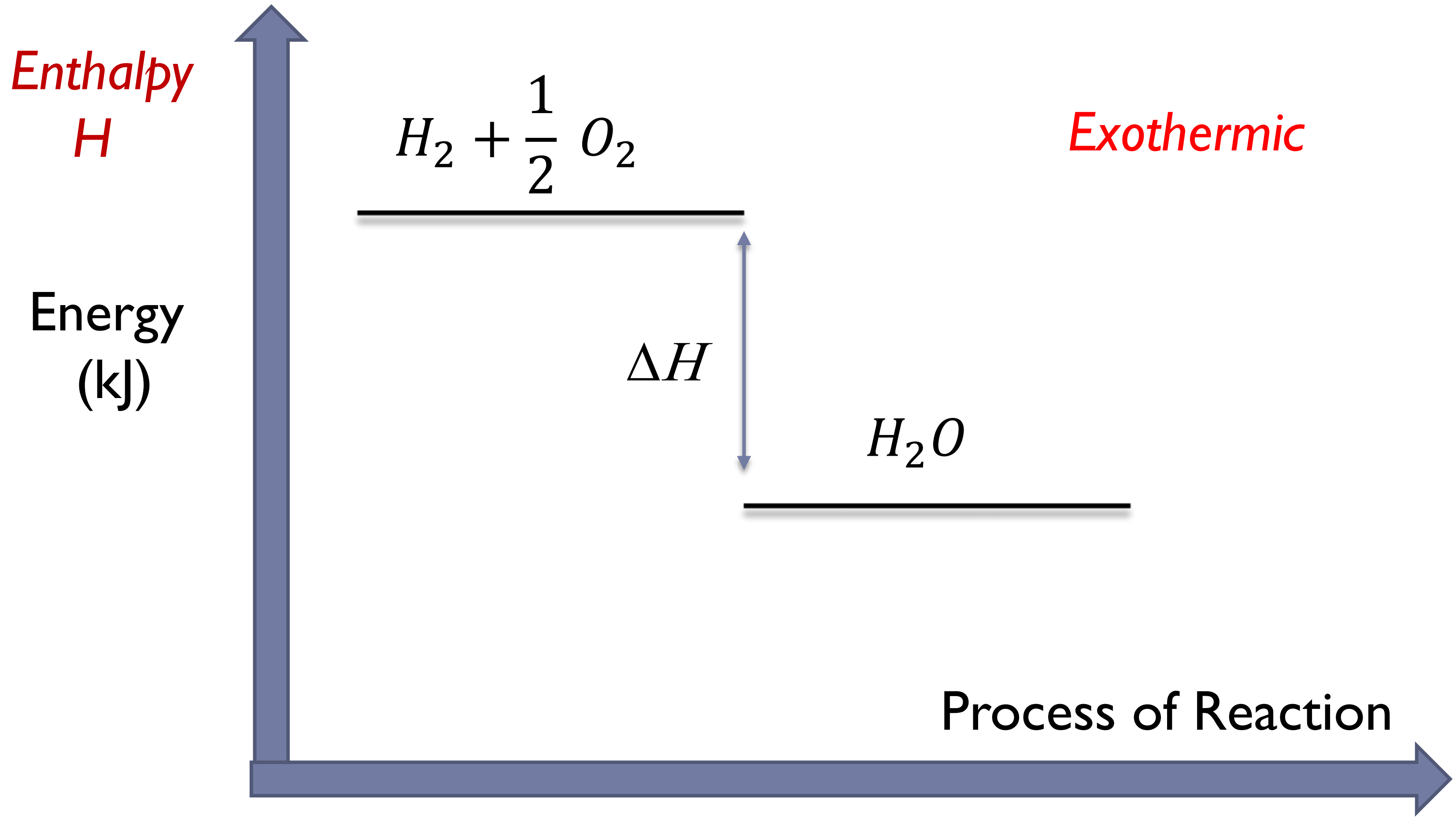
Ideally, the whole Gibbs' energy becomes electric.

Total charge through the load

Cell reversible ideal open circuit voltage

F ~ Faraday constant 96 485 C/mol

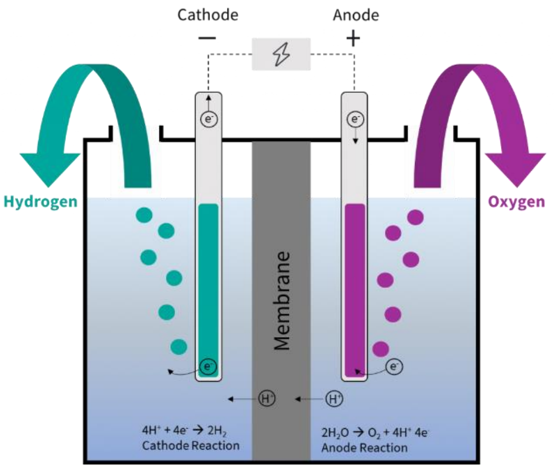
The electrical chemistry and thermodynamics of the fuel cell will be discussed in more detail in the advanced course



$$\Delta H = H_{(Products)} - H_{(Reactants)} < 0$$

ΔH shows how much energy is released

Gibbs Free Energy



$$g = h - Ts$$

$$\Delta g = \Delta h - T\Delta s$$

Produced heat in the cell

$$E = \frac{-\Delta g}{z F}$$

Δg:n määrittäminen

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

$$g = h - Ts$$

missä *h* on ominaisentalpia, *s* ominaisentropia (moolia kohti) ja *T* kennon toimintalämpötila

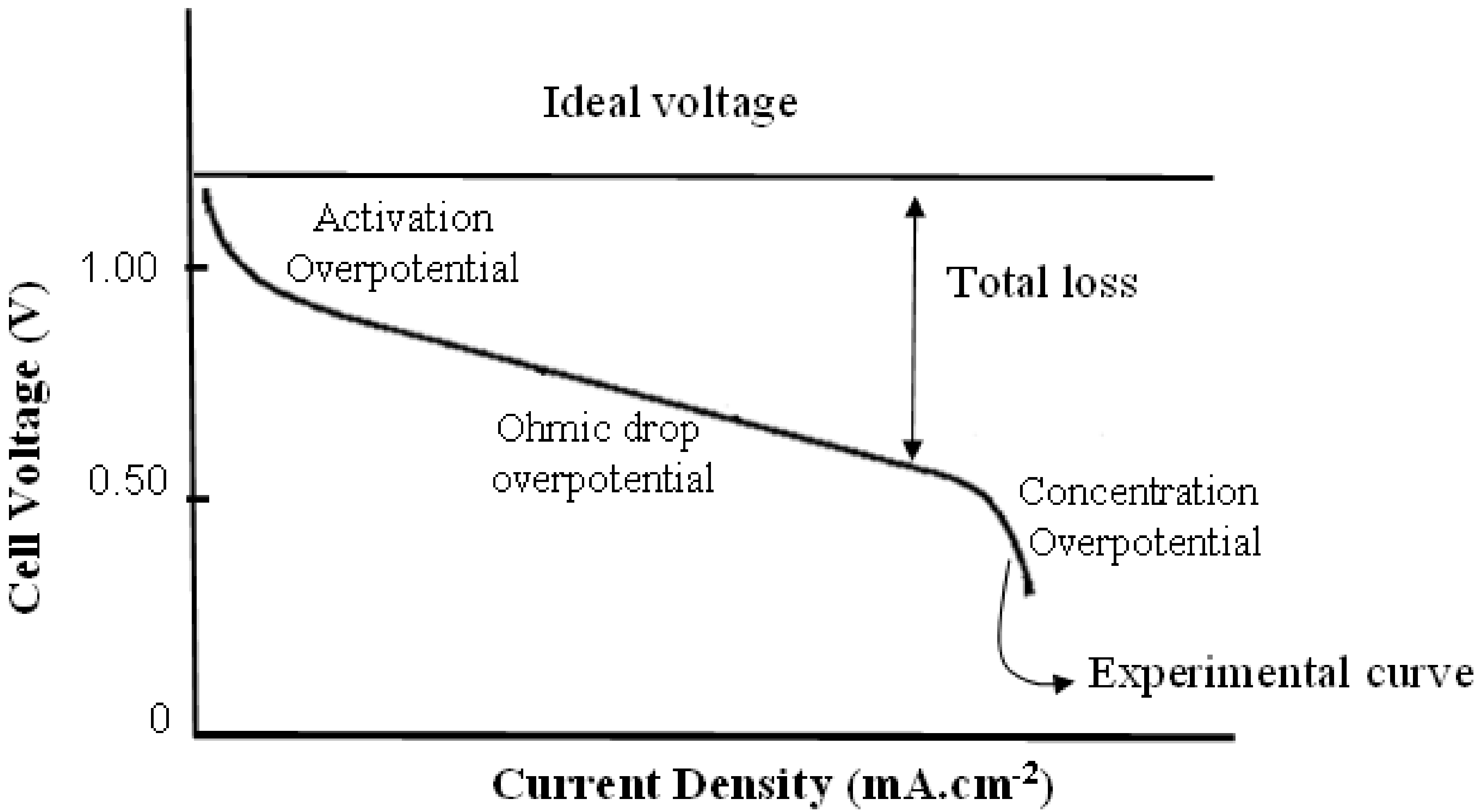
Muutos

$$\Delta g = \Delta h - T \Delta s$$

$$\Delta h = (h)_{H_2O} - (h)_{H_2} - \frac{1}{2}(h)_{O_2}$$

$$\Delta s = (s)_{H_2O} - (s)_{H_2} - \frac{1}{2}(s)_{O_2}$$

Real cell voltage



Fuel cell irreversibilities

$$E = \frac{-\Delta g}{zF}$$

- Activation losses
- Fuel crossover
- Ohmic losses
- Concentration losses

Exercise

What is an ideal amount of hydrogen mass flow (kg/h) in the PEM cell to produce a 1 A cell current?
Hydrogen molest mass M_{H2} = 2.0158 g/mol.

Solution

As two electrons move in the PEM cell through the external load per one-brought hydrogen molecule, the transferred total charge *Q* is

$$Q = 2\,F\,n_{H2}$$

Where *F* is the Faraday and n_{H2} the amount of hydrogen in moles. Derivate the equation for time *t*:

$$\frac{dQ}{dt} = I = 2\,F\,\dot{n}_{H2}$$

$$\Rightarrow \quad \dot{n}_{H2} = \frac{I}{2\,F} = \frac{1\,A}{2 \cdot 96485\,C/mol} = 5.18 \cdot 10^{-6}\ \frac{mol}{s}$$

$$\Rightarrow \quad \dot{n}_{H2} = 5.18 \cdot 10^{-6}\ \frac{mol}{s} \times 2.0158 \frac{g}{mol} = 1.045 \cdot 10^{-5}\ \frac{g}{s} = 3.76 \cdot 10^{-5}\ \frac{kg}{h}$$

Commercial Fuel Cell types

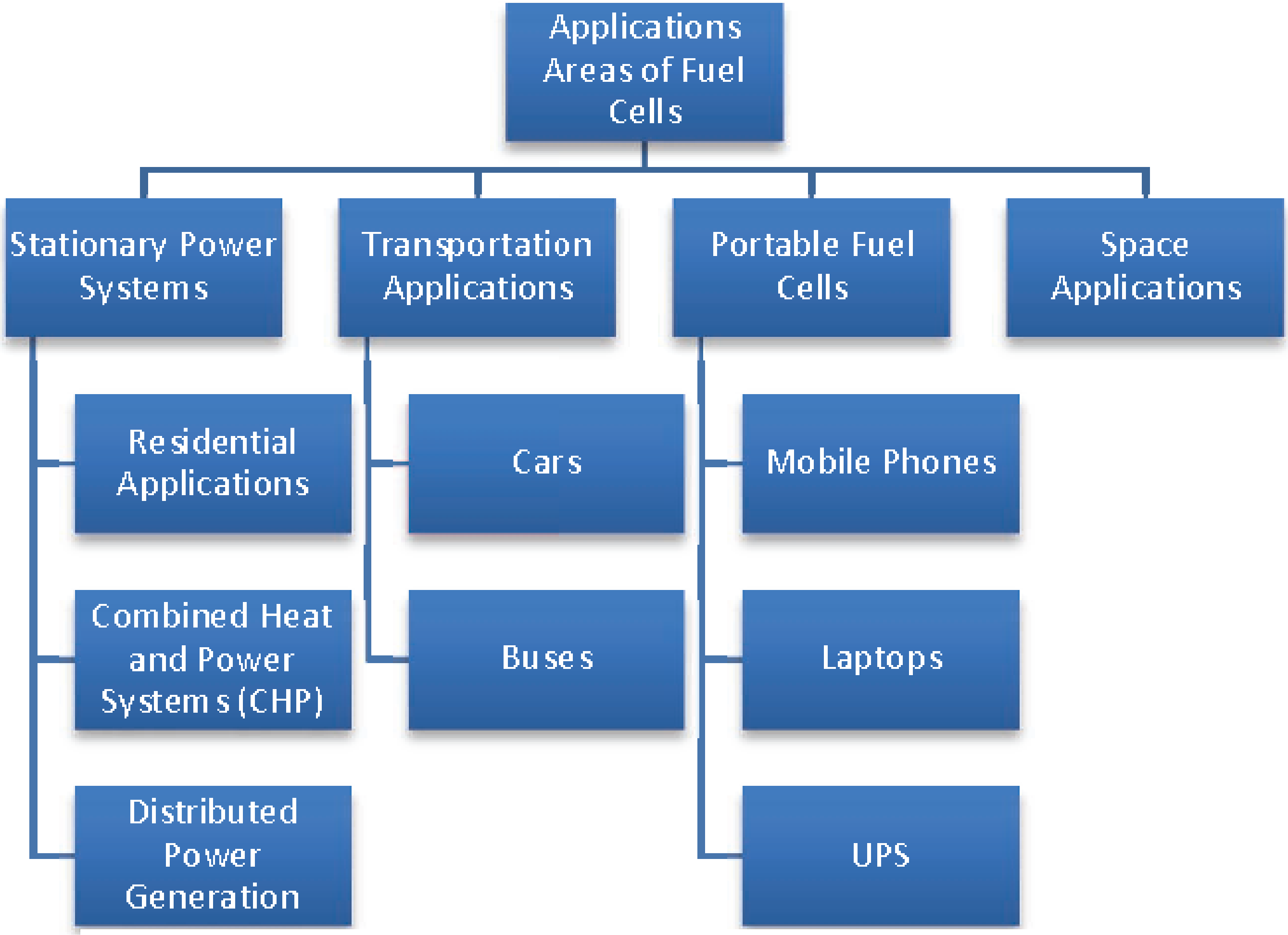
- Fuel cells can be classified, for example, according to the electrolyte or operating temperature used
- High Temperature Fuel Cells:
- SOFC – Solid Oxide Fuel Cell (kiinteäoksidikenno), T_{op} = 800 … 1000 ^{0}C
- MCFC – Molten Carbonate Fuel Cell (sulakarbonaatti-kenno), T_{op} = 600 … 650 ^{0}C

Commercial Fuel Cell types(Cont.)

- Low Temperature Fuel Cells

- PAFC – Phosphoric Acid Fuel Cell (fosforihappokenno), T_{op} = 200 …220 ^{0}C
- AFC – Alkaline Fuel Cell (alkaalikenno), T_{op} = 80 … 100 ^{0}C
- PEM – Solid Polymer Fuel Cell (kiinteä polymeerikenno), T_{op} = 70 … 80 ^{0}C
- DMFC – Direct Methanol Fuel Cell (suora metanoliken-no), T_{op} = 110 …130 ^{0}C

4 Fuel Cells – Applications areas



Fuel Cells – Application areas (1)

Stationary Power Systems

Limited transfer capacity

Distributed generation

The Gyeonggi Green Energy fuel cell park in Hwaseong City

MCFC

59 MW

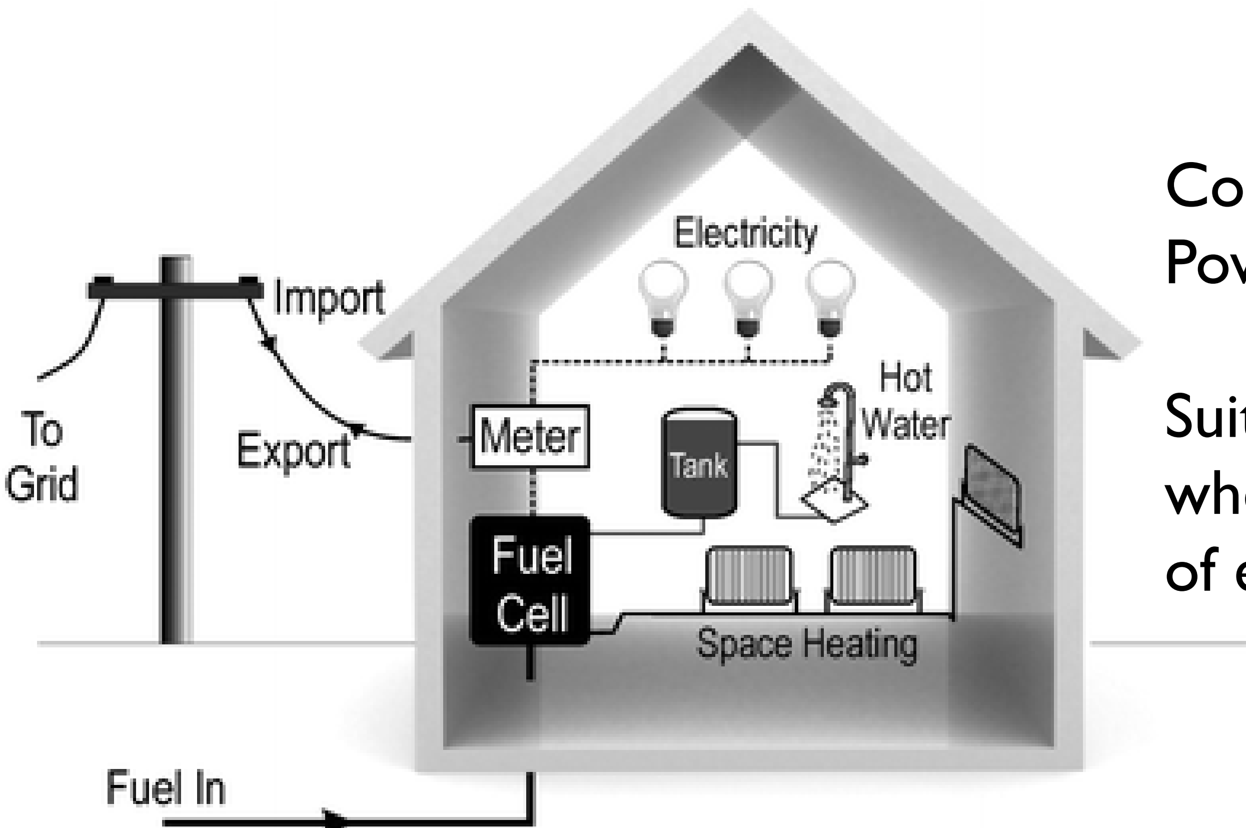
Fuel Cells – Application areas (2)

UPS

Uninterruptible
Power
Supply

Fuel Cells – Application areas (3)

Household specific CHP (micro-CHP)



Combined Heat and Power

Suitabale for areas where the infrastructure of electricity is weak

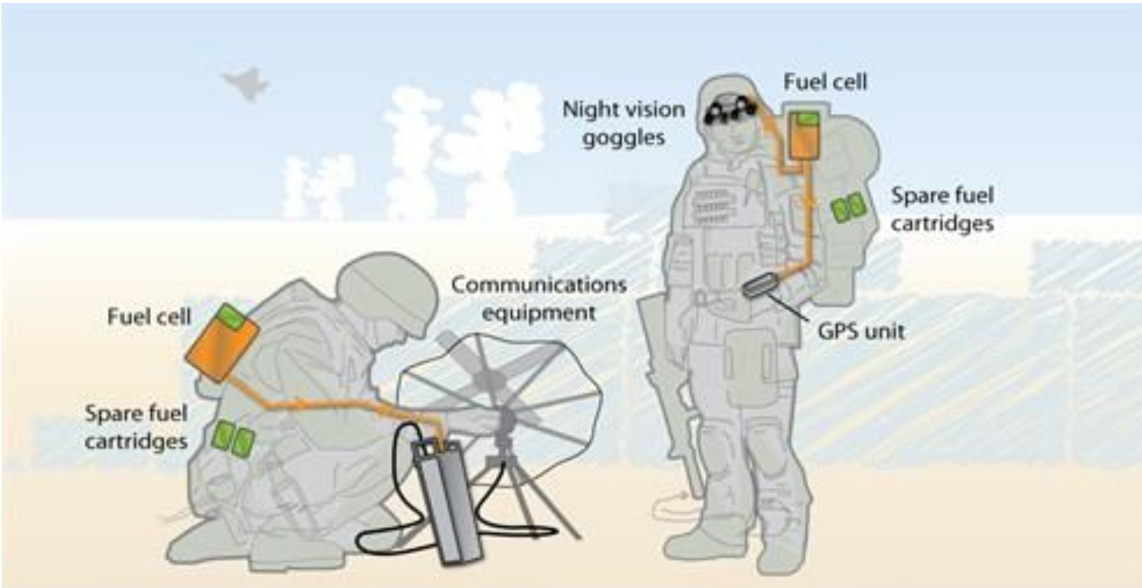
Fuel Cells – Application areas (4)

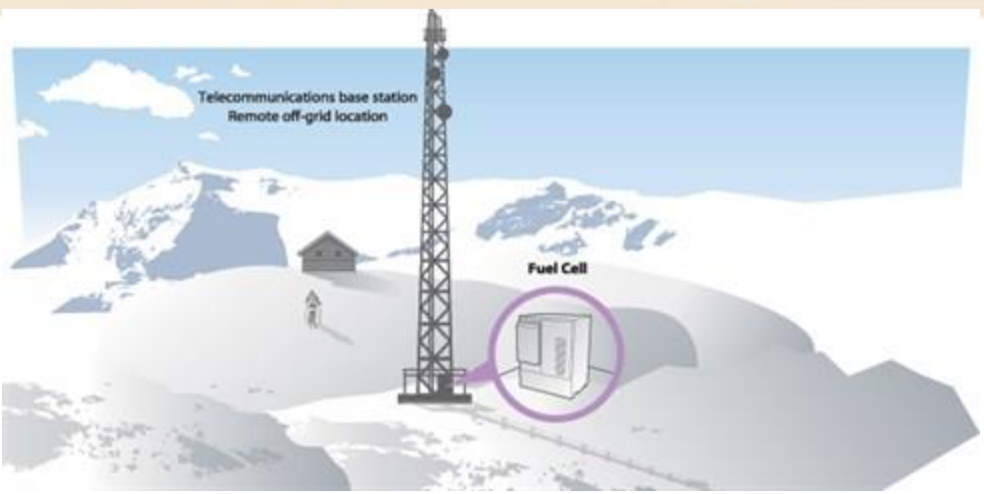
Small and portable applications

Charging devices

'Batteries' for mobile devices

Fuel Cells – Application areas (4) Cont.





Telecommunication and networks

'Portable Power'

Remote control systems

Fuel Cells – Application areas (5)

Special vehicles and working machines

Mine vehicles & small locomotives

Forklifts

Harbor cranes

Electricity production for ships

Fuel Cells – Application areas (6)

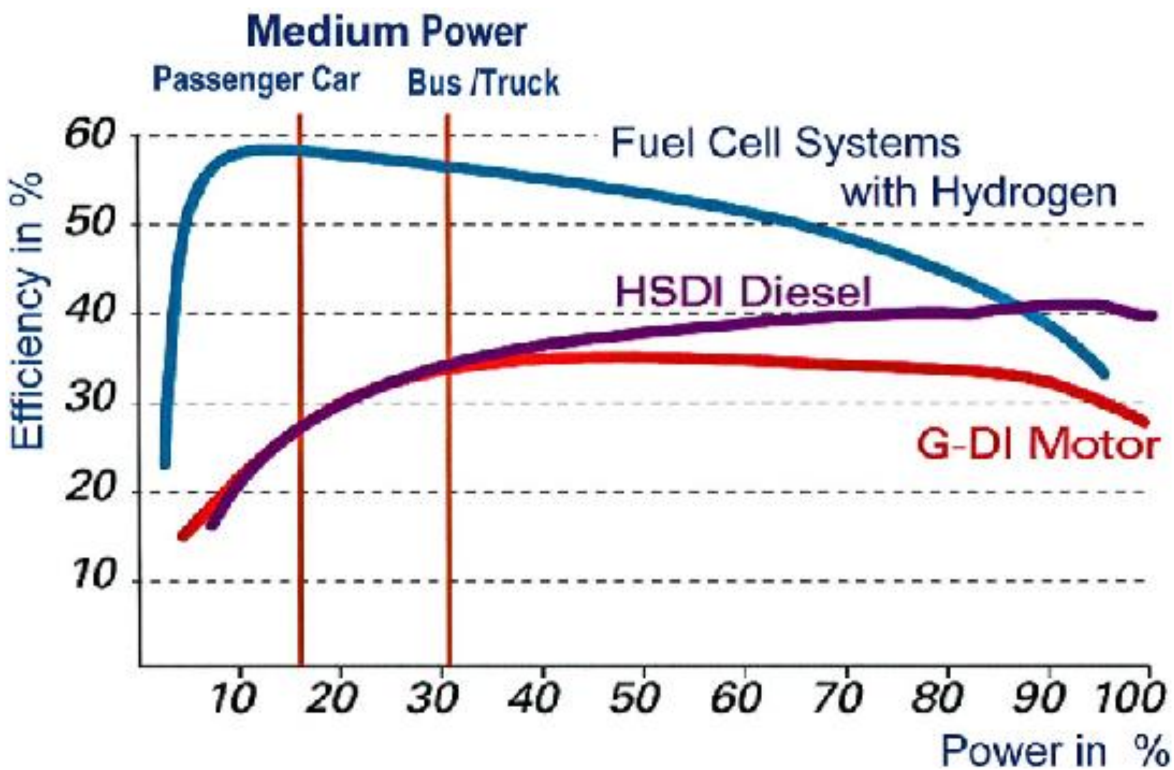
Fuel Cell Vehicles (FCEV)

As a starting point for emissions and use of energy

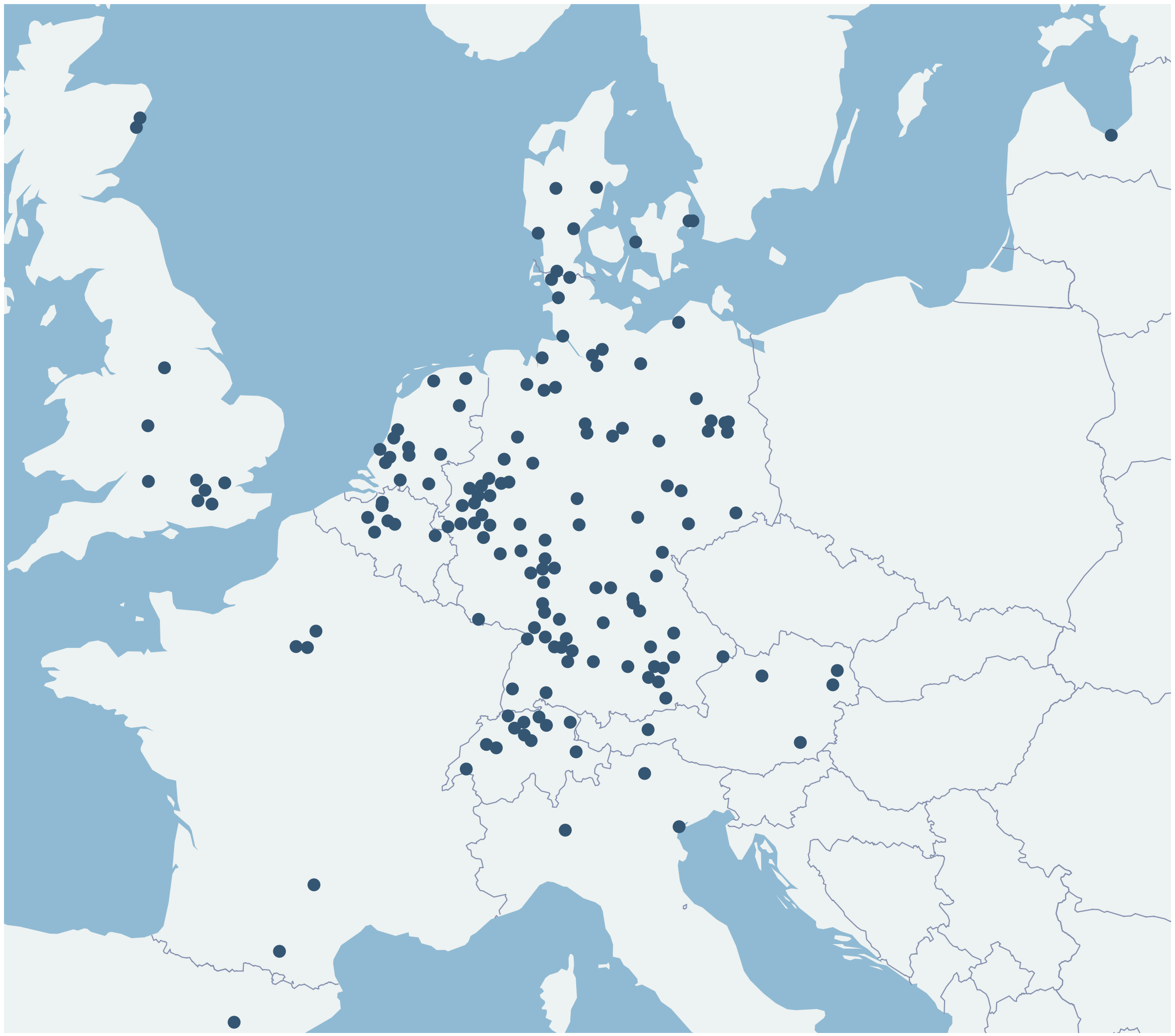
All large car manufacturers have their own product development programs

So the supply exists… who does the market opening?
…Toyota

FCEV vs combustion engine



Hydrogen filling stations in Europe



At the end of 2021

Europe	228
Globally	685

Fuel Cell + Hydrogen in heavy traffic

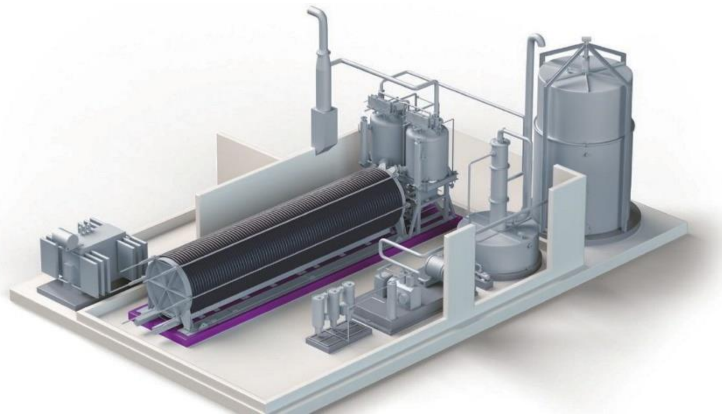
FCEV powertrains for trucks are cost competitive with BEV from 100 km range

Hydrogen refueling is 15 times faster than fast charging

Recharging infrastructure requires 10-15x less space

Hydrogen raodmap Europe 2019

5 Conclusions

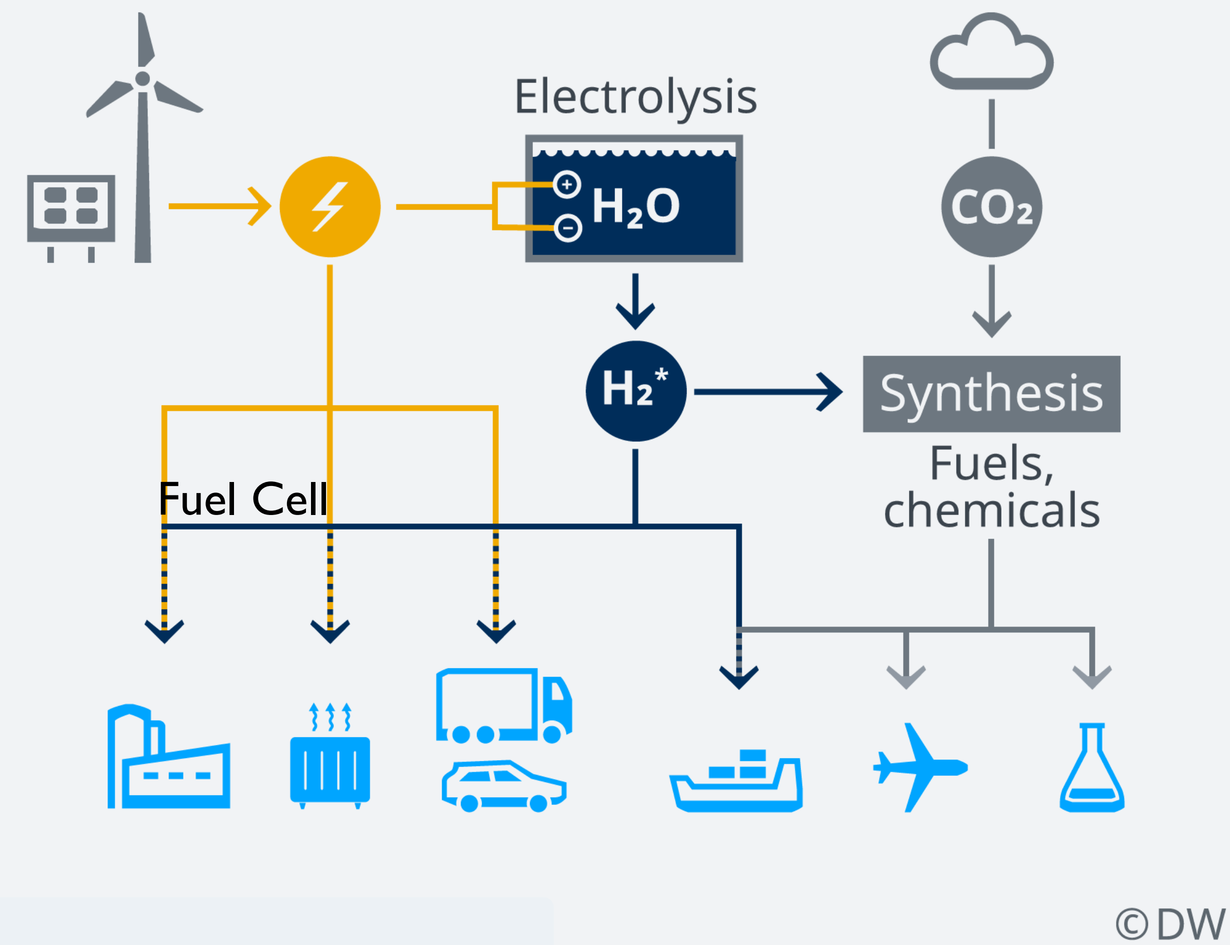


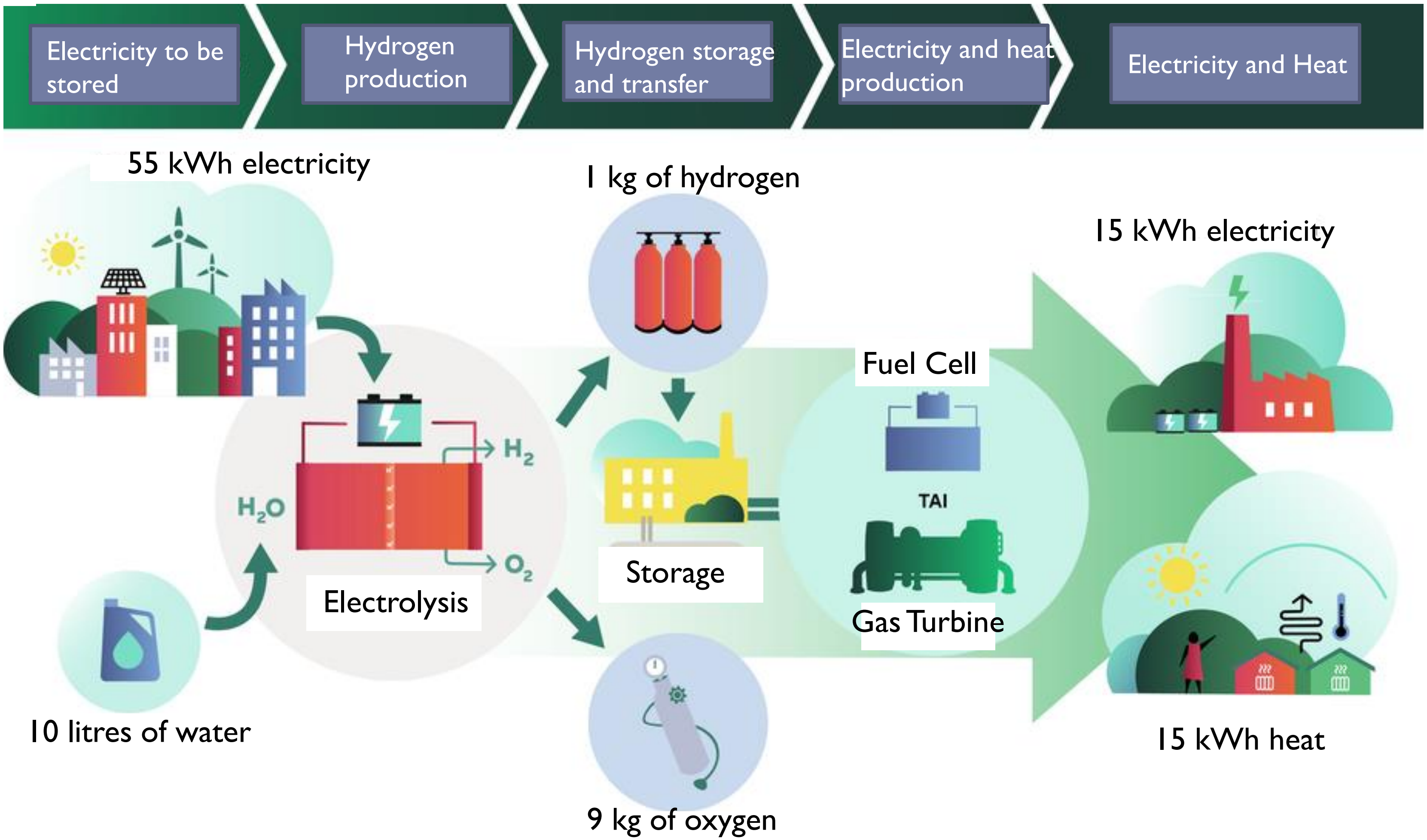
Electrolyser

Hydrogen Storage

Fuel Cell

Power-to-x: carbon-neutral fuels





Solar and wind power can be used in electrolysis to decompose water molecules into oxygen and hydrogen. Hydrogen can be stored and later used in fuel cells or gas turbines to generate electricity and heat. There is no carbon emissions from burning hydrogen. The only by -product in addition to energy is water

Fuel Cells – Pros.

High Efficiency, 45-55 %

No emission (in use)

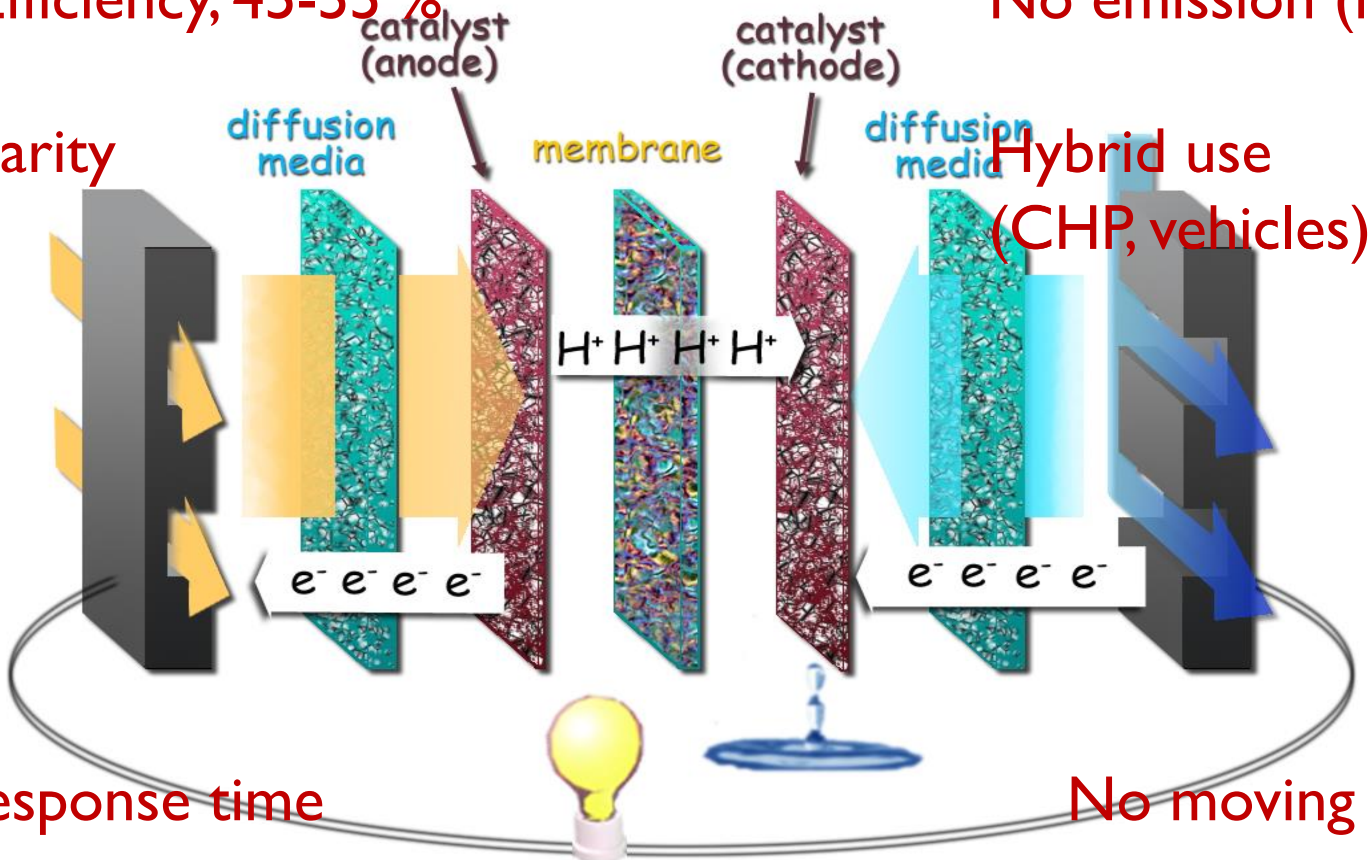
Modularity

Hybrid use (CHP, vehicles)

Silent

Fast response time

No moving parts

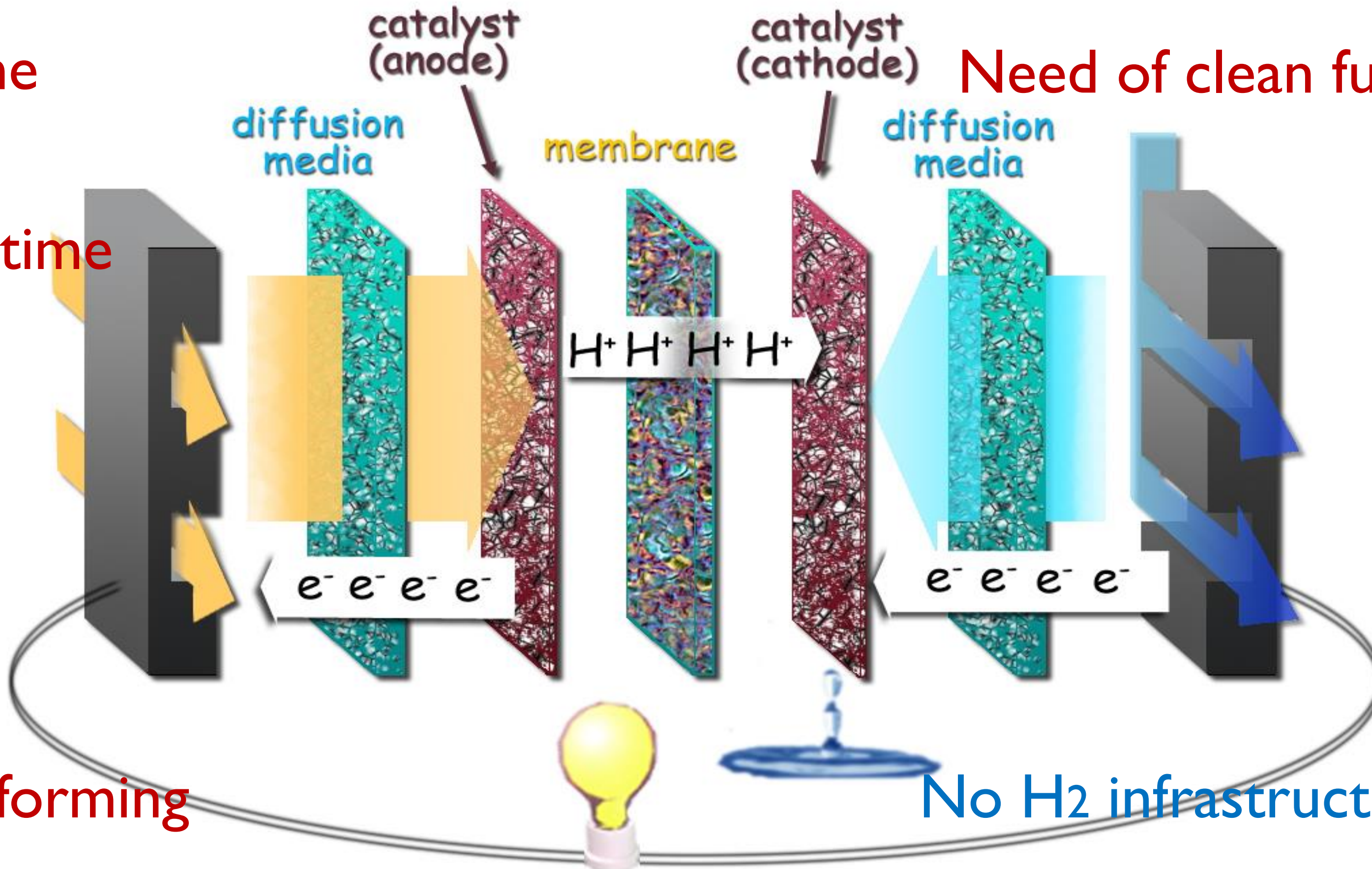


Fuel Cells – Cons.

Life time

Start up time

Need of clean fuels



Fuel reforming

No H_2 infrastructure

High price, > 700 €/kW


Energy Station
BENSIINI
DIESEL
UREA
MAA-
KAASU
SÄHKÖ
VETY