UN Department of Economic and Social Affairs
Division for Sustainable Development

Learning Centre @ CSD14
A series of lectures on the subject:

How to Ensure Sustainable Development using Hydrogen

Sponsored by the Government of Iceland

IPHE
International Partnership for the Hydrogen Economy

How to Ensure Sustainable Development using Hydrogen

- The element hydrogen is in many ways quite remarkable. It can be produced by various methods and it can serve as an energy carrier: a fuel.
- It burns in the atmosphere and creates water.
- Iceland, the country of the world with the highest proportion of renewables in its total primary energy portfolio, is aiming to basing its energy economy solely on renewables and hydrogen.
- The next few hours will describe how such a transition is made possible.
- First of all we need to understand the nature of hydrogen:

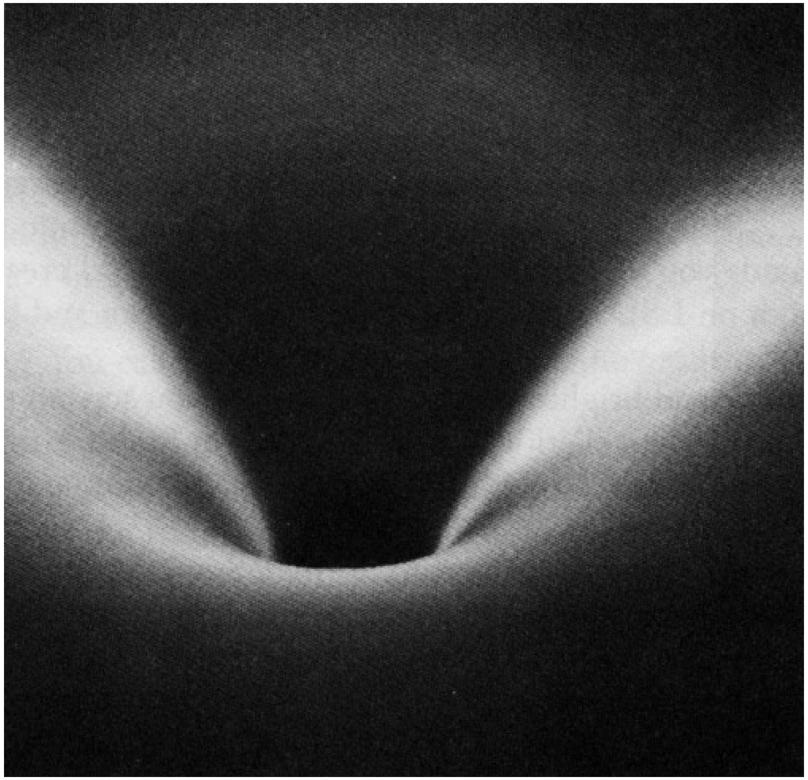
Hydrogen
The energy carrier of the future

Thorsteinn I. Sigfusson
Professor of Physics University of Iceland
CoChair of International Partnership for the Hydrogen Economy

This talk is about:

- Part I: Origins and nature of hydrogen
- Part II: Production of hydrogen
- Part III: Storage and Utilization of hydrogen

The world just before Big Bang: The dawn of time

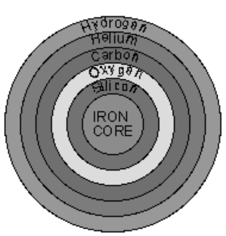


- The Eddas of Snorri Sturluson describe some of the oldest accounts of the origins of our universe, the view of Norse Mythology
- The Eddas described the initial VOID called Ginnunga-Gap
- Out of this void the world appeared

The Sun was the first Hydrogen container in our part of the world!

- The Sun was formed 4.6 billion years ago and is fuelled by Hydrogen which fuses into Helium and sending out energy from the "burning" of 600 million tonnes of Hydrogen every second

- Stars are the initial phase of a cosmic element factory for producing ever higher mass elements.....

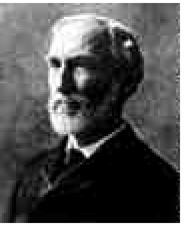


Academia has known Hydrogen for a long time

- In 1671 Robert Boyle described the chemical properties of Hydrogen
- 1776 Hydrogen was isolated by Henry Cavendish
- 1843 William Grove discovered the Fuel Cell
- Lavoisier gave Hydrogen its name!

$$H_2$$

Energy Paradigm Shift: Gibbs energy era replaces the Carnot energy era



In the latter half of the 20th century solid electrolytes were developed and a new “Gibbs Free Energy Era” emerged from the classical “Carnot Era”

Combustion - as directed by the fossil burning humans – was in principle replaced by a much more sophisticated “direct conversion of hydrogen to electricity” in accordance with Grove´s invention

Fuel Cells get much more work out of hydrogen than do combustion engines

- On one hand combustion engines can only yield useful energy, work or exergy, out of the fuel within the limitation of Carnot´s law

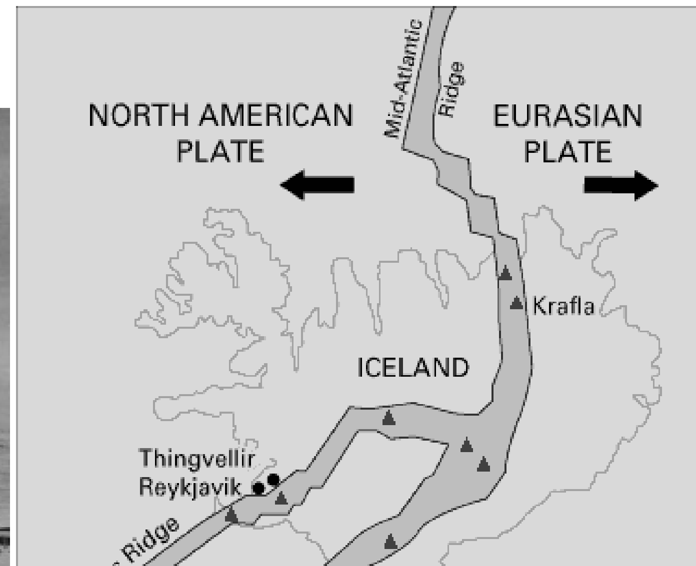
- On the other hand, fuel cells can yield more exergy out of hydrogen fuel because they obey Gibbs Free Energy

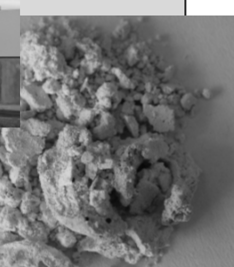
Free hydrogen escapes from Earth and is only rarely found in the molecular state on Earth

- The exemption is for example found in Iceland…..

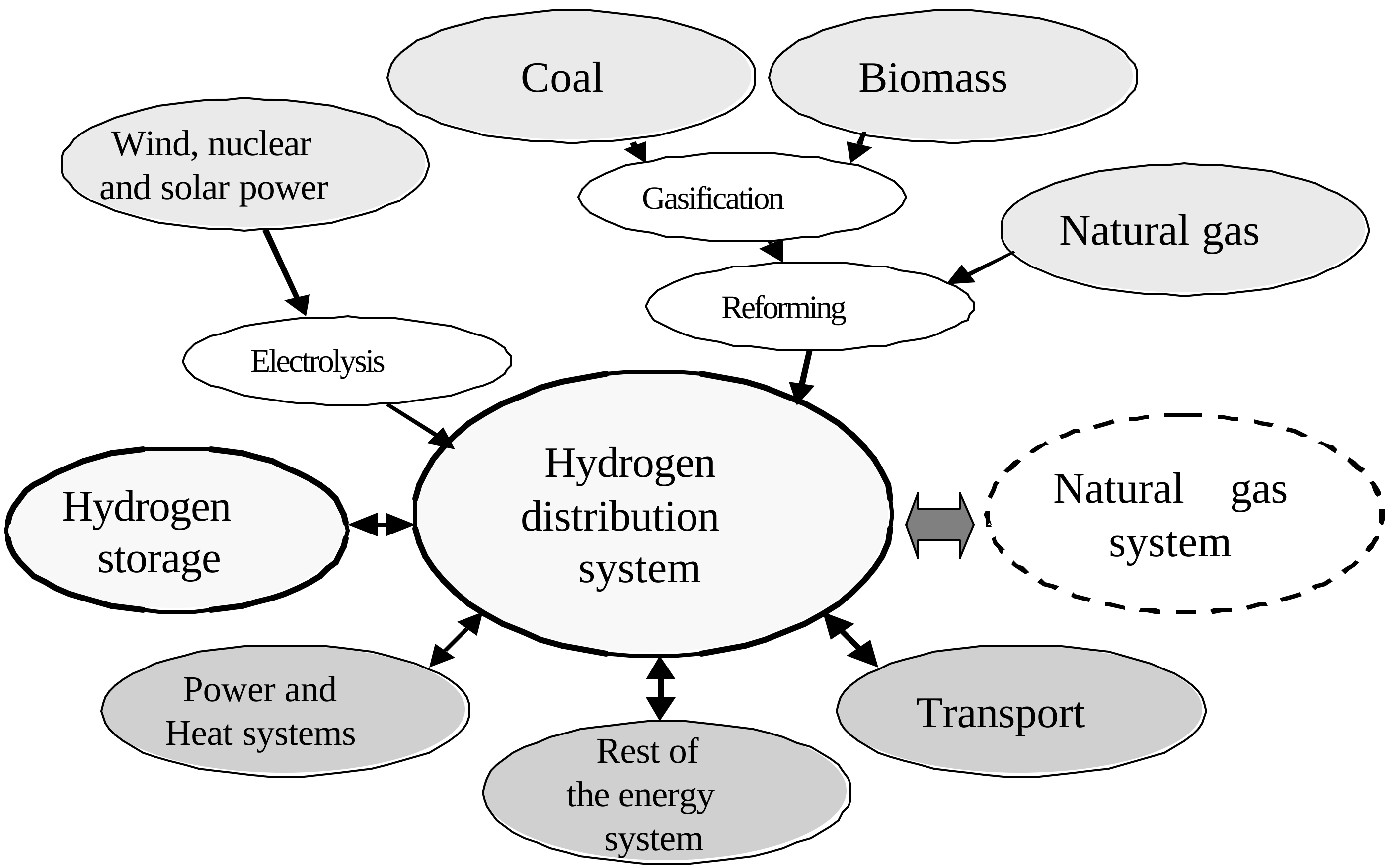
The Mid-Atlantic Ridge divides Iceland; the country drifts apart by an inch a year. Magma fills the void. There are boreholes in Iceland bleeding up to 50 tonnes of molecular hydrogen annually.

Geothermal Vents Along the Terrestrial Section of the Mid-Atlantic Ridge at the Bjarnarflag Geothermal Field, Near the Krafla Volcano, Northern Iceland…



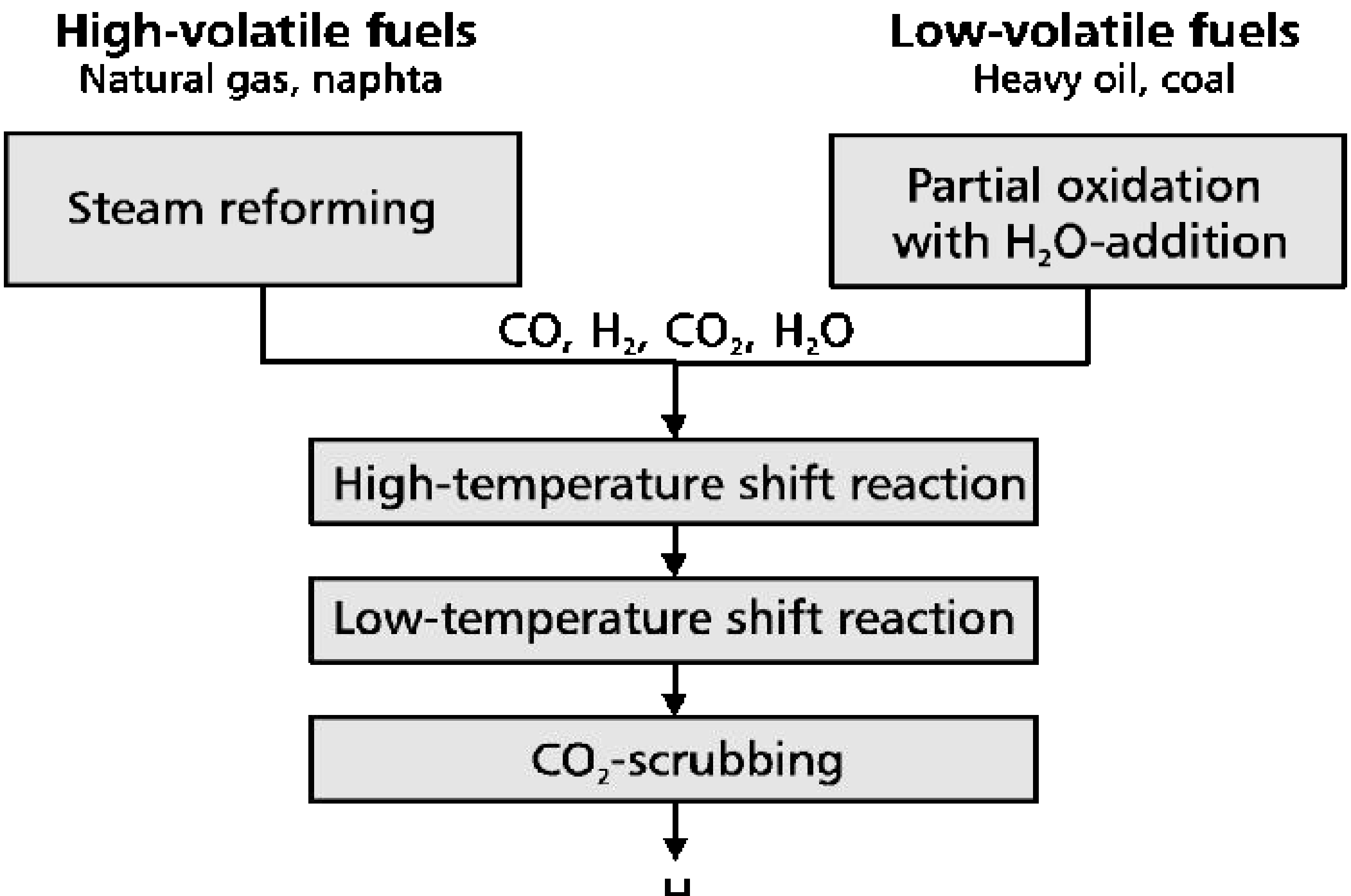


Hydrogen as an energy carrier needs primary energy sources and thus defines a link in an energy chain:
The world production exceeds 50 million tonnes annually.



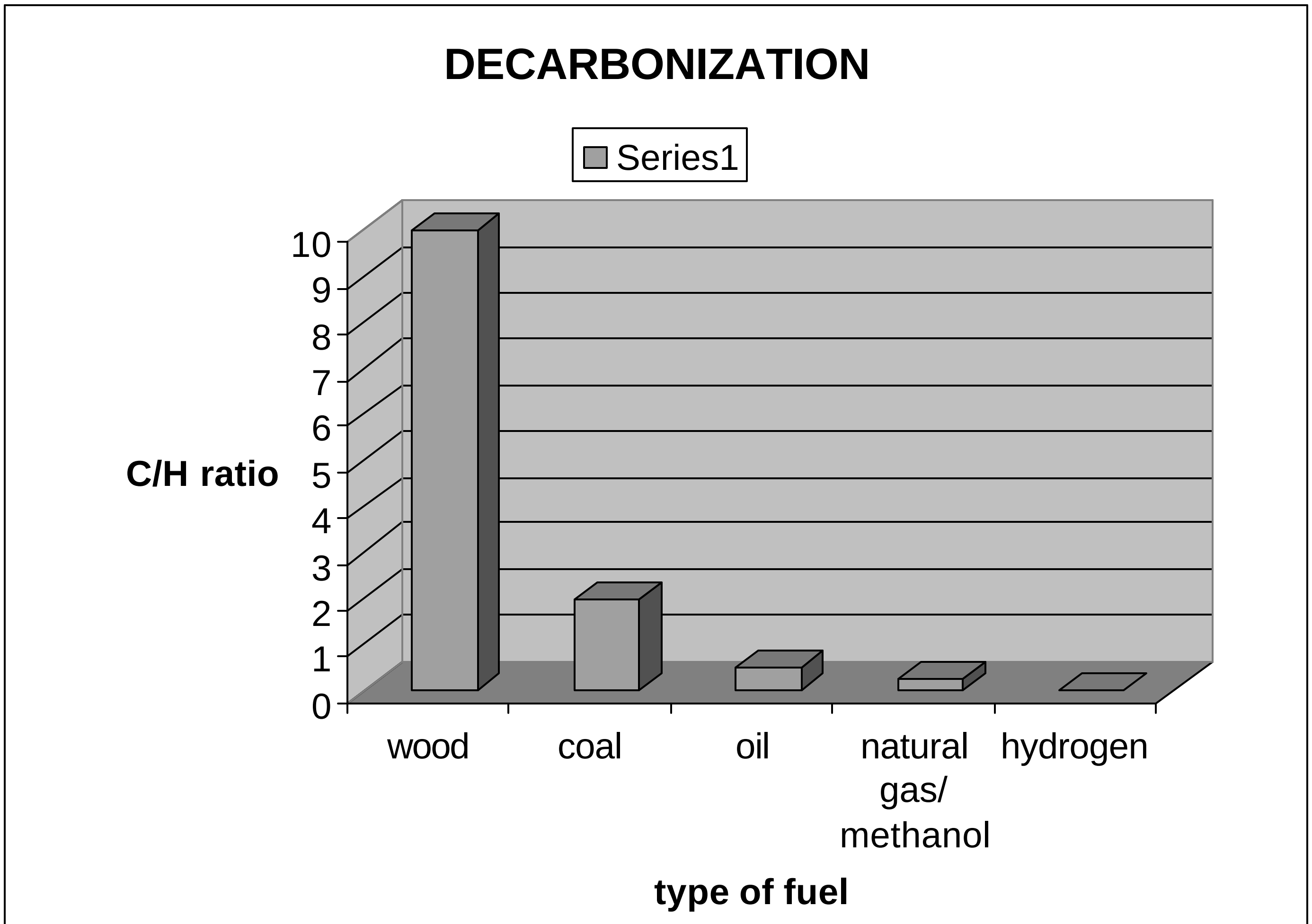
Primary Method	Process	Feedstock	Energy	Other
Thermal	Steam Reforming	Natural Gas	Heat, possibly from nuclear power plants	70% efficient. Will require carbon sequestration
	Thermochemical Water Splitting	Water	High temperature heat from advanced gas-cooled nuclear reactors	No emissions
	Gasification	Coal, Biomass	Steam and oxygen at high temperature and pressure	Some emissions. Will require carbon sequestration
	Pyrolysis	Biomass	Moderately high temperatures steam	Some emissions. Will require carbon sequestration
Electrochemical	Electrolysis	Water	Renewables, including wind and solar, and electricity	Some emissions depending on source of electricity
	Photoelectrochemical	Water	Direct sunlight	Minor emissions
Biological	Photobiological	Water and algae strains	Direct sunlight	No emissions
	Anaerobic Digestion	Biomass	High temperature steam	New, undeveloped technology
	Fermentative Micro-Organisms	Biomass	High temperature steam	New, undeveloped technology

Steam reforming or gasification of fossil fuels, schematic

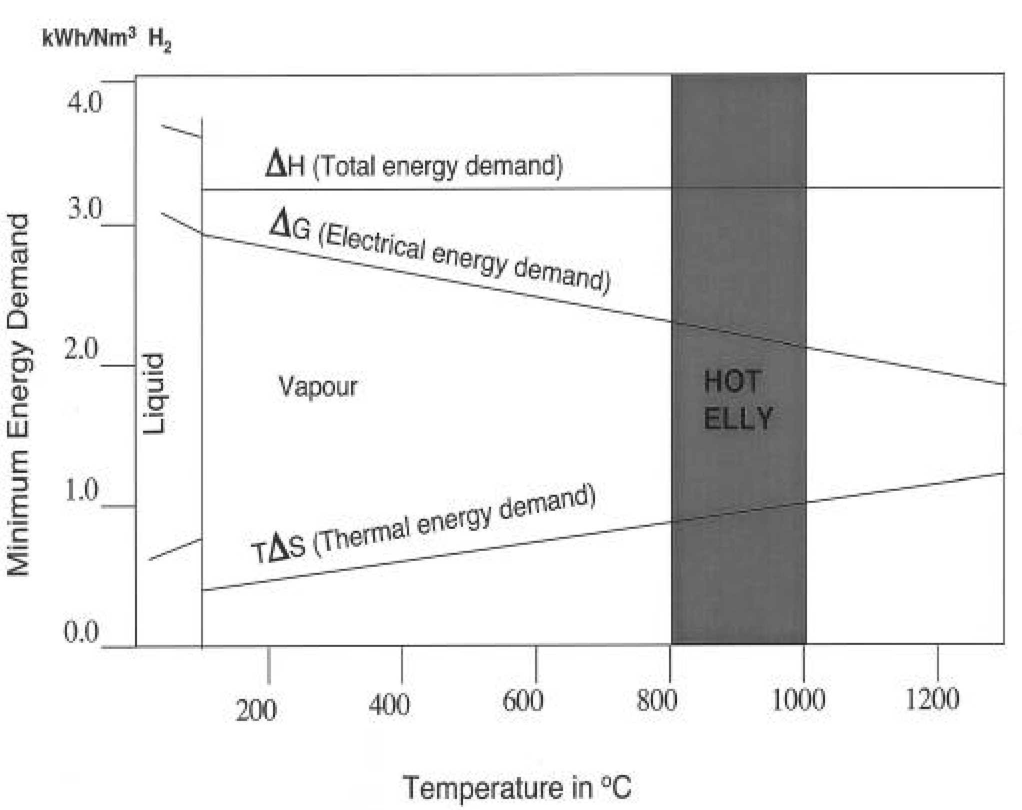


- Sulphur is a catalyst poison, it needs removal prior to the process start
- All processes are endothermic, heat provided alothermically or autothermically
- The significant difference of dissimilar processes is shown in the first process step

Decarbonization The ratio of C/H atoms in carbohydrides approaches zero in energy utilization



Minimum Energy Needed to Split Water



Energy changes for splitting water, either in liquid or gaseous phase, are given by the thermodynamic equation.

? H = ? G + T? S

? H: The enthalpy change or total energy demand
? G: The Gibbs free energy or the minimum work
T: The absolute temperature
? S: The entropy change

The term T? S can be considered as the total amount of thermal energy needed to split water.

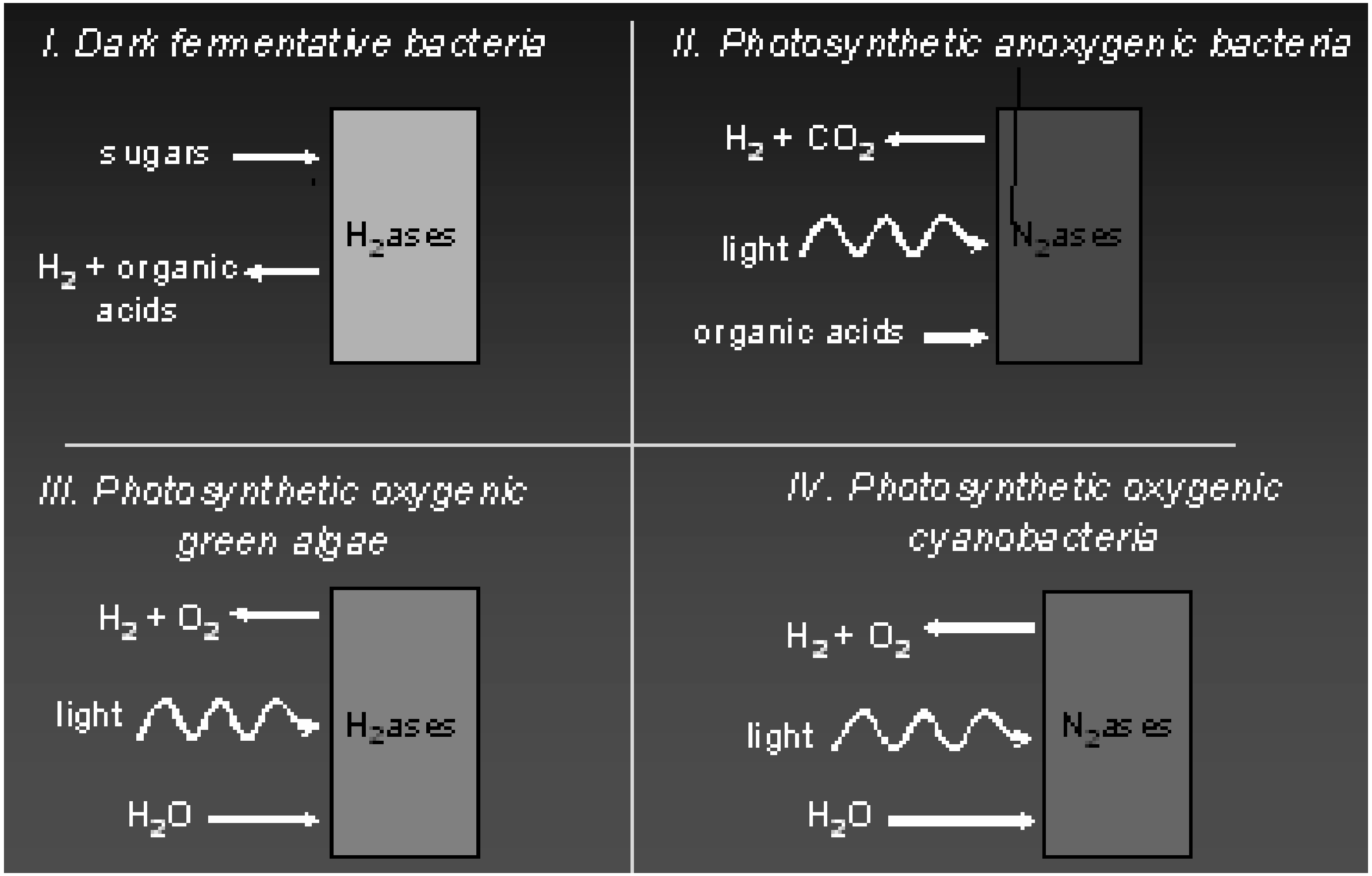
- As can be seen from the figure the total energy demand for water splitting is lower in the vapour phase than in the liquid phase by the amount of the energy of vaporisation.
- The minimum electrical energy demand needed to split water decreases with increasing temperature. The thermal energy demand increases with increasing temperature.

Development successes in the past year

- Cost of natural gas-based hydrogen production has been reduced from $5.00 per gallon gasoline equivalent down to
- $3.60 using innovative reforming and purification technologies

- Goal is still $2-3 per gallon gasoline equivalent!
- DoE USA

Biological Pathways to Hydrogen



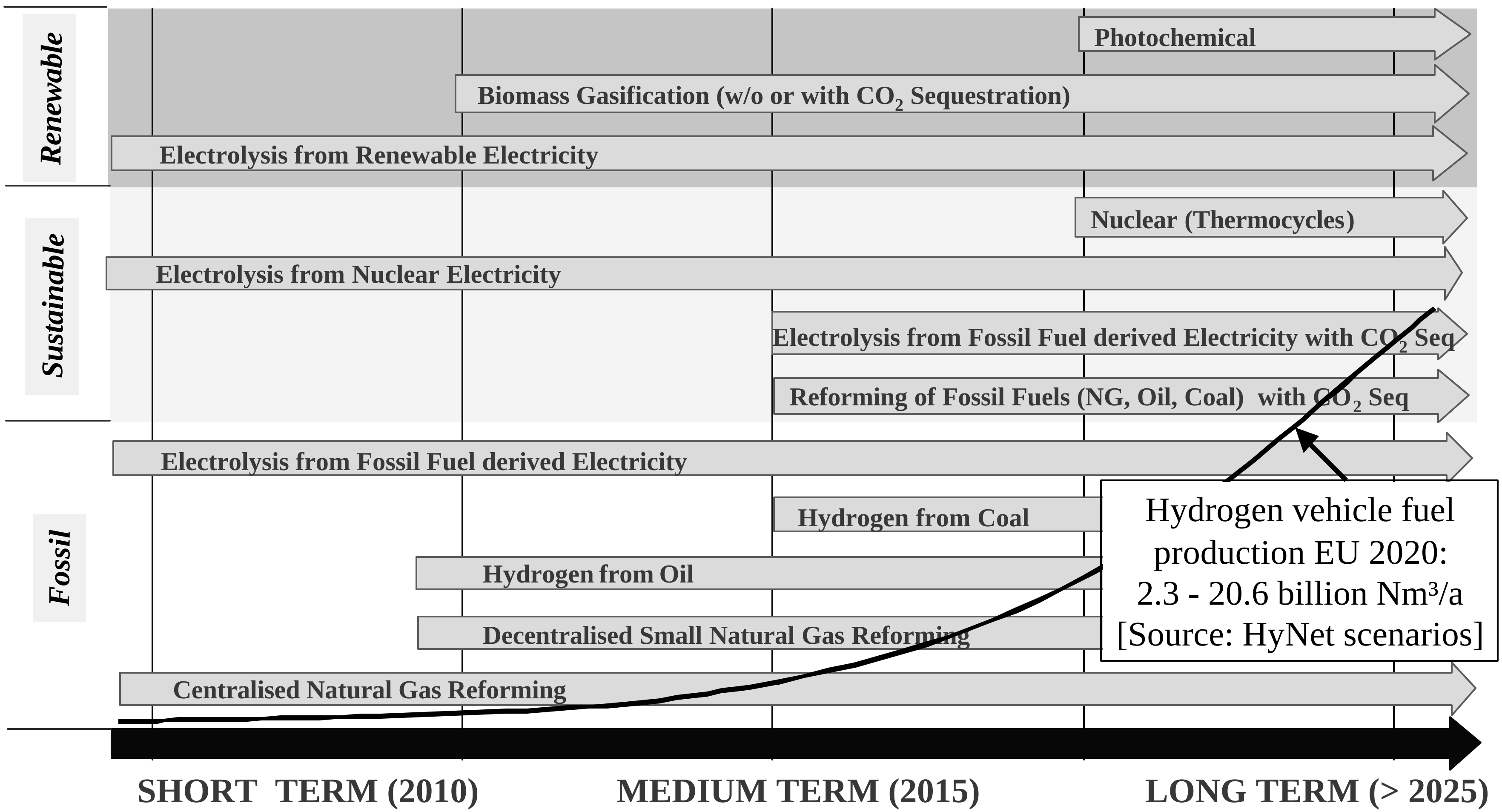
Source: NREL

HydroCarbons on Earth originate from processes kindled by sunlight

- Possibilities for artificial production of hydrogen by the use of sunlight:

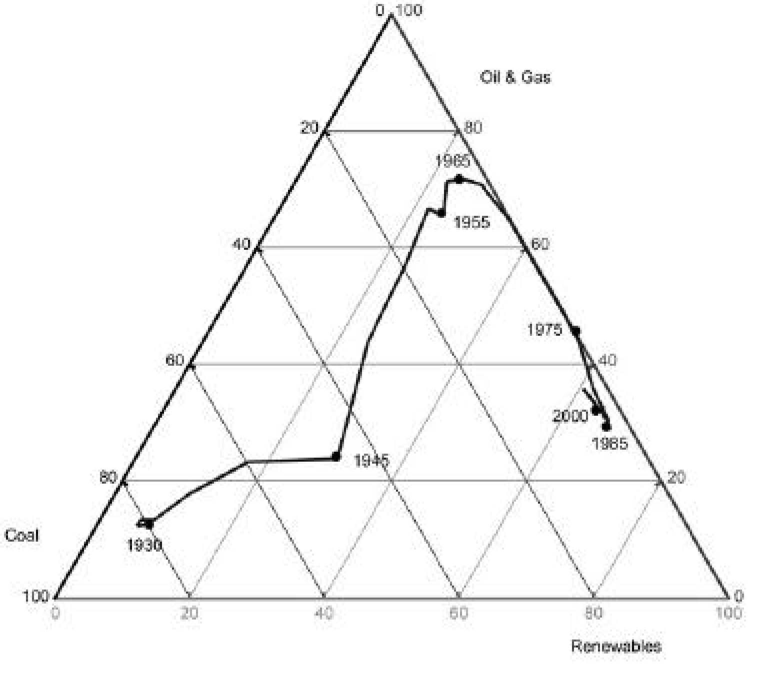
- **Photochemical methods**
- **Photoelectrochemical methods**
- **Photobiological methods**

Multidude of future scenarios and pathways



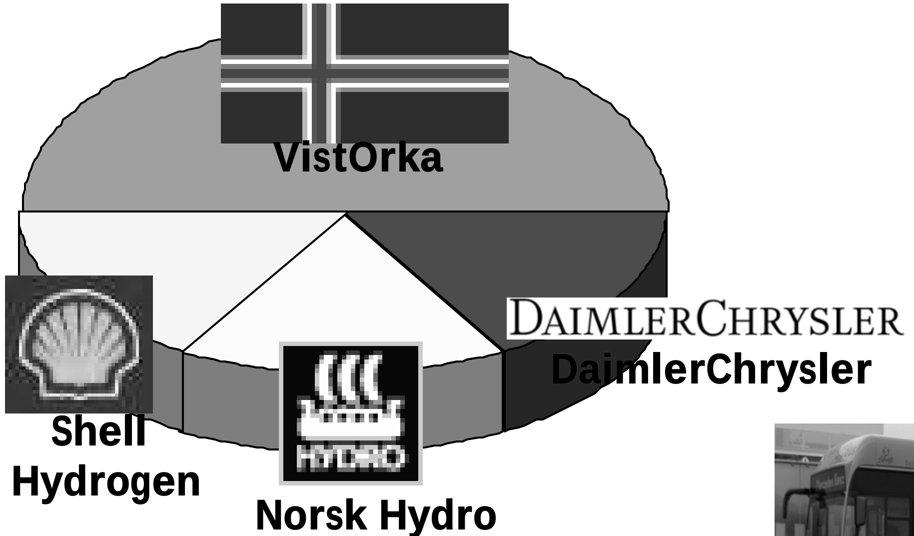
Example of renewable hydrogen potential: Iceland

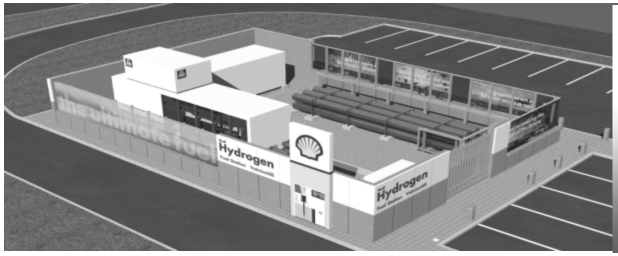
- The highest ratio of renewable energy in any country of the world is in Iceland where it amounts to about 71%.
- The renewable energy comes from hydroelectric as well as geothermal sources.
- The only remaining main no-renewable sector in Iceland is transport/ fishing and some of the industries
- The Icelandic government has an aim to create a hydrogen economy in Iceland

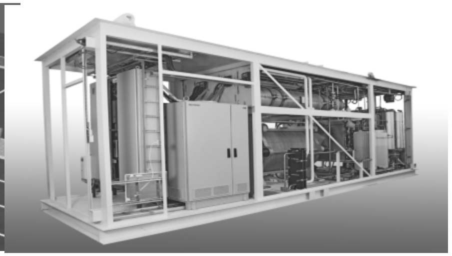


Unique Icelandic New Energy

Public Private Entity to build the Hydrogen Economy







Part II: Hydrogen storage

Hydrogen storage criteria

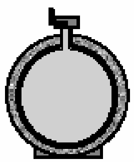
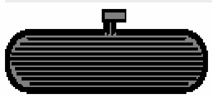
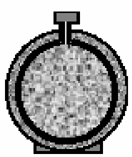
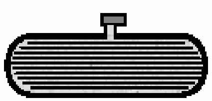
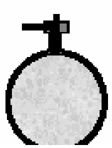
- We need to pack the Hydrogen as close as possible
- and use as little additional material as possible
- this means reducing an enormous natural volume of Hydrogen gas

Hydrogen requires large space

- A kilogramme of Hydrogen in gaseous state requires about 11 cubic metres of space
- We have a few options:

- We can apply work to compress it
- We can lower the temperature and liquefy the gas
- Or we can reduce the repulsion by letting the H-atoms interact with another material

Hydrogen storage media

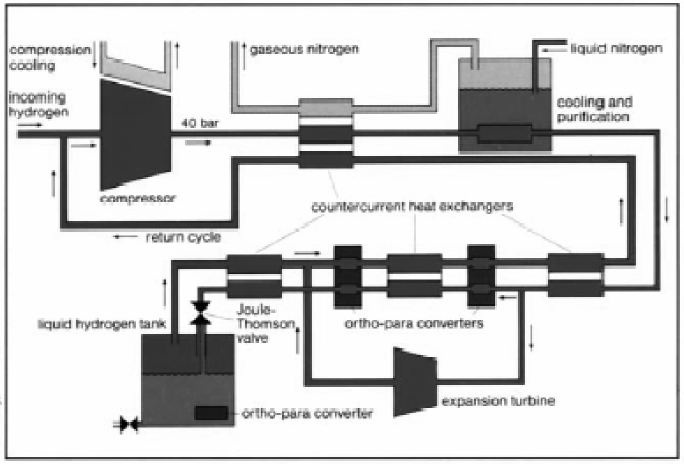
Storage Media	Volume	Mass	Pressure	Temperature	
	max. 33 kg $H_2 \cdot m^{-3}$	13 mass%	800 bar	298 K	Composite cylind.
					established
	71 kg $H_2 \cdot m^{-3}$	100 mass%	1 bar	21 K	Liquid hydrogen
	max. 150 kg $H_2 \cdot m^{-3}$	2 mass%	1 bar	298 K	Metalhydrides
	20 kg $H_2 \cdot m^{-3}$	4 mass%	70 bar	65 K	Physisorption
	150 kg $H_2 \cdot m^{-3}$	18 mass%	1 bar	298 K	Complex hydrides
					reversibility ?
	>100 kg $H_2 \cdot m^{-3}$	14 mass%	1 bar	298 K	Alkali + H_2O

High pressure gas storage

- Cylinders about 20MPa
- up to 80 Mpa where Hydrogen reaches volumetric density of 36 kg/m^3
- ASI 316 and 304 steels

Liquid Hydrogen

LIQUID HYDROGEN



Claude process for liquefying hydrogen

75% Orthohydrogen | Energy

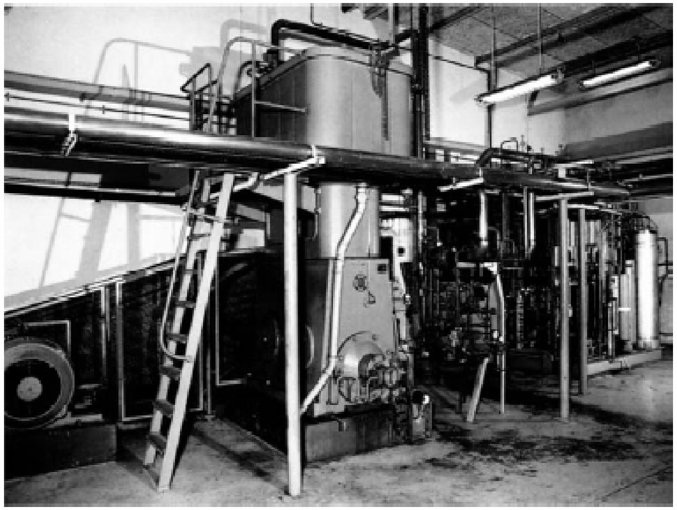
at RT

25% Parahydrogen

Energy use for liquefaction:
W_{th} = 3.92 kWh·kg^{-1}
W_{prac} = 10 kWh·kg^{-1}

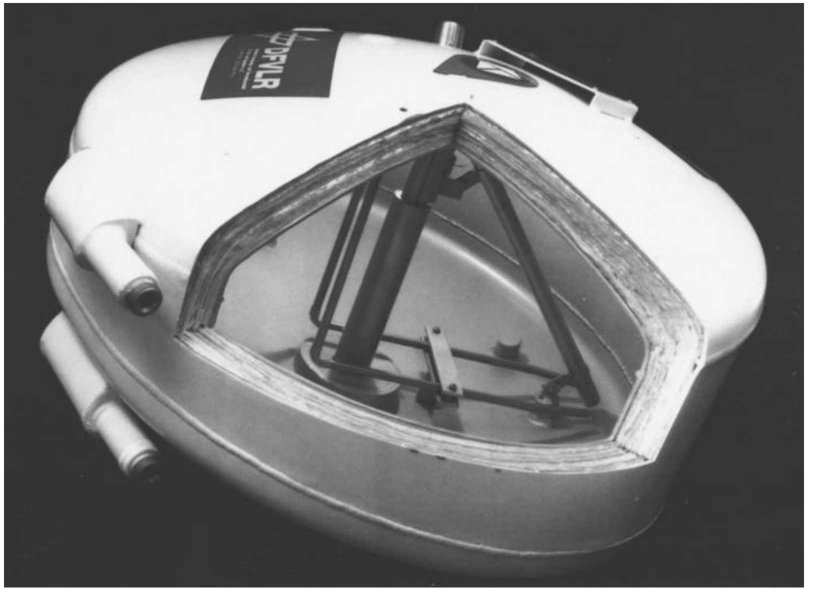
Density (H_2 liq.) = 70.8 kg·m^{-3}

Plant for liquefying hydrogen (Linde)

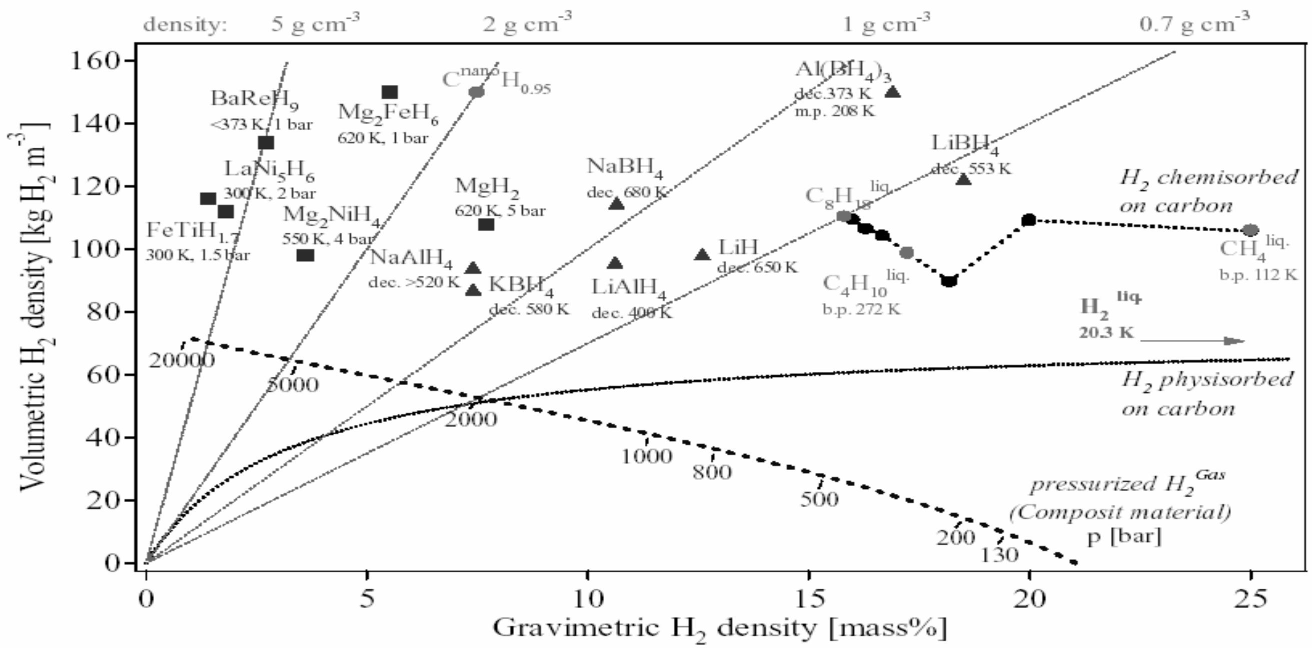


One of the first l-H tanks

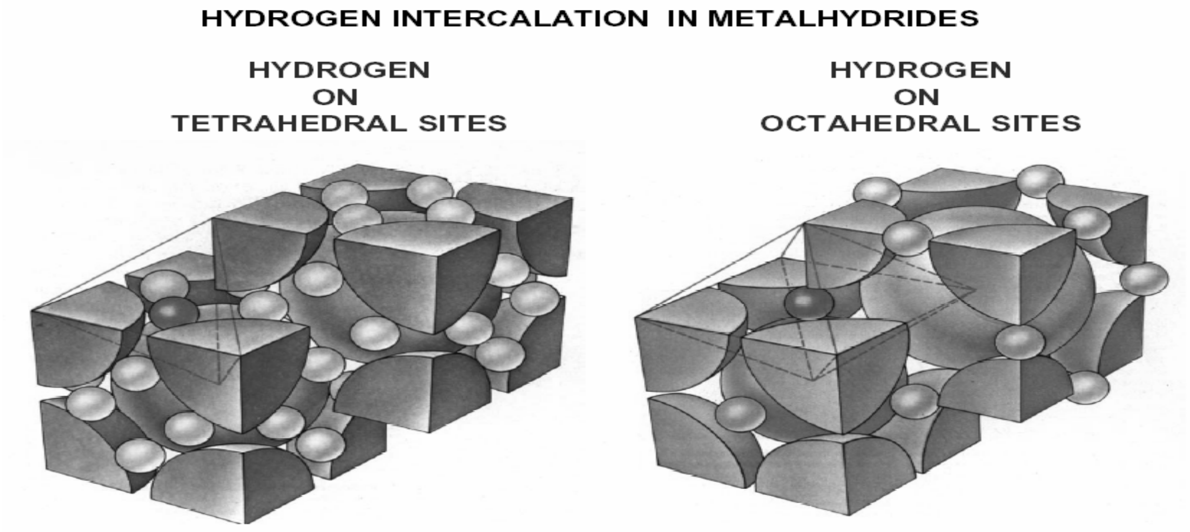
- 130 litres



STORING HYDROGEN IN COMPOUNDS (Zuettel)

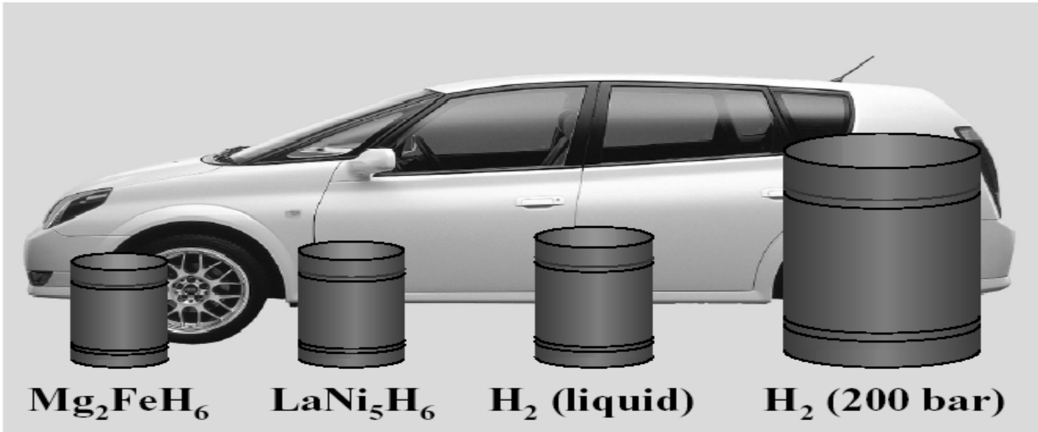


Hydrogen finds its place



Fuel takes up space!

4 kg hydrogen = 560 $MJ_{therm.}$

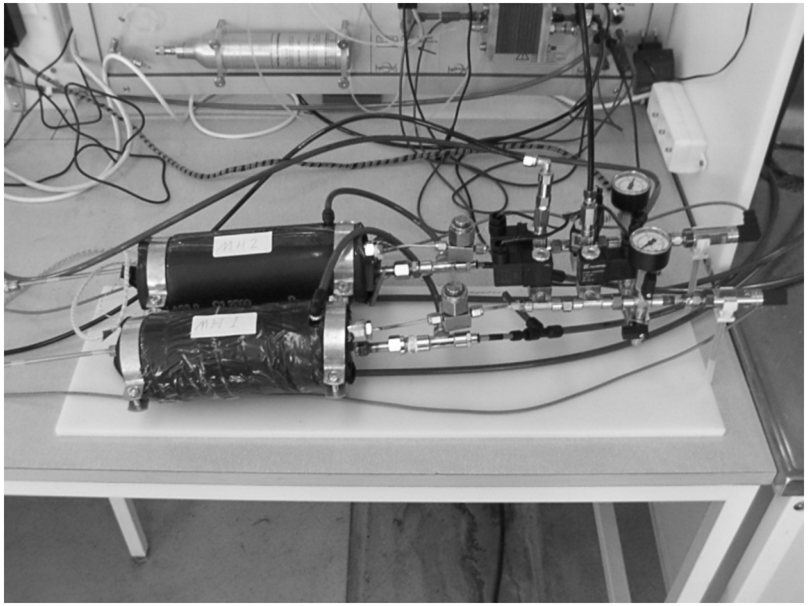


3 l gasoline / 100 km = 9 $kWh_{mech.}$ / 100 km = 32 $MJ_{mech...}$ / 100 km

Ref.: Louis Schlapbach & Andreas Züttel, NATURE | VOL 414 | 15 NOVEMBER 2001 | pp. 353-358

Geothermally Operated Hydrogen Compressor

- This metal hydride-based compressor was designed and constructed as a joint effort between the University of Iceland and Varmaraf ehf. This device is capable of pressurizing hydrogen gas up to 10 bars and is intended to represent a component of a proposed hydrogen fueling station. Hallmar Halldorsson and Thorsteinn I Sigfusson

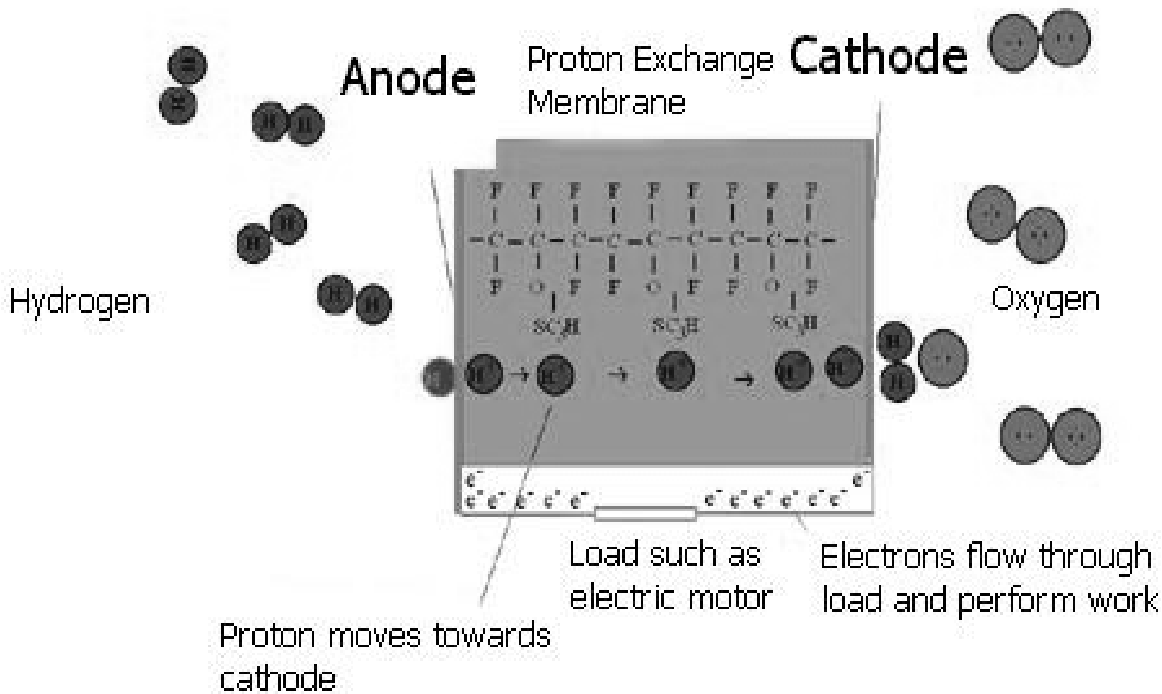


What is a fuel cell?

- An electrochemical device that converts hydrogen and oxygen into water producing electricity and heat.

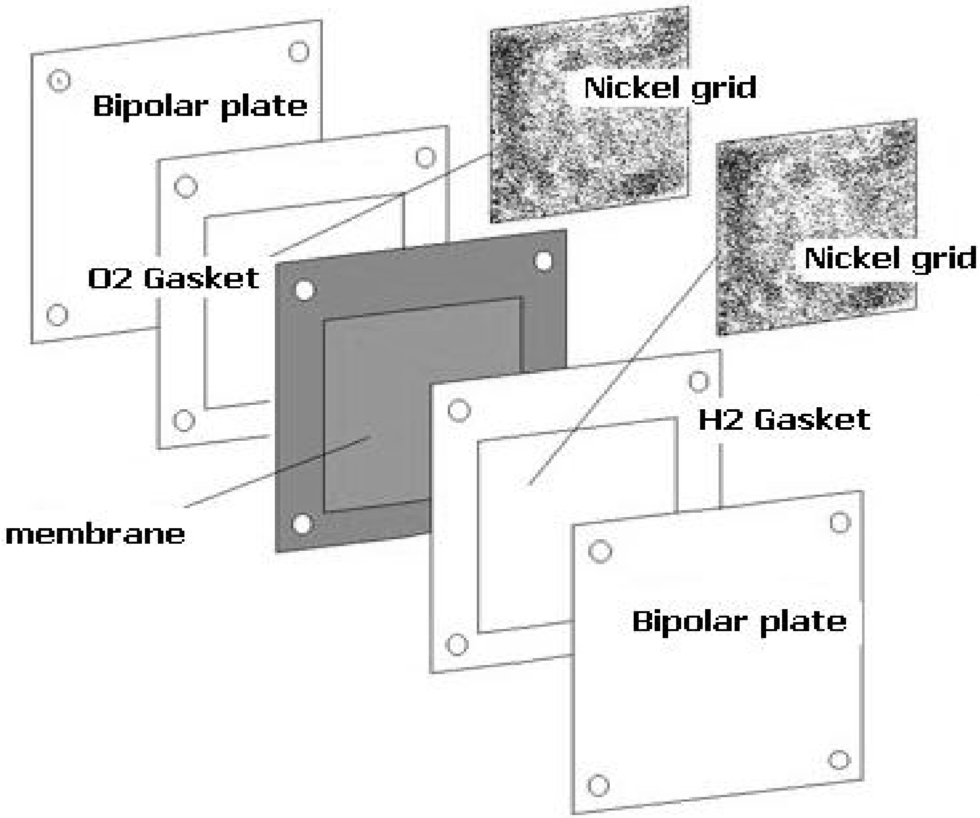
- Unlike battery a fuel cell needs the fuel and the oxidiser; batteries have them inside.

PEM Fuel Cell Basics



Visindavefurinn, University of Iceland Science Web -Sigfusson 2002/3

Elements of a basic PEM sandwich



"Build your own fuel cell" T. I. Sigfusson, UI, Science Web. Visindavefurinn 2002/3

SOFC characteristics

- Use hard, non-porous ceramic compound as electrolyte. Since electrolyte is solid, cells do not have to be constructed in plate-like configuration typical of other fuel cell types.
- Around 50-60% efficient at converting fuel to electricity. If capture and utilize system's waste heat (co-generation), overall fuel use efficiencies could exceed 80-85%.
- Operate at around 1,000 °C
- High temperature operation removes need for precious-metal catalyst, reducing cost.

Also allows SOFCs to reform fuels internally, enabling use of variety of fuels and reduces cost of reformer.

- Are most sulfur-resistant fuel cell type; Can tolerate several orders of magnitude more sulfur than other cell types.
- Are not poisoned by carbon monoxide (CO), which can even be used as fuel. This allows SOFCs to use gases made from coal.

SOFC Materials

- $Co\text{-}ZrO_2$ or $Ni\text{-}ZrO_2$ (anode) and
- Sr-doped $LaMnO_3$ (cathode)
- Two geometries:
- tubular - array of meter-long tubes
- compressed disc
- Large high-power applications (electricity
- generating stations)

Fuel Cell Energy Systems

Life Cycle Analysis

INPUT	UTILIZATION	OUTPUT
System manufacture Precious Metals Organic Polymers Ceramics Metals e.g. Ni Cu Fe Alkali carbonates Phosphoric acid	Fossil fuel e.g. natural gas Water Purification filters Site location Maintenance materials and costs Stack replacement Electrical power Noise CO2 and gas emissions	Disposal phase Precious metals Organic Polymers Ceramics Metals Alkali carbonates Phosphoric acid

Utsira: the island off the coast of Norway 250 inhabitants - Wind/Hydrogen FC

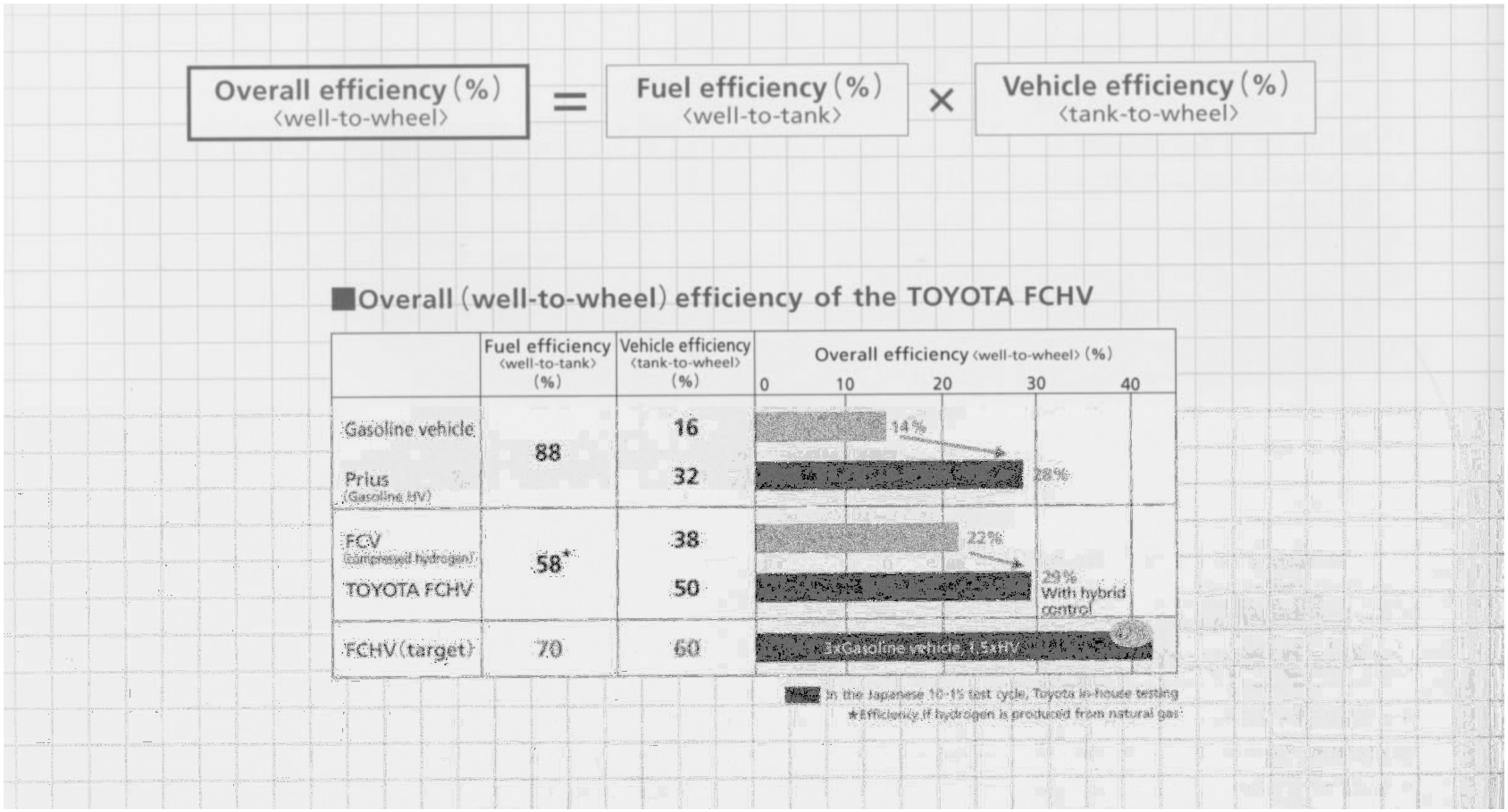
The combination of wind power and hydrogen
The idea is to use the excess energy from the windmills to produce hydrogen. Hydro's particular solution for Utsira is to erect a windmill that will be linked to a hydrogen production unit.

Hydrogen is produced by means of an electrolyser delivered by Hydro Electrolysers. Hydrogen is then used to produce electricity when wind cannot be used. To begin with a hydrogen-run generator will produce the additional electricity, but in the spring of 2004 a fuel cell will be installed which will provide electricity directly from hydrogen.

The energy plant shall be ready in January 2004. The digging work will start in June, and the two windmills will be built during August this year. The hydrogen plant will then be completed during the autumn.

NORSK HYDRO PROJECT

Toyota FCHV
Well-to-wheel as advertised



	Fuel efficiency ⟨well-to-tank⟩ (%)	Vehicle efficiency ⟨tank-to-wheel⟩ (%)	Overall efficiency ⟨well-to-wheel⟩ (%)
Gasoline vehicle	88	16	14%
Prius (Gasoline HV)		32	28%
FCV (compressed hydrogen)	58*	38	22%
TOYOTA FCHV		50	29% With hybrid control
FCHV (target)	70	60	3xGasoline vehicle, 1.5xHV

In the Japanese 10-15 test cycle, Toyota in-house testing

*Efficiency if hydrogen is produced from natural gas

In the next talks we will examine projects with hydrogen in Iceland and China and the world a a whole

- Thank you for your attention