Hydrogen – A zero-carbon energy vector for a change of energy systems management paradigm

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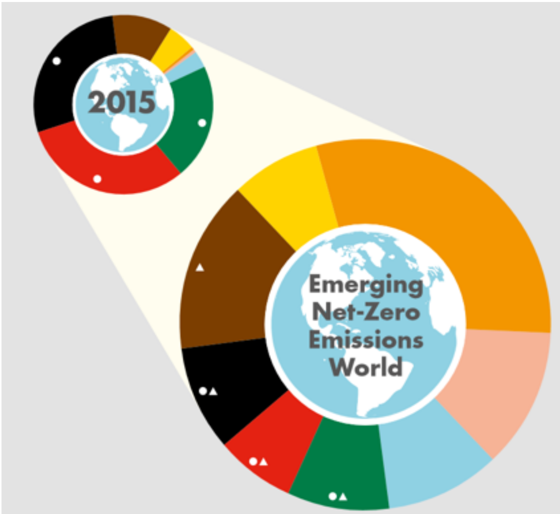
Outline

- Introduction
  - Hydrogen – a carbon-free energy vector
  - Why “hydrogen economy”?
- Hydrogen value chain
  - Production
  - Storage and transport
  - End uses
- “Hydrogen territories”
- Conclusion

Limiting temperature increase well below 2°C requires net-zero emissions in 2050

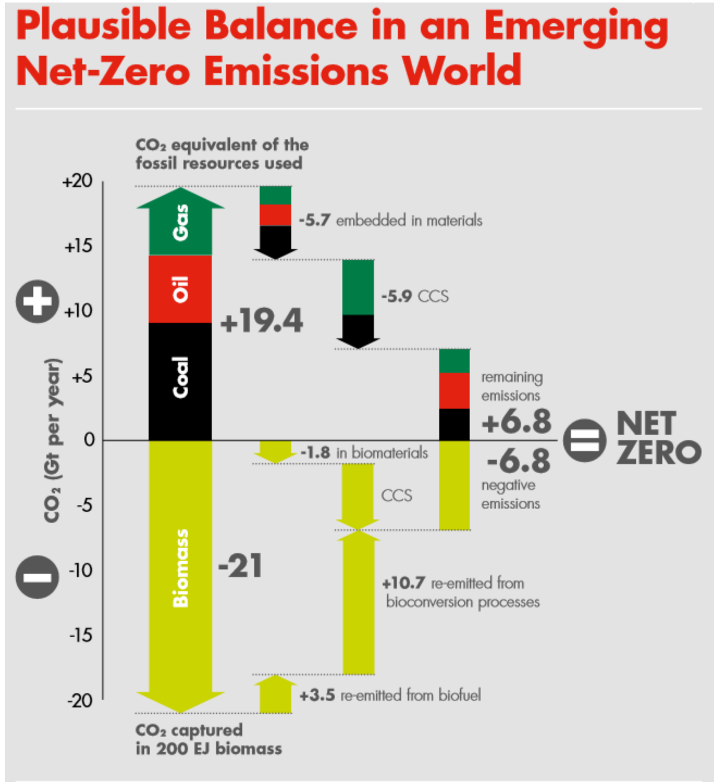
The energy system will likely double over the century

Carbon budget: ~1000 Gt
Carbon lock-in: 4/5



Net-zero emissions in 2050 requires:

- CCS (10Gt)
- « negative emissions » (6,8Gt)
- 50% electrification of end use



Fossil — With Carbon Capture and Storage — Approximately 50% electrification of end use.

ENERGY SOURCE	GAS	OIL	COAL	BIOENERGY	NUCLEAR	SOLAR	WIND	OTHER
2015	21%	31%	28%	11%	5%	0.5%	0.5%	3%
Net-Zero emissions world	9%	7%	9%	15%	8%	30%	12%	10%

For a world with widespread prosperity, the energy system will double over the course of this century.

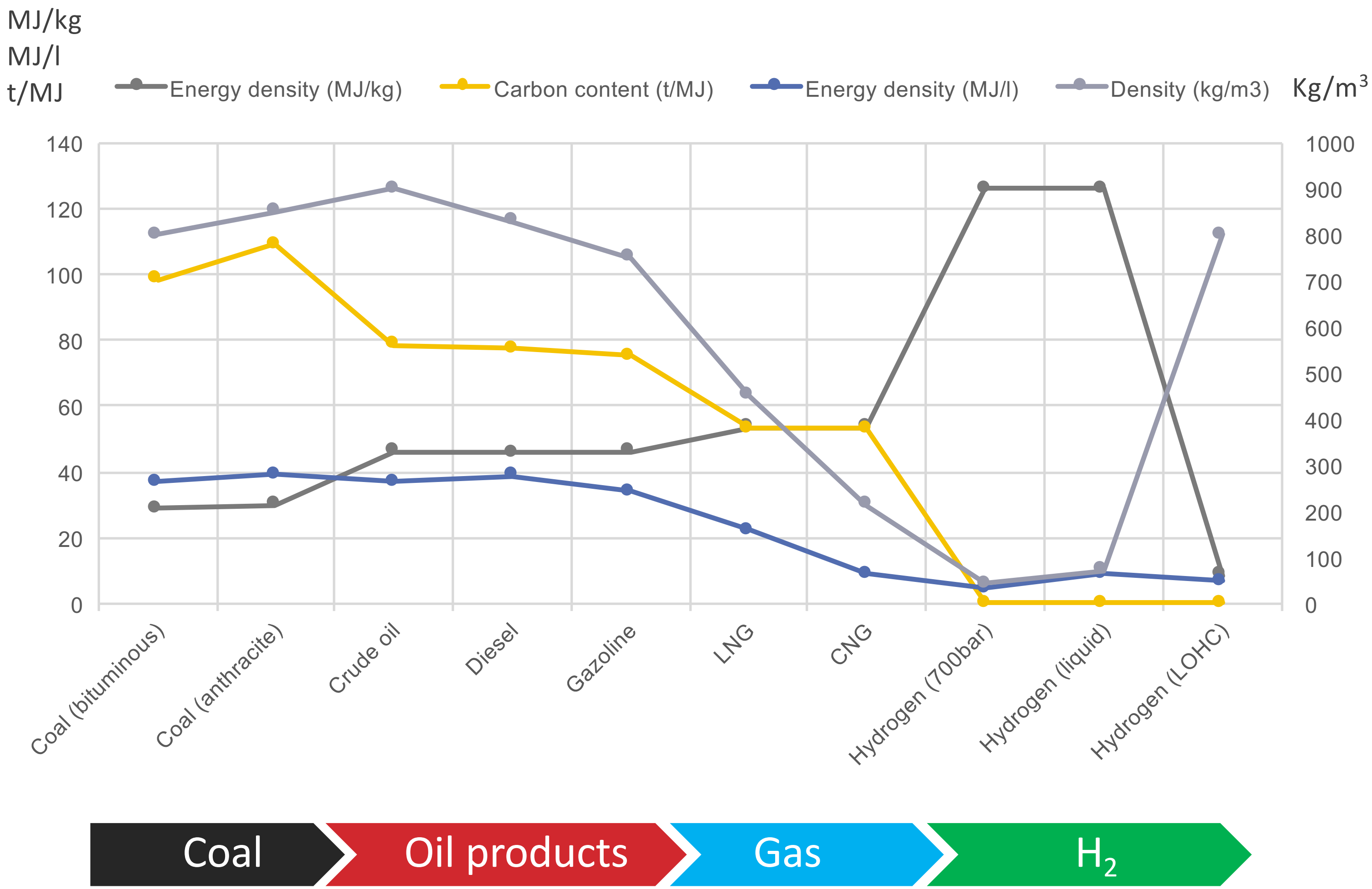
Source: Shell analysis

Hydrogen can play a significant role

- To improve integration of renewables and the overall efficiency of the energy system
- To foster the electrification of end use

Hydrogen can compensate for a smaller contribution of CCS (or to further decrease the use of Fossil Fuels for Power)

Hydrogen is a high-energy density carbon-free energy vector in the energy transition

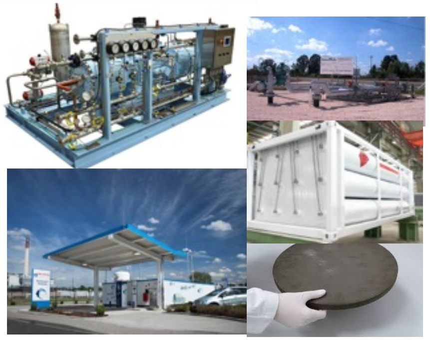


Hydrogen is an carbon-free energy vector with multiple applications (energy storage, end-uses, feedstock…)

Renewable electricity, Natural gas

Hydrogen production (SMR / Electrolysis…)

Conditioning / storage / distribution

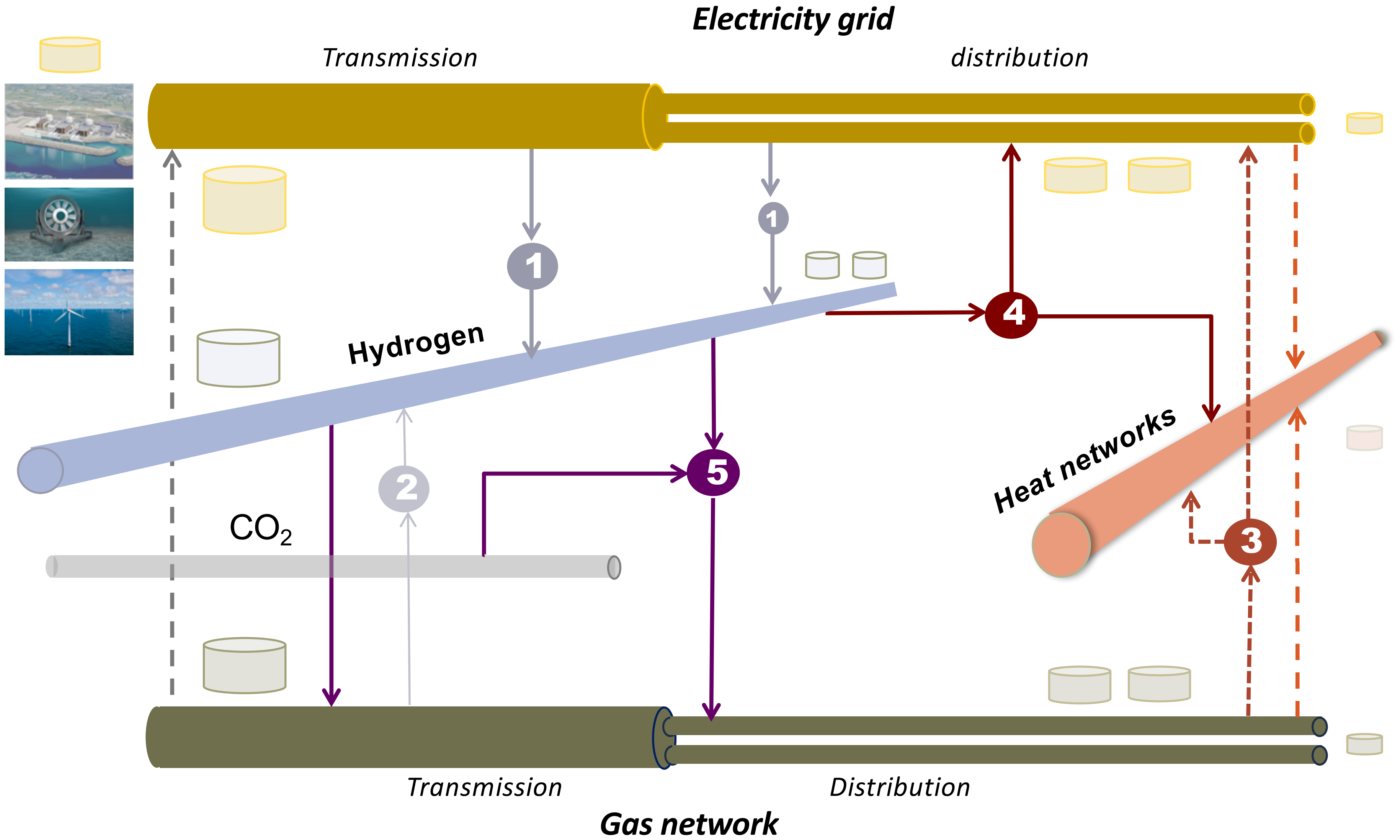


Mobility
(Cars, buses, trucks, ships..)

Heat and electricity production (cogeneration)

Production of chemicals and synthetic fuels

Hydrogen is a mean to couple energy systems, introducing additional degrees of freedom for a global optimization



Hydrogen production through:
1 Water electrolysis
2 Natural gas reforming

Fuel cells using:
3 Natural gas
4 Hydrogen

« Power-to-gas »
5

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Hydrogen is produced from Fossil Fuels (SMR / gasification) or water electrolysis

Production from fossil fuels

- 95% of the world production
- Centralized production
- Industrial customers mainly

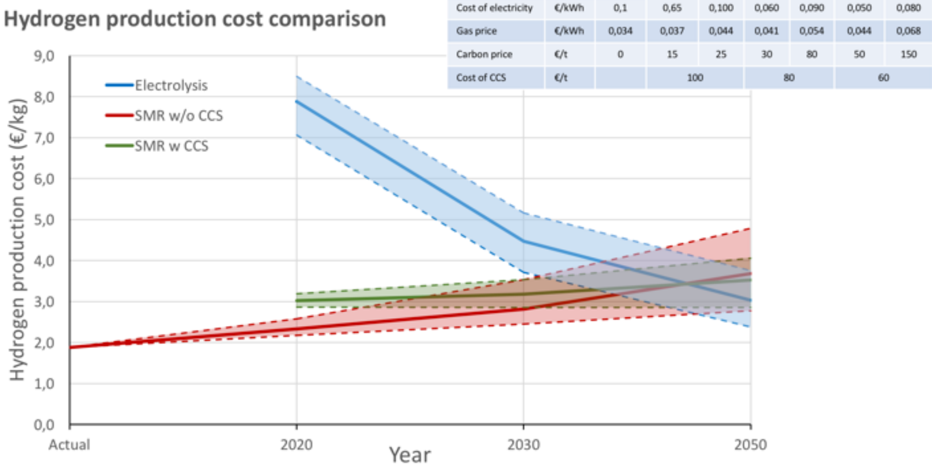
Focus on SMR (Natural gas)

- Production costs: 1,5 to 2 €/kg of H_2
- 9 to 12 t/CO_2 emitted for 1t/H_2 produced

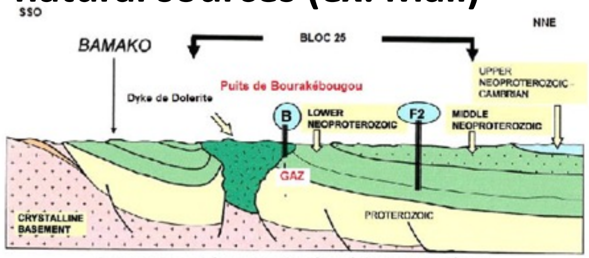
Production from water electrolysis

- 5% of the world production
- Decentralized or centralized production
- Production costs: above 10€/kg of H_2, mainly dependent on electricity price and number of operating hours
- CO_2 footprint depends on electricity carbon footprint

Parameter	Unit	Actual	2020		2030		2050	
			Low	High	Low	High	Low	High
Cost of electricity	€/kWh	0,1	0,65	0,100	0,060	0,090	0,050	0,080
Gas price	€/kWh	0,034	0,037	0,044	0,041	0,054	0,044	0,068
Carbon price	€/t	0	15	25	30	80	50	150
Cost of CCS	€/t		100		80		60	



Hydrogen can also be produced from natural sources (ex: Mali)



Puits de Bourakébougou - Modèle géologique de départ

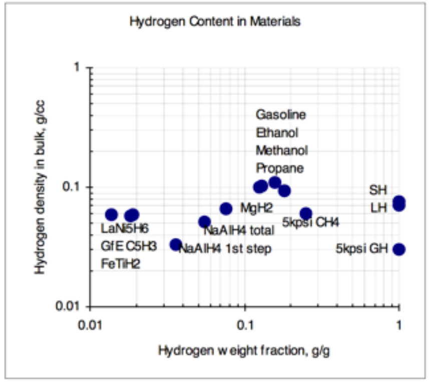
Other production techniques:

Thermochemical cycles

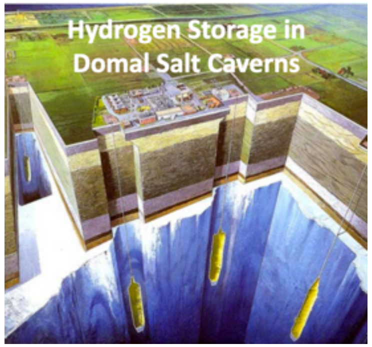
Hydrogen is conditioned and stored for transport and distribution

Hydrogen can be stored in different forms

- Compressed gas
  - 200, 350 or 700 bars
  - Tube trailers / On-going work on high-pressure logistics
- Liquid
  - Cryogenic
  - LOHC
  - Ammonia
- Solid
  - Metal hydrides
  - …



Underground storage for large volumes

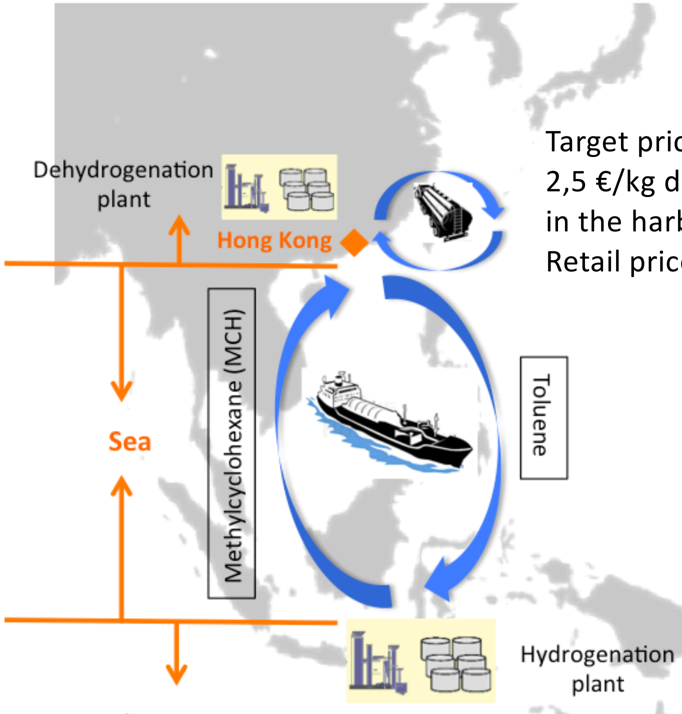


- Stores ~ 92,000 MWh as ~2,500 Mt "working" Hydrogen
- "Full" at 150 bar = 2,250 psi
- Cavern top ~ 700m below ground
- 860,000 cubic meters typical physical volume
- $ 15 M average CAPEX per cavern
- CAPEX= $160 / MWh = $0.16 / kWh

Source leightyfoundation

Hydrogen transportation for imports

Chiyoda H_2 storage & Transportation System by Organic Chemical Hydride method



Target price (2025-2030): 2,5 €/kg delivered in the harbour

Retail price: 6-7 €/kg

Kawazaki
Liquid hydrogen carrier vessel

Hydrogen allows widening applications of electrical propulsion

Technology is commercial

Vehicles
- Utility vehicles
  - HyKangoo – Range extender
- Sedan
  - Hyundai
  - Honda / Toyota
- Buses
  - Van Hool

Refuelling stations

Development of new applications

(trucks, tractors, ships…)

Germany (H2 mobility): 400 recharge stations by 2023

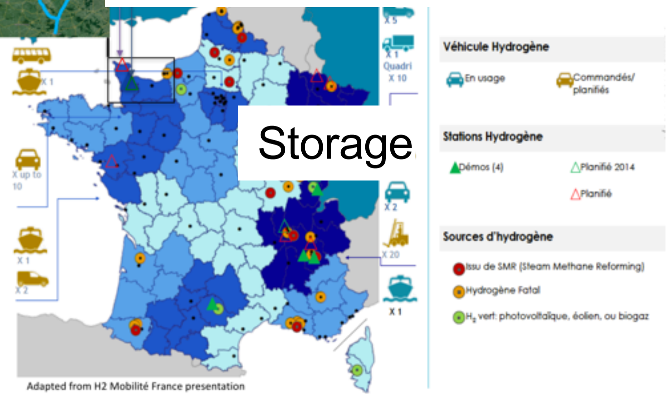
California: 20 stations publicly accessible (2016)

$20 million a year for up to 100 stations

Demonstration / Deployment

Example of Normandy region in France

Recharge stations located on the comprehensive network:
- **15 kg/j (12 stations)**
- **50 kg/j (3 stations)**



Japan: Hydrogen highway in Fukuoka prefecture

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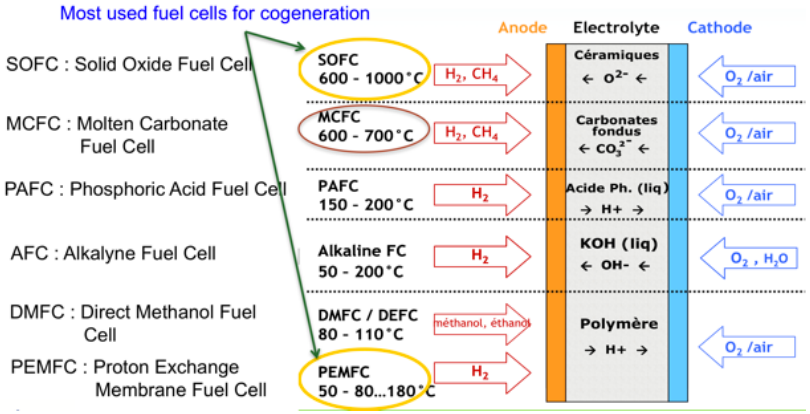
Fuel Cells are used for cogeneration of heat/cold and electricity

Fuel cells used for cogeneration



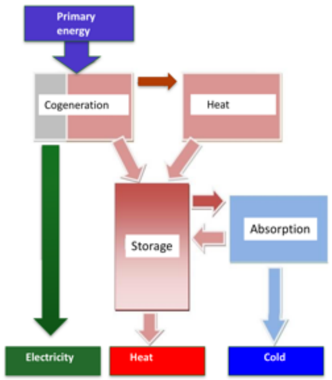
Item	To-date	Target
CAPEX	1600 €/kW	600€/kW
Syst. efficiency	82%	91%
Lifetime	15y	25y

SOEC performance

Coupling with a chiller for trigeneration

(production of electricity, heat and cold)

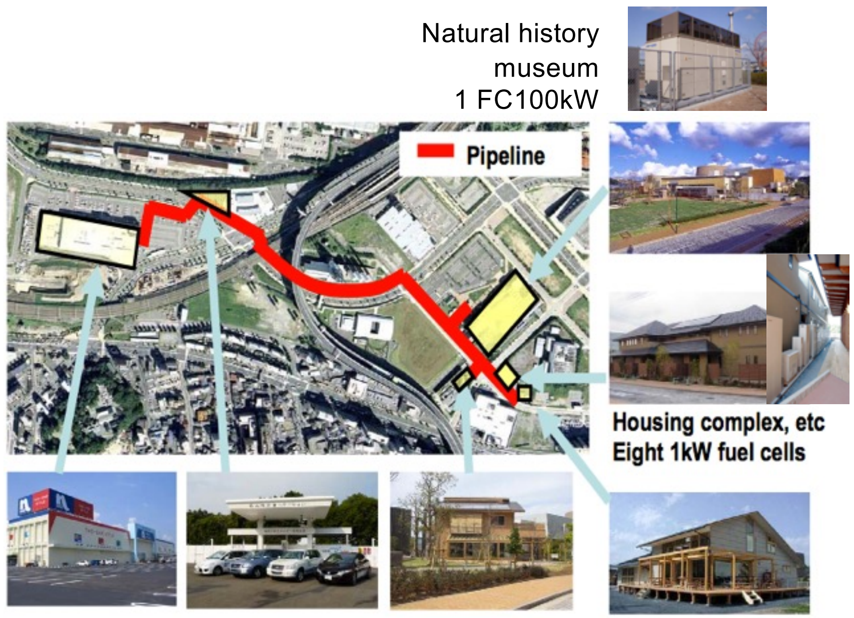
On-going R&D and demonstration



Demonstration

JAPAN

- Kitakyūshū hydrogen town - Fukuoka prefecture
- Hydrogen supplied by a 1,2km pipeline

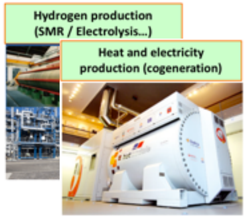


DIY Big Box Store
1 PAC 1kW
Forklifts

Refuelling station
1 FC 3kW

Green House
1 FC 1kW

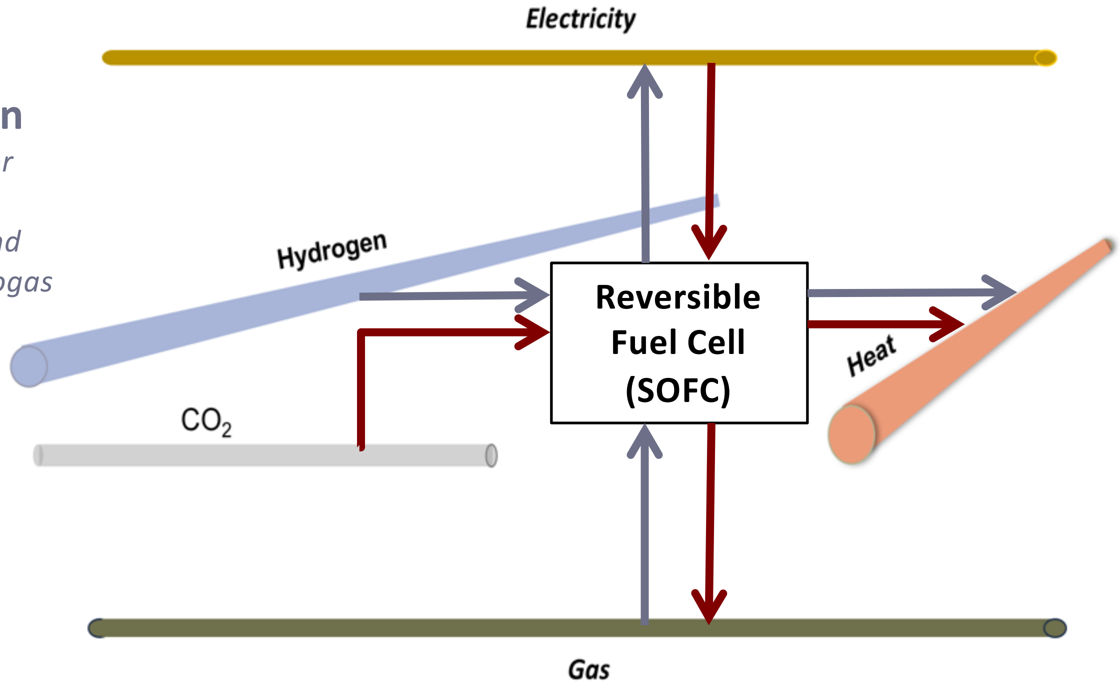
Green Club-house
2 FC 1kW
1 bike



Reversible fuel cells gives flexibility for an optimum management of energy systems

Fuel cell mode: Electrical production

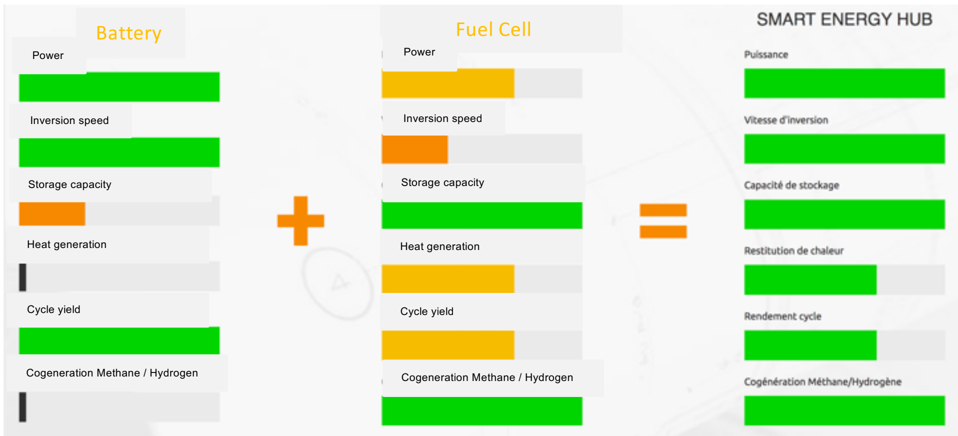
Expensive electricity and/or cheap gas:
Production of electricity and heat from natural gas / biogas or hydrogen



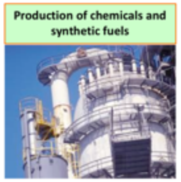
Electrolysis mode: H2 production

Cheap electricity:
Production of hydrogen and heat

The Sylfen® smart energy hub (Battery / SOFC-based)



http://sylfen.com/fr/accueil/



Hydrogen can be used as a feedstock for chemical or fuel production: example of CO_2 conversion

Hydrogenation of CO_2

Formic acid / Methanol / Methane / synthesis fuels

- Indirect hydrogenation

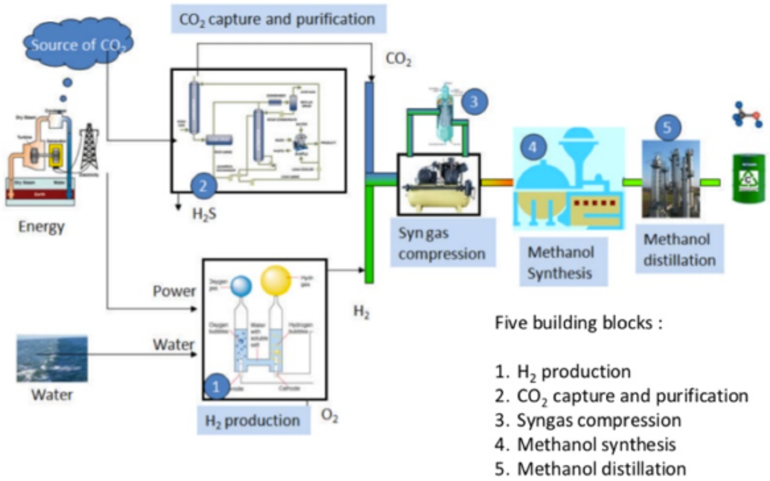
Product	Chemical reaction
Monoxyde de carbone	$CO_2 + H_2 \rightarrow CO + H_2O$

Reverse water-shift gas reaction

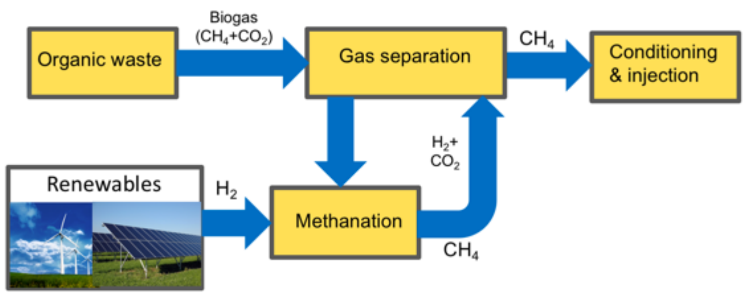
Product		Chemical reaction
Méthanol	Synthèse de méthanol	$CO + 2H_2 \rightarrow CH_3OH$
Hydrocarbures	Fischer Tropsch	$CO + 2H_2 \rightarrow CH_2\!- + H_2O$

- Direct hydrogenation

Product	Chemical reaction
Acide formique	$CO_2 + H_2 \rightarrow HCOOH$
Méthanol	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
Méthane[10]	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$



Methanisation/methanation coupling



Other chemical routes

- Organic synthesis (Urea, polycarbonates…)
- Mineralisation ex-situ
- Co-electrolysis of CO2 and H2

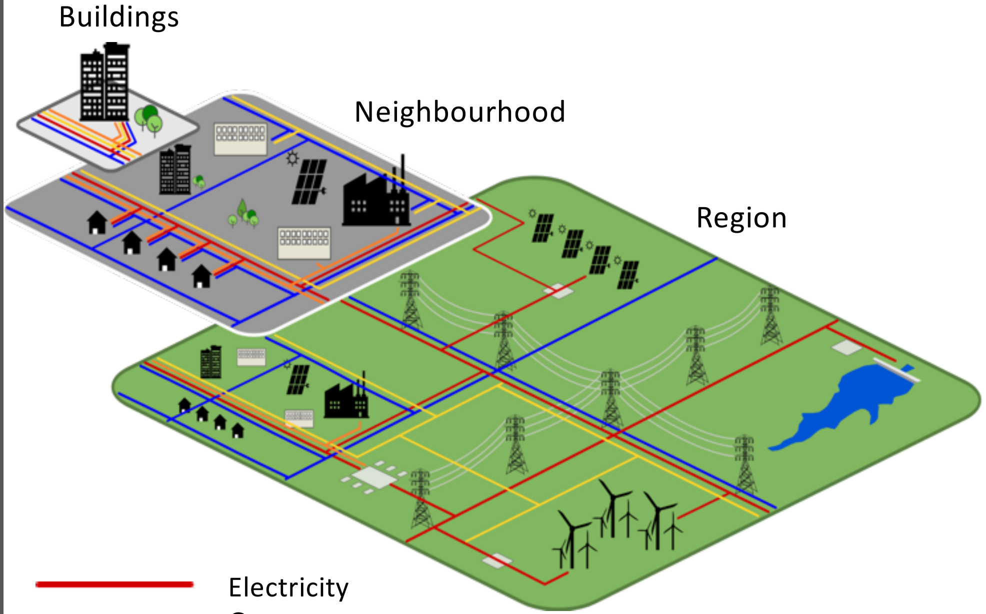
Source: http://www.ademe.fr/valorisation-chimique-co2-etat-lieux-quantification-benefices-energetiques-environnementaux-evaluation-economique-trois-voies-chimiques

Planning the deployment of hydrogen technologies at the scale of a geographical area fosters economic viability through synergies

Hydrogen can be used **as a bridge** between energy networks, as an **energy storage** mean and for multiple **end uses**

Smart network technologies helps managing interdependencies and interactions between the different energy networks to reach **a global optimization**

Different energy systems with different sizes



Windmill by Fabio Grande, building and factory by Lil Squid from The Noun Project

The example of Berlin Airport

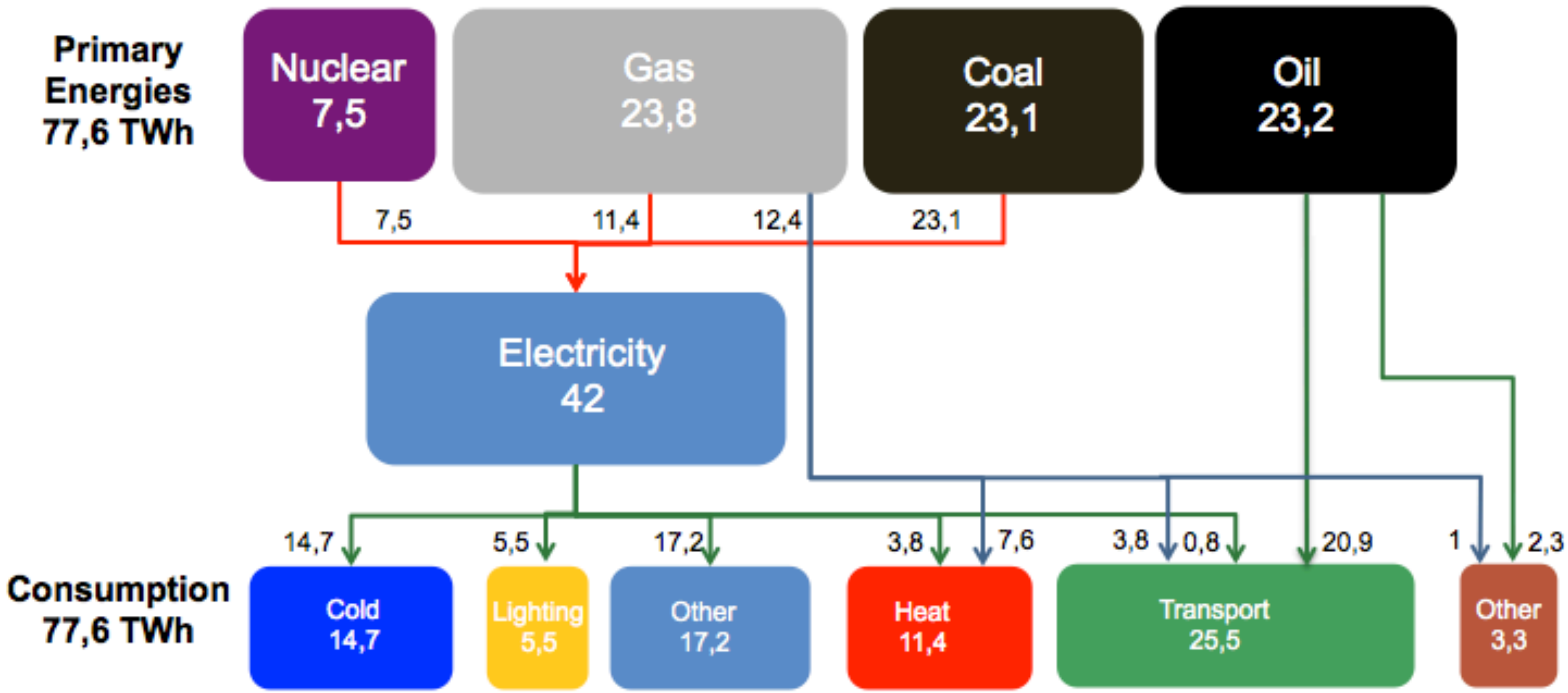
Source McPhy

"hydrogen territories" in France

Typical areas
- Industrial zones
- Local communities
- Airport area
- Dispersed habitat area
- Region

Applications
- Mobility
- Cogeneration
- Energy storage
- Power-to-gas

Hydrogen in Hong Kong - The Hong Kong Energy Balance (2010)



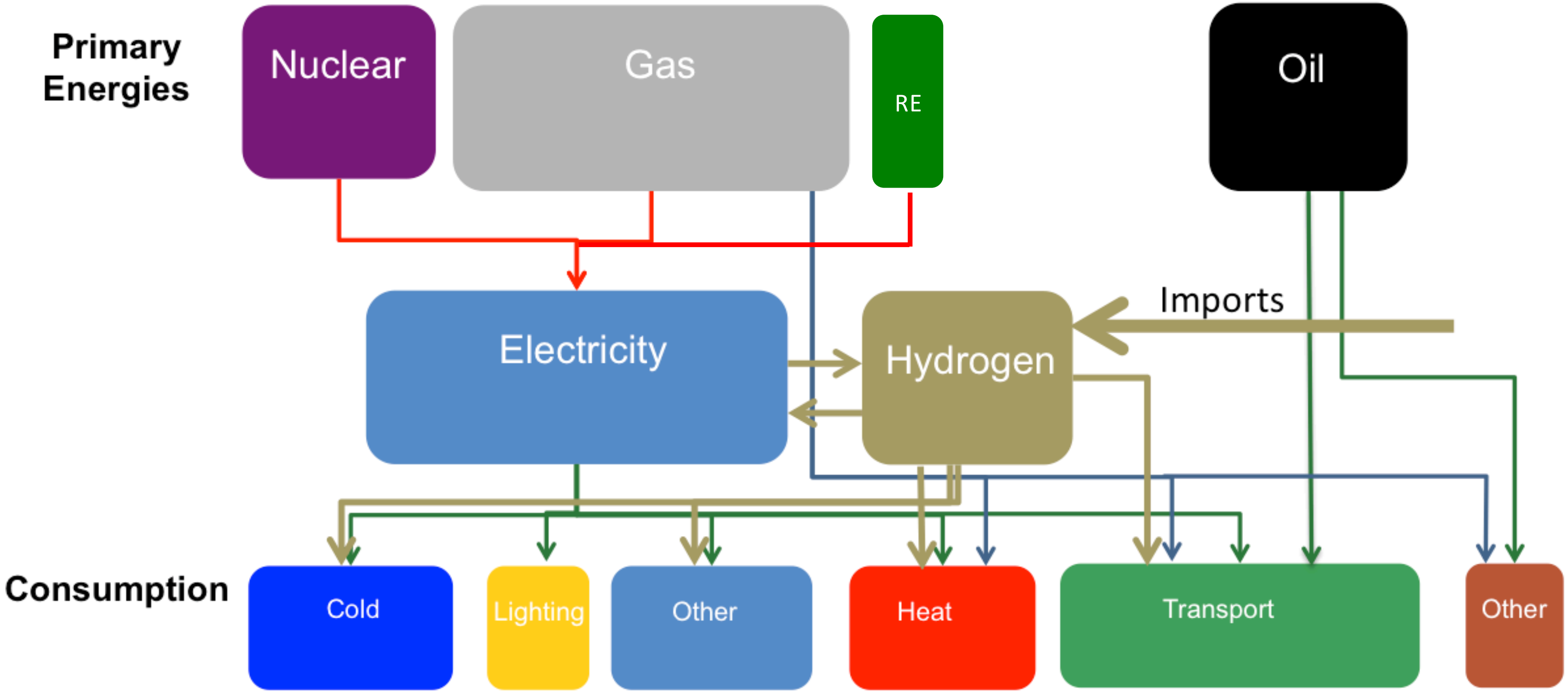
A significant proportion of Fossil Fuel imports for local electricity production

high level of CO_2 and particles emissions

Cold and refrigeration accounts for 1/3 of the electricity consumption

Fossil fuels largely used for transportation

The possible role of hydrogen in the Hong Kong energy balance



Hydrogen production / supply
Local green hydrogen production is limited. Still, town gas contains 55% of Hydrogen.
Hydrogen could be imported as for Japan

Transport
Hydrogen mobility could complement electric vehicles to decarbonate the transport sector (when autonomy is needed, for heavy duty vehicles such as buses, trucks)

Energy supply
Small and mid-size co- and tri-generation systems can help meeting the needs for energy supply of buildings / small neighborhoods

Conclusion: the hydrogen economy – myth or reality?

Positive points

- Hydrogen is a zero-carbon energy vector when produced from renewables and / or SMR+CCS, contributing to address environmental issues (climate change and local pollutions)
- Hydrogen technologies allow **coupling energy systems** and bring additional degrees of freedom for a global optimisation
- The development / deployment of hydrogen technologies can contribute to the development of the **green economy**, creating economic value and jobs
- Hydrogen technologies can enhance **energy security** and **energy independence**
- Hydrogen technologies are getting close to market (e.g. mobility) in terms of competitiveness
- International (IEA), national (Japan…) and regional roadmaps are being established
- Related industrial sectors and R&D efforts are growing fast
- The issue of infrastructure deployment and financing is partially addressed (Japan, EU)

Watch points

- Multiple energy **conversion** steps **impact the techno-economic performance** (ex: re-electrification)
- Performance of technologies (electrolysers, fuel cells, storage, methanation) must be further **improved for efficiency, reliability and cost**
- **Development of infrastructures** (transport, distribution & storage) is a hurdle that can impact deployment (largely political decision)
- Access to **low cost electricity and long operating times are critical** for a cost-efficient green hydrogen production
- Hydrogen technologies must be deployed in **large enough energy systems** to benefit from economies of scale and complementarity of valorisation routes