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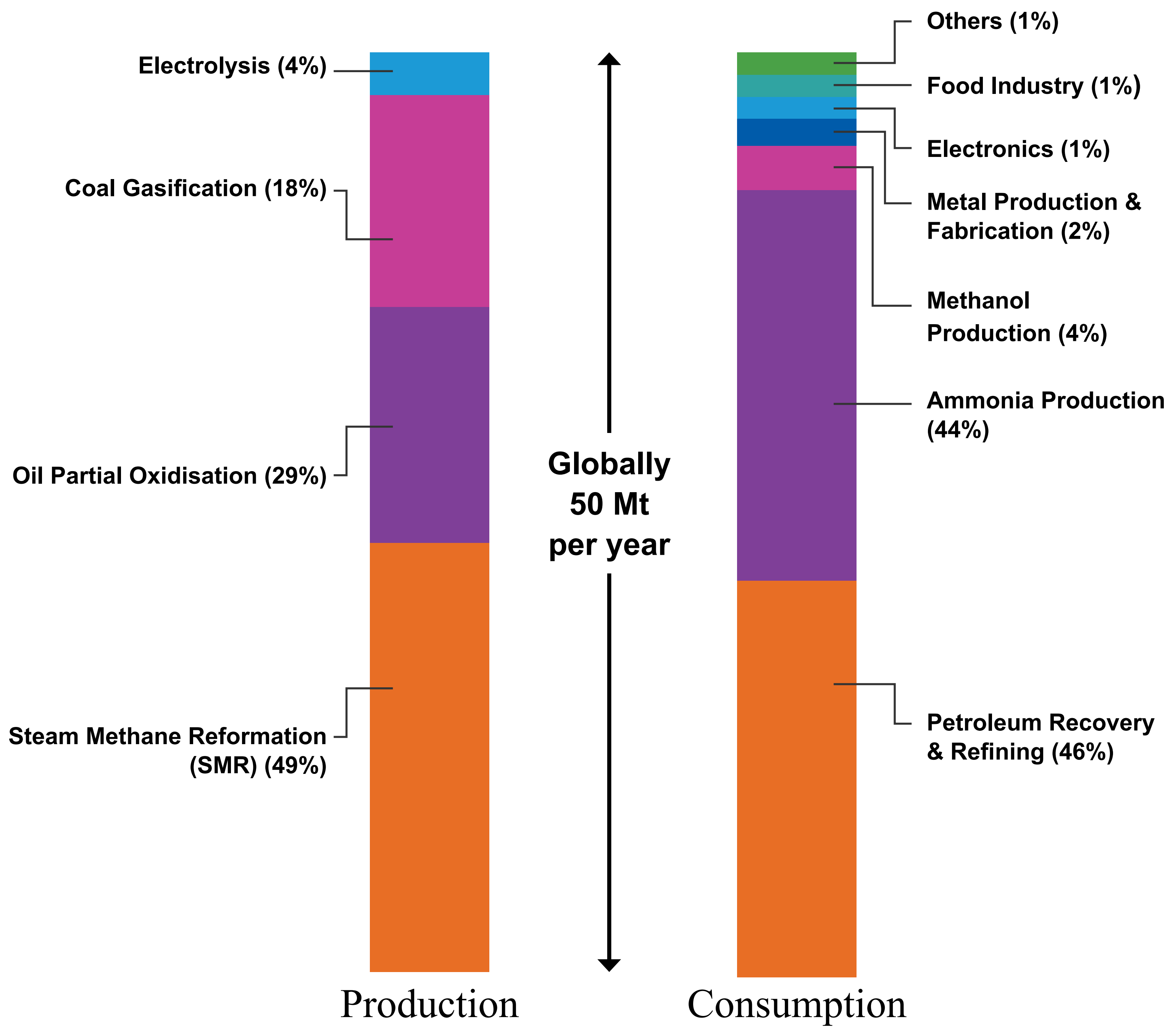
Five minute guide

Hydrogen

The hydrogen economy

Hydrogen is a future energy vector with a significant potential for the transfer and storage of renewable energy, and the supply of clean fuel for residential, industrial and transport activity. Today, substantial quantities of hydrogen are produced and consumed in various industrial processes.



Source: US DoE Hydrogen Production Expert Panel

Hydrogen is an emerging energy vector, many components of which are mature technologies. Current hydrogen technology is already able to provide advantages over other energy vectors and many of its challenges are being actively addressed by research and development.

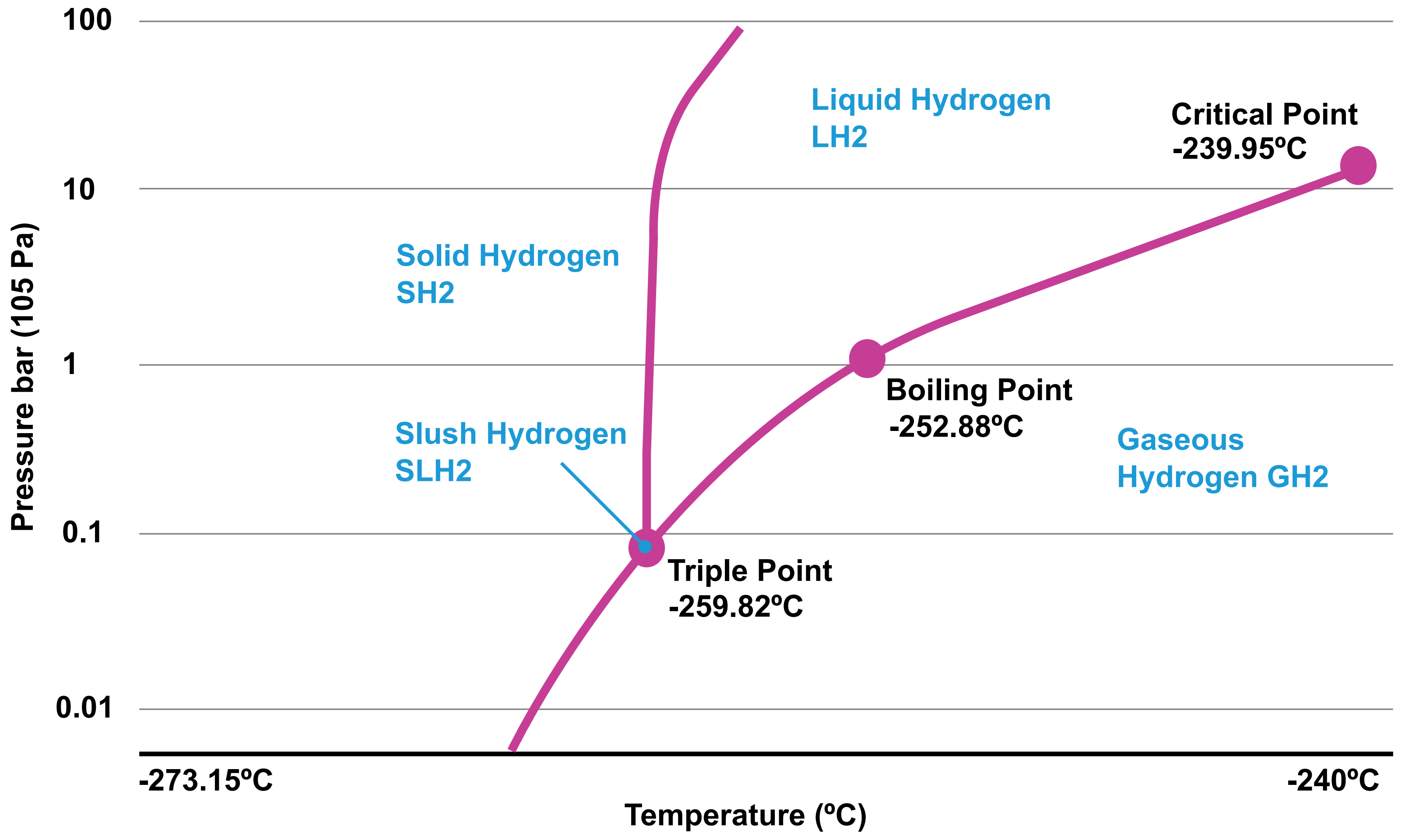
Advantages	Challenges
✓ Energy storage solution to enable the growth of renewable energy generation	× Overall low cycle efficiency
✓ Enable capturing constrained or intermittent renewable energy generation	× Immature infrastructure
✓ Seasonal and diurnal resilience and security	× Underdeveloped technology supply chain
✓ Distributed seasonal energy storage using Power to Gas (P2G) technologies	× Public perception of safety is historically influenced
✓ Decarbonised gas energy into urban centres	× Storage technologies under development
✓ Can be produced from a wide range of feedstocks	× Well ventilated siting and careful system design required
✓ Can be stored and transported in various methods depending on scale	× High cost of fuel cells and other hydrogen equipment
✓ Potential natural gas transition to zero carbon fuel	× Regulatory and policy under development
✓ Decarbonised and integrated energy system including stationary, industry and transport	
✓ Very low or zero greenhouse gas emission at point of use	
✓ Rapid vehicle refuelling to achieve long driving range	
✓ Future low carbon nuclear based hydrogen production	
✓ Safety considerations similar to natural gas or petroleum	

Characteristics of hydrogen

Uniquely identified by Henry Cavendish in 1776, it was named ‘Water Maker’ or Hydrogen by Antione Lavoiser in 1783.

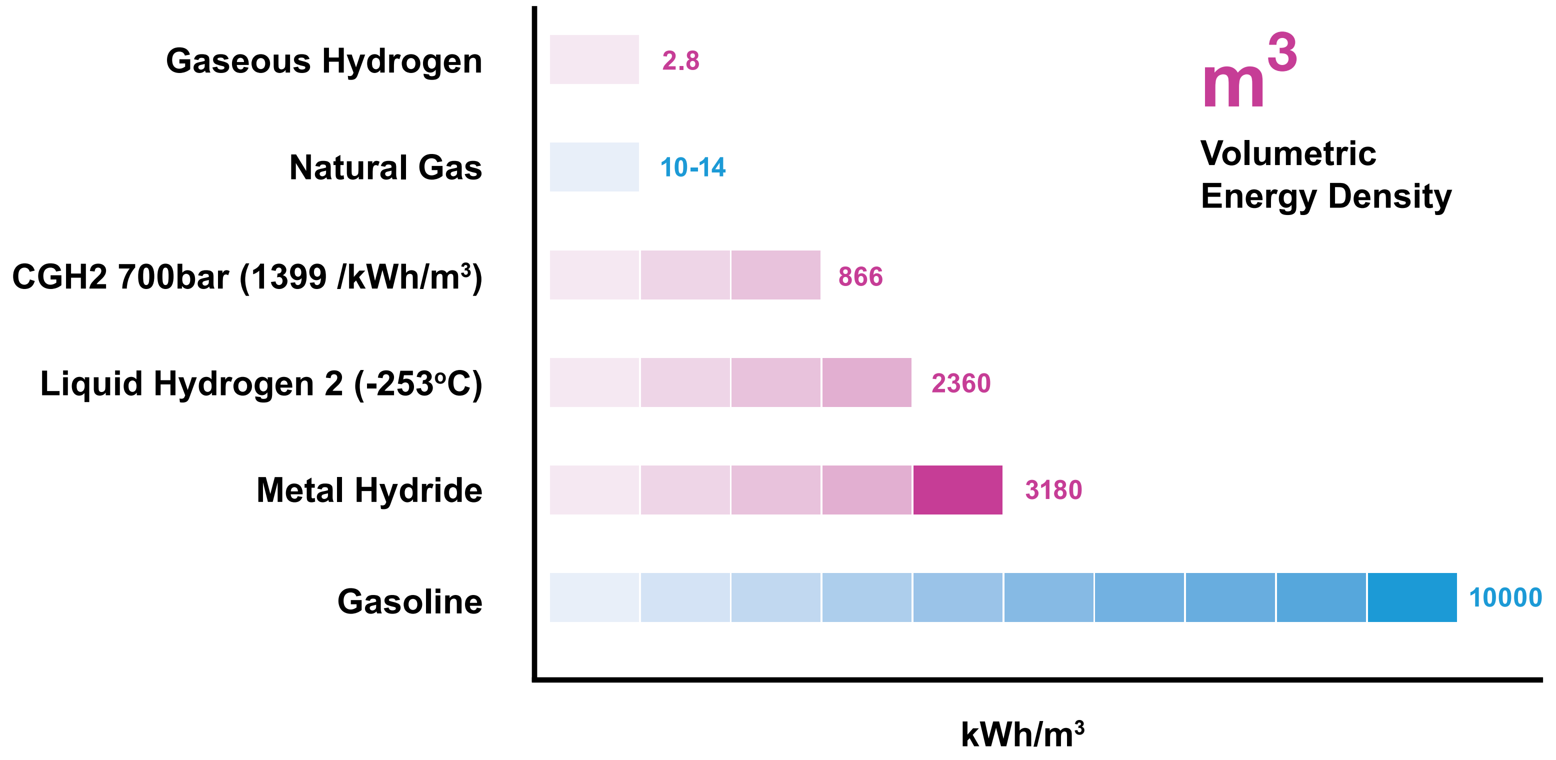
Generally encountered in compounds such as water (H_2O), methane (CH_4), etc. Molecular hydrogen (H_2) can be produced from many feedstocks and used as an energy vector (means of transfer and storage). It is not a primary energy source.

Hydrogen phase diagram



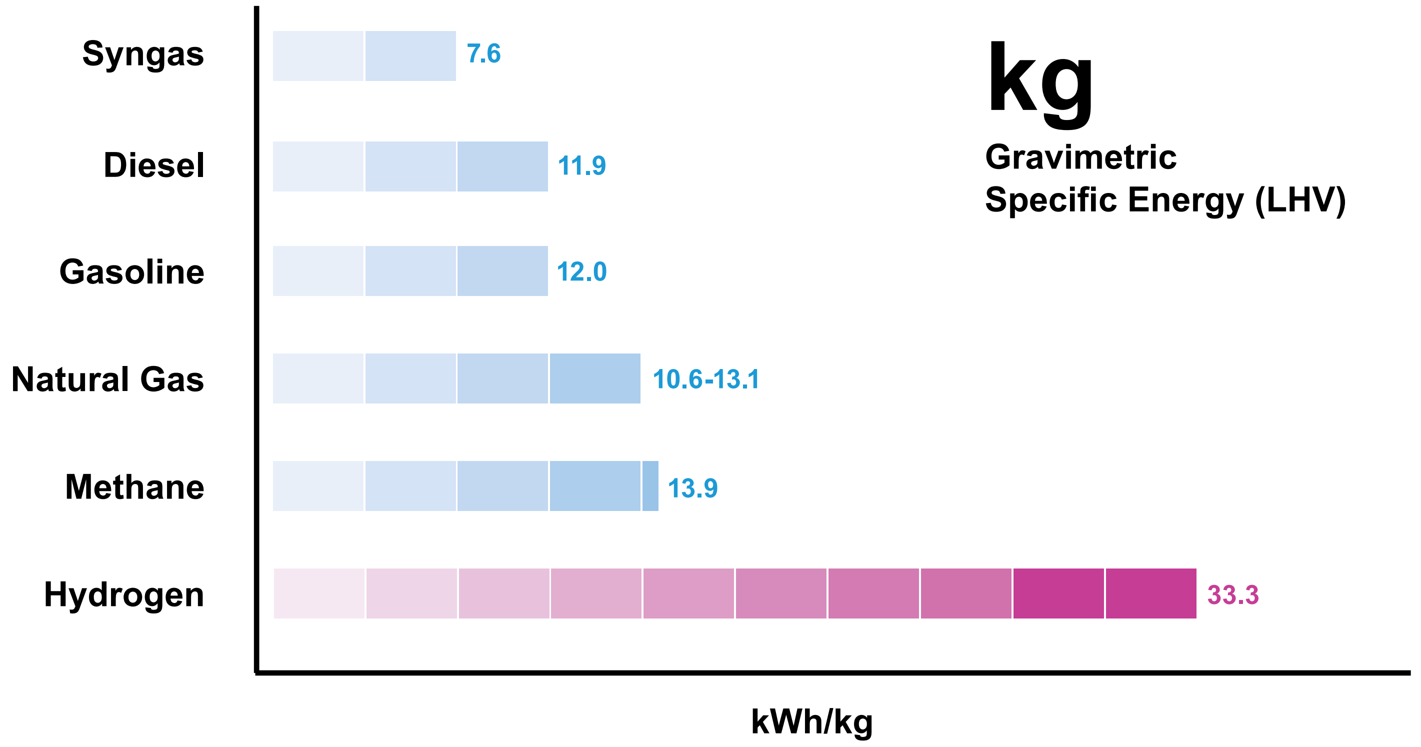
By volume, gaseous hydrogen contains a third of the energy of the same volume of Methane.

Gaseous diagram



On a weight basis it contains three times the energy of Methane.

Weight diagram



Compressed gaseous hydrogen (CGH_2) is the preferred form in most practical applications.

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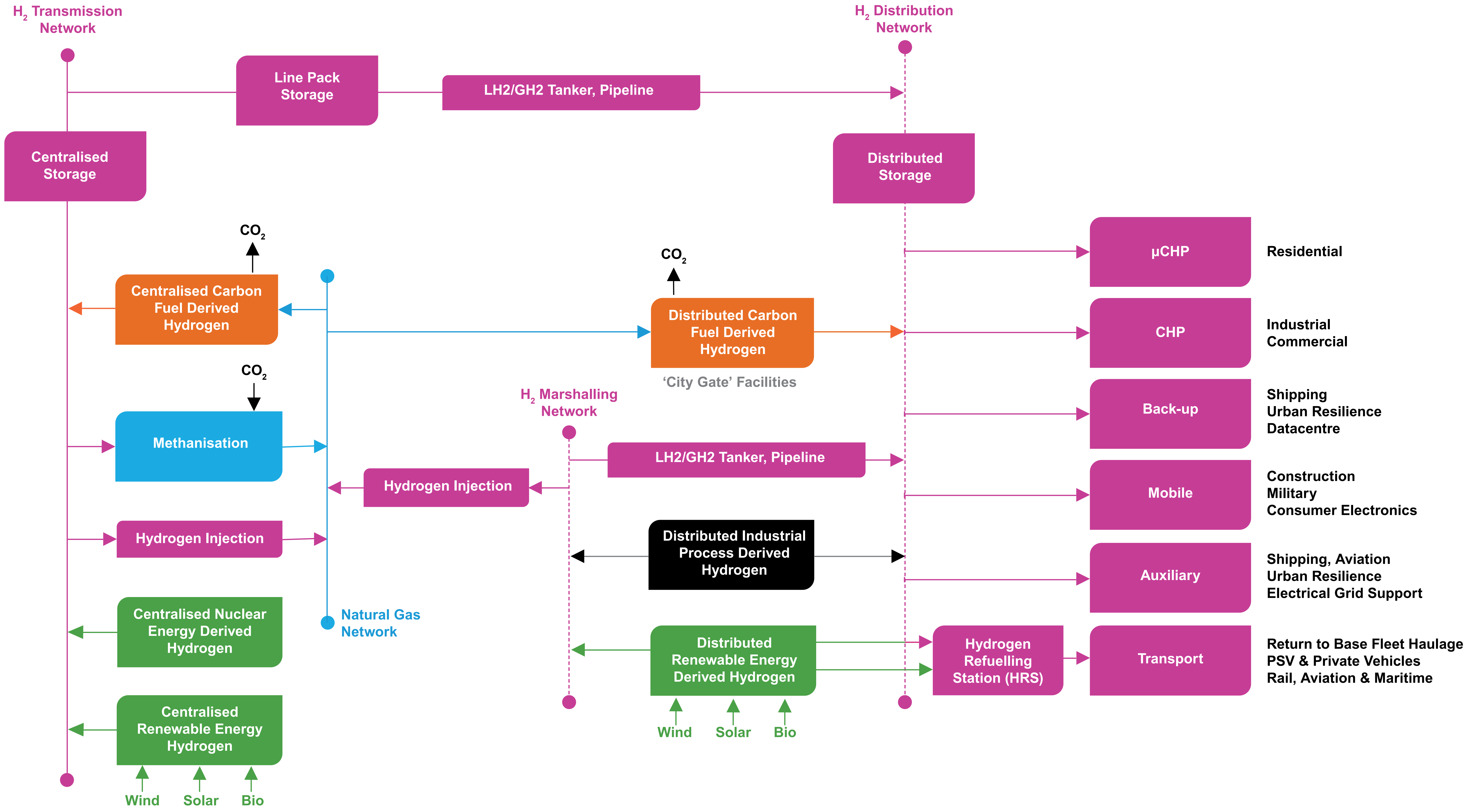
Hydrogen network anatomy

Hydrogen can be derived, stored and converted through various processes, each of which represents different levels of carbon intensity, efficiency and end use functionality.

Key

- 🟪 Hydrogen
- 🟩 Low Carbon Derived (Green) Hydrogen
- 🟧 Carbon Fuel Derived (Brown) Hydrogen
- ▨ Industrial Process Derived (Grey) Hydrogen
- 🟦 Natural Gas



H_2 Transmission Network

Line Pack Storage

LH2/GH2 Tanker, Pipeline

H_2 Distribution Network

Centralised Storage

Distributed Storage

CO_2

Centralised Carbon Fuel Derived Hydrogen

CO_2

Distributed Carbon Fuel Derived Hydrogen

'City Gate' Facilities

CO_2

Methanisation

H_2 Marshalling Network

LH2/GH2 Tanker, Pipeline

Hydrogen Injection

Hydrogen Injection

Distributed Industrial Process Derived Hydrogen

Natural Gas Network

Centralised Nuclear Energy Derived Hydrogen

Distributed Renewable Energy Derived Hydrogen

Wind Solar Bio

Centralised Renewable Energy Hydrogen

Wind Solar Bio

Hydrogen Refuelling Station (HRS)

µCHP	Residential
CHP	Industrial Commercial
Back-up	Shipping Urban Resilience Datacentre
Mobile	Construction Military Consumer Electronics
Auxiliary	Shipping, Aviation Urban Resilience Electrical Grid Support
Transport	Return to Base Fleet Haulage PSV & Private Vehicles Rail, Aviation & Maritime

Hydrogen safety and public perception

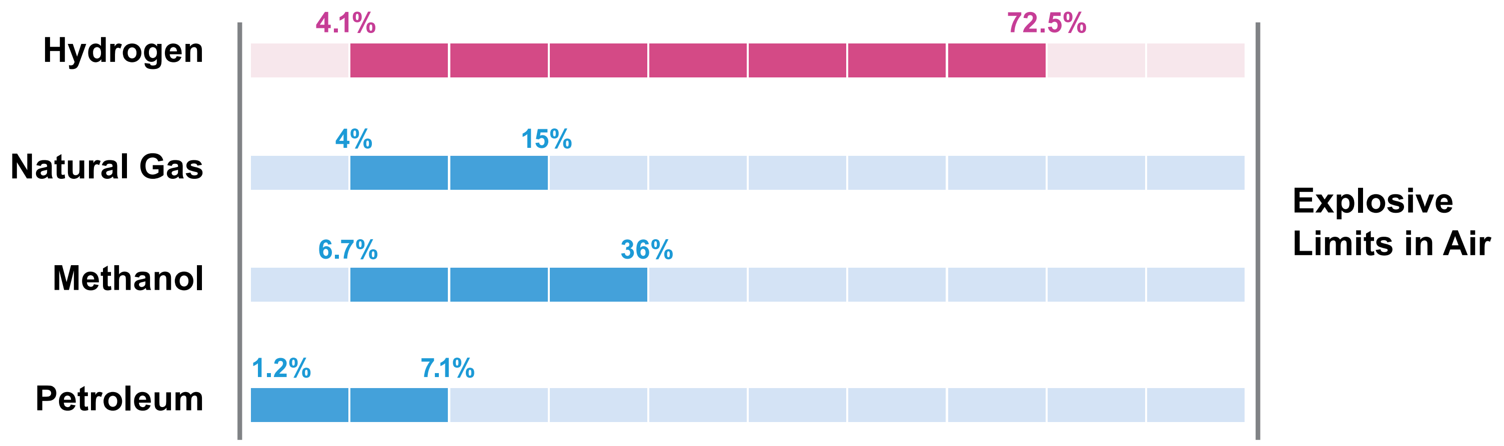
Hydrogen is not more or less dangerous than other energy carriers. As with hydrocarbon fuels like petroleum or natural gas, hydrogen needs to be carefully managed in appropriately designed infrastructure, facilities and products.

Public perception and historical legacy

Events such as the LZ129 Hindenburg airship disaster in 1939 remind us of the need to carefully design and manage inherent hydrogen risks (although it is hypothesised that hydrogen was not the causal factor). Equally the Abbeystead explosion in 1984 reminds us that methane must also be treated carefully, as does the Buncefield petroleum fire in 2005.

Hydrogen explosive limits

In the event of a leak, the lower explosive limit is the first threshold to be reached. This threshold for hydrogen is similar to natural gas at 4.1% hydrogen in air and better than the 1.2% limit of petroleum in air. Although hydrogen does have much larger range between the lower and higher explosive limits, this is not an overriding factor in most real life situations where dilution and dispersion keep the gas/air ratio low.



Energy density and leakage

Hydrogen has about a third of the energy density of methane, but due to the small molecular size of hydrogen it has a greater propensity to leak by a factor of three, so the net energy loss from leakage is about the same. Storage and transport of hydrogen at higher pressures to counteract the lower energy density can increase its propensity for leakage.

Flame visibility and smell

Light emitted from burning pure hydrogen is in the ultraviolet range and is not visible to the human eye, however it does burn with a coloured flame in the presence of combustion contaminants. Petroleum based flame is highly visible and natural gas is visible to a lesser degree. Similar to methane, pure hydrogen cannot be detected by smell. Hydrogen flame detectors are readily available and research into additives which generate a visible flame and odorise the gas are under development.

Rapid buoyant dispersion

Hydrogen is 14.5 times more buoyant than air, whereas methane is only 4 times more buoyant and petroleum vapour is less buoyant, so hydrogen disperses and dilutes most rapidly. Adequate ventilation is an effective measure to prevent build up potential overhead gas pockets and prevent reaching explosion limits.

Radiant heat

Combustion of hydrogen produces less radiant heat than comparable hydrocarbons, reducing its propensity to ignite adjacent materials, but also meaning that the flame is less noticeable to people or thermal detection systems.

Hydrogen production and evolving solutions

1 - Steam Methane Reformation (SMR)

A mature thermochemical process that delivers ~95% of current H_2 production. Methane at ~3-25 bar reacts with high temperature steam (700-1000ºC) to produce H_2 and CO. In the presence of steam, 'water-gas-shift' reaction occurs to convert CO and water into further H_2 and CO_2. Purification processes such as Temperature or Pressure Swing Absorption are used to remove contaminants from the H_2 stream. Generally large scale centralised, oxygen free production.

2 - Partial Oxidisation (POX)

Endothermic partial oxidisation of natural gas followed by 'Water-Gas-Shift'. Faster and smaller than SMR, and produces less hydrogen per unit of gas feedstock.

$CH_4 + ½\ O_2 \blacktriangleright CO + 2H_2$ *(+ + heat)*

then, $CO + H2O \blacktriangleright CO_2 + H_2$ *(+heat)*

3 - Autothermal Reformation (ATR)

Another thermochemical process, it uses oxygen and carbon dioxide or steam to produce H2. The reaction is exothermic with output temperature of 950- 1100ºC. Smaller and less efficient than SMR.

$2CH_4 + O_2 + 2H_2O$ *(+ heat)* $\blacktriangleright 3CO + 3H_2 + 3CO + H_2O$ *(++ heat)*

or, $4CH_4 + O_2 + 2H_2O$ *(+ heat)* $\blacktriangleright 2CO + 10H_2$ *(++ heat)*

4 - Low Temperature Plasma Reformation

Partial oxidation plasma pyrolysis of methane. This process is at an early technology readiness level but is showing promising low energy reformation potential.

5 - Reformer Electrolyser Purifier (REP)

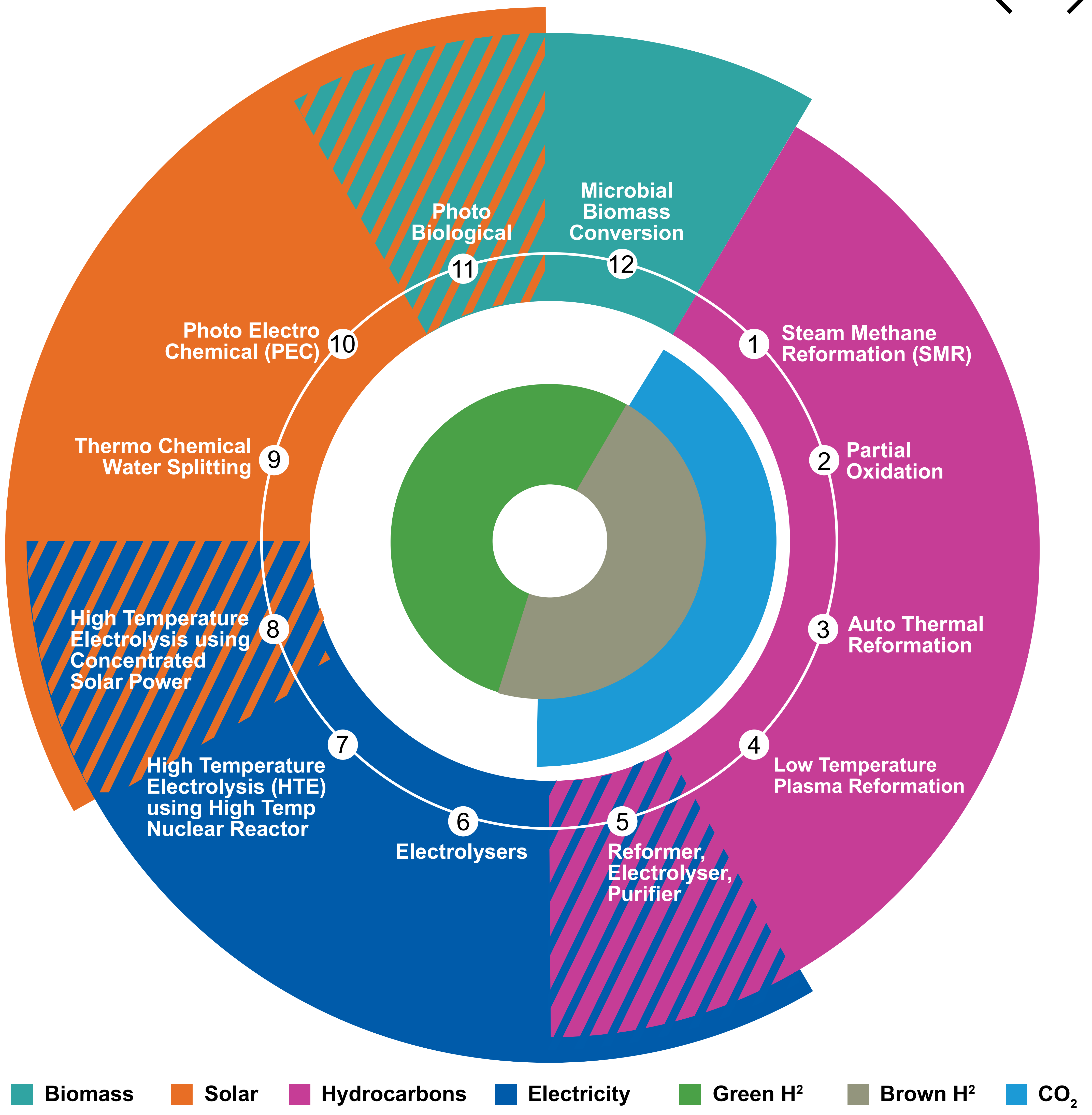
A developing technology which reforms and purifies in one step, combining SMR with molten carbonate electrolysers. The SMR utilises waste heat from electrolysis, while the electrolyser extracts CO_2 from the hydrogen stream and produces further hydrogen. More efficient than SMR and scalable for centralised of distributed use.

$CH_4 + H_2O$ *(+ + heat)* $\blacktriangleright CO + 3H_2$

then $CO + H_2O \blacktriangleright CO_2 + H_2$ *(+heat)*

6 - Electrolysers

Electrolysers split water into hydrogen and oxygen using electricity input. The carbon footprint of the hydrogen depends upon the carbon footprint of the source electricity and electrolysis efficiency. Polymer Electrolyte Membrane (PEM) is based on a solid polymer electrolyte operating at 70-90ºC, while an Alkaline Electrolyser uses a Sodium or Potassium Hydroxide or solid alkaline electrolyte at 100-150ºC and the Solid Oxide Electrolyser uses a solid ceramic electrolyte operating at about 700-800ºC.



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Hydrogen production and evolving solutions

7 - High Temperature Electrolysis (HTE)

High Temperature Electrolysis or steam electrolysis works on the basis that electrolysis of water can be more efficiently achieved at high electrolyte temperatures in the range of ~100-850ºC with an external heat input. By utilising heat from concentrated solar power, parabolic solar system, or reject heat from high temperature nuclear reactors the electrical energy input can be more effectively converted into hydrogen.

8 - HTE + Nuclear

High Temperature Electrolysis (HTE) can take advantage of heat input at ~100-850ºC derived from high temperature nuclear reactors to increase hydrogen electrolysis efficiency. This approach may be particularly relevant with respect to waste heat from small modular reactors which could be accessible to gas networks.

9 - Thermo Chemical Water Splitting

Using high temperatures generated from solar (Solar Thermochemical Hydrogen, STCH) or nuclear energy, water splitting cycles produce hydrogen and oxygen from water. Typically dual stage cerium oxide (2000/400ºC) or copper chloride hybrid (500/400ºC), but ~300 process variants are at various technology readiness levels.

10 - Photo Electro Chemical (PEC)

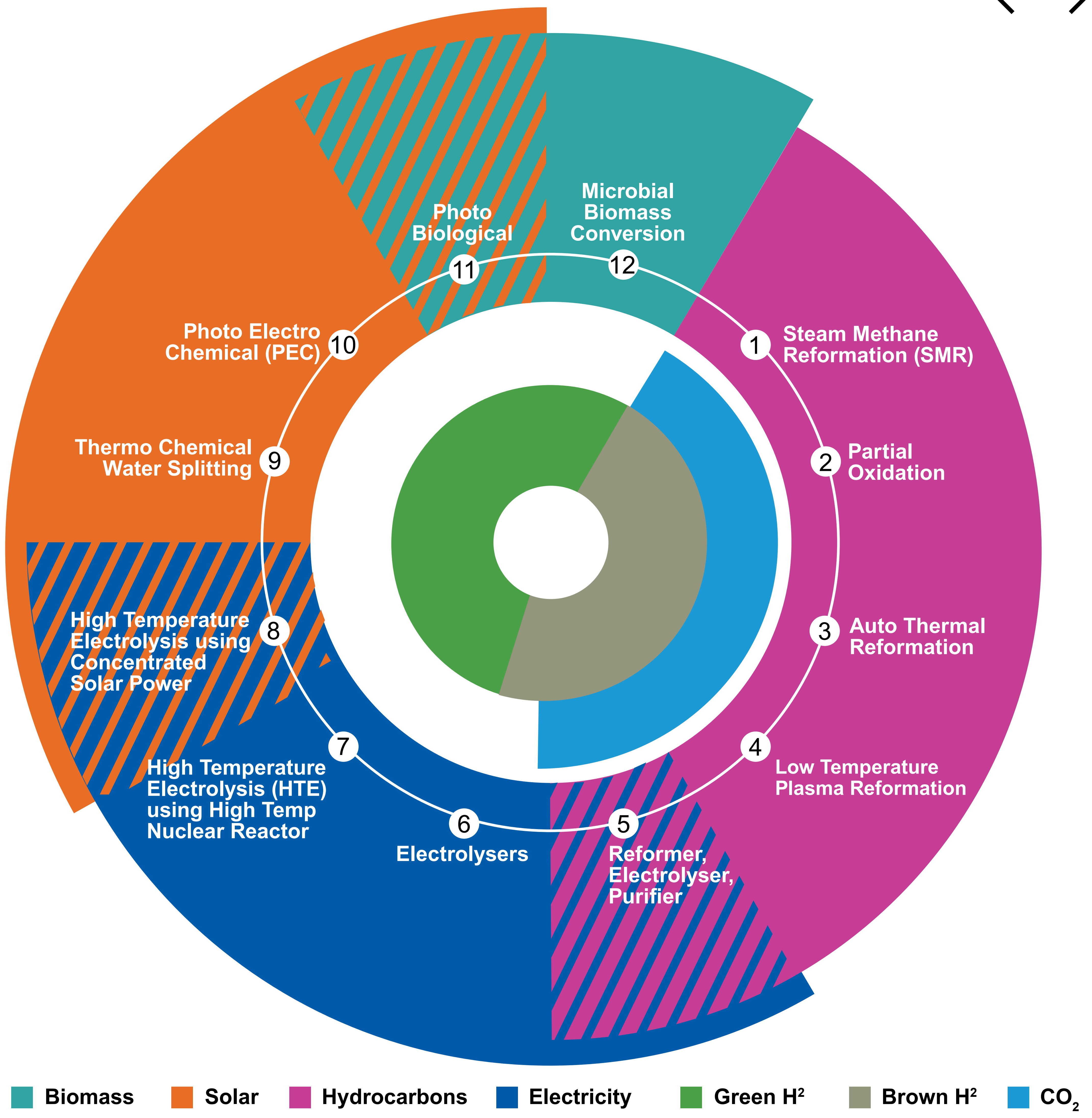
The PEC process uses semiconductors immersed in a water based electrolyte or a photo-reactive slurry to convert solar energy into chemical energy in the form of hydrogen and oxygen as a by-product. This developing technology can be applied in a similar manner to photovoltaic panels at various scales, both centralised and distributed.

11 - Photobiological

Micro-organisms such as micro-algae or cyano-bacteria absorb sunlight to produce hydrogen. Alternatively photo-synthetic microbes photo-ferment biomass to produce hydrogen. These processes currently have a low hydrogen yield and are inhibited by concurrent oxygen generation. Further research is anticipated to increase effectiveness

12 - Microbial Biomass Conversion

Dark fermentation of biomass using micro- organisms produces hydrogen and carbon dioxide. Alternatively Microbial Electrolysis Cells (MECs) combine biomass, micro-organisms and a small electrical input to increase hydrogen yield. This approach has long-term potential to produce H_2 from wastewater.



1 Steam Methane Reformation (SMR)

2 Partial Oxidation

3 Auto Thermal Reformation

4 Low Temperature Plasma Reformation

5 Reformer, Electrolyser, Purifier

6 Electrolysers

7 High Temperature Electrolysis (HTE) using High Temp Nuclear Reactor

8 High Temperature Electrolysis using Concentrated Solar Power

9 Thermo Chemical Water Splitting

10 Photo Electro Chemical (PEC)

11 Photo Biological

12 Microbial Biomass Conversion

🟦 Biomass 🟧 Solar 🟪 Hydrocarbons 🟦 Electricity 🟩 Green H^2 ⬜ Brown H^2 🟦 CO_2

Transmission & distribution

Hydrogen properties present transmission and distribution challenges and trade-offs. Hydrogen can be transported as compressed gas, liquid hydrogen or using liquid hydrogen organic carriers (LCOH) or as other chemical compounds such as ammonia.

Transmission Pipelines are suited to large volume, long distance GH2 transport. Reuse of steel natural gas pipelines is a challenge due to propensity for hydrogen embrittlement. CGH2 transmission by pipeline already exists for industrial purposes. Lower volumetric energy density of CGH2 compared with natural gas means that flow volumes and consequent gas velocity are higher in hydrogen based systems for comparable energy transfer.

High Pressure Tube Trailers are suited for low quantity delivery to discrete demand centres. Relatively large heavy goods vehicles require access space at a discharge location.

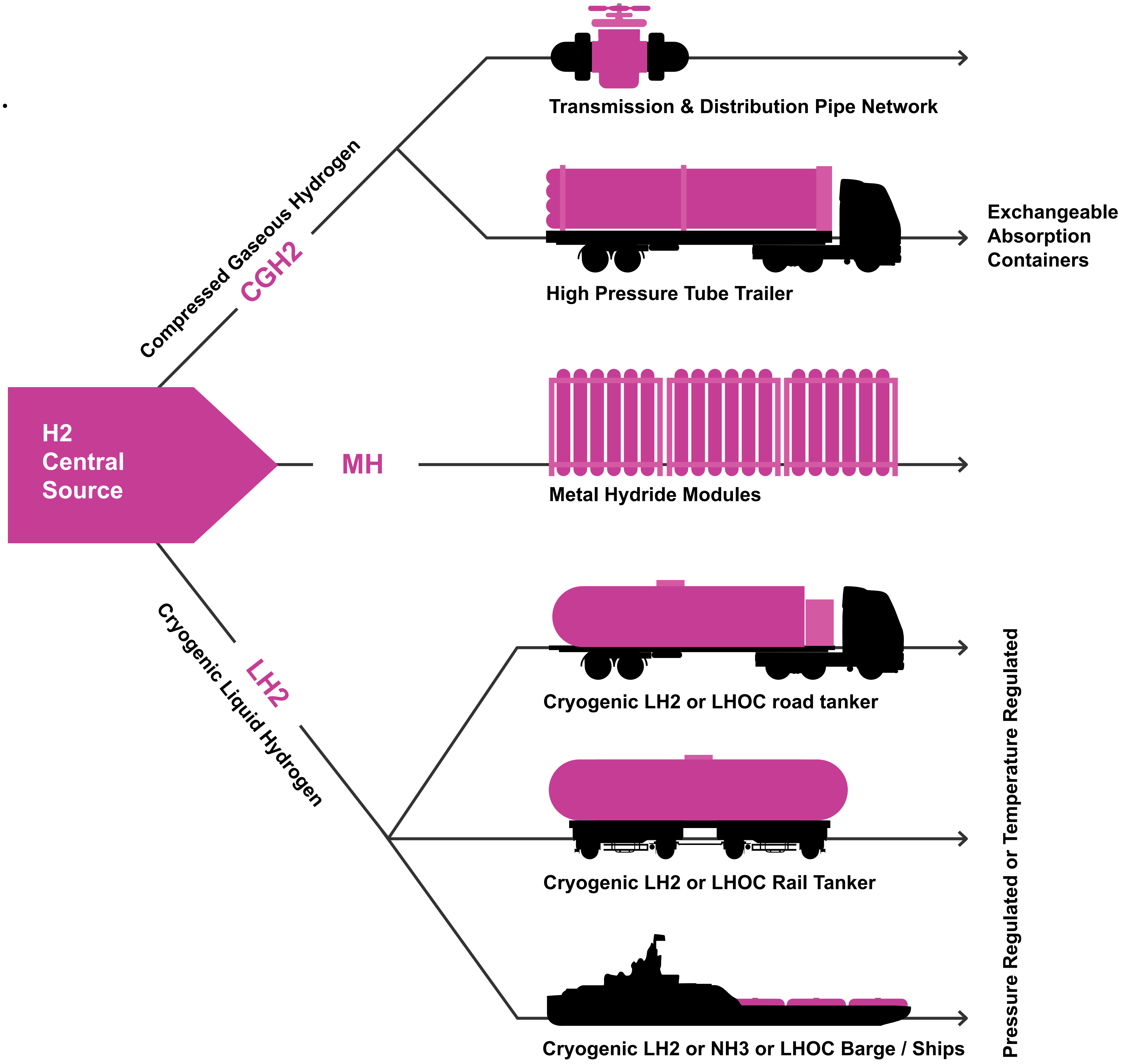
Distribution Pipelines are suited to large volume, medium distance GH2 transport. Replacement of cast iron natural gas mains with polyethylene (PE) means that natural gas distribution networks are substantially hydrogen ready. Challenges with sulphur containing odourisers (eg: Mercaptans) 'poisoning' fuel cell catalysts.

Metal Hydrides are suited for small quantities of H_2 absorbed in the Metal Hydride with a high volumetric energy density. Containerised modules are transported by road, rail or marine transport.

Cryogenic Road Tankers are suited for medium quantity delivery to discrete demand centres. Relatively large heavy goods vehicles require access space at discharge location. Energy losses through gradual warming of the cryogenic LH2 results in 'boil off' of gaseous H_2 (Pressure Regulated) unless actively cooled (Temperature Regulated) or utilised onboard.

Cryogenic Rail Tankers are suited for medium quantity delivery to discrete demand centres over long distances on the rail network from one industrial centre to another. Challenges of boil off or cooling energy losses.

Cryogenic Barges/Ships are suited for large quantity delivery over long distances similar to LNG carriers enabling international transport of LH2.



Storage

H_2 is a useful energy storage medium covering the needs of diurnal to seasonal timelines.

Line-stack Storage in Pipelines

The system pressure in conventional gas pipelines is increased within limits to store gas. CGH2 has a third of the volumetric energy density of natural gas, so the energy equivalent 'line-stack' storage capacity for a given pipeline is less.

Underground Storage

In a similar manner to natural gas, pressurised GH2 is stored underground in suitable geology such as salt caverns. The large volumes of gas facilitate seasonal storage of renewable energy.

Cryogenic LH2 Storage

LH2 storage is an energy dense way of storing hydrogen, but it does have higher 'round trip' losses associated with liquefaction combined with time proportional 'boil off' or cooling requirements (It boils at -253ºC) which are less suited to long term or inter-seasonal storage. Additionally, LH2 introduces challenges in terms of handling and transport.

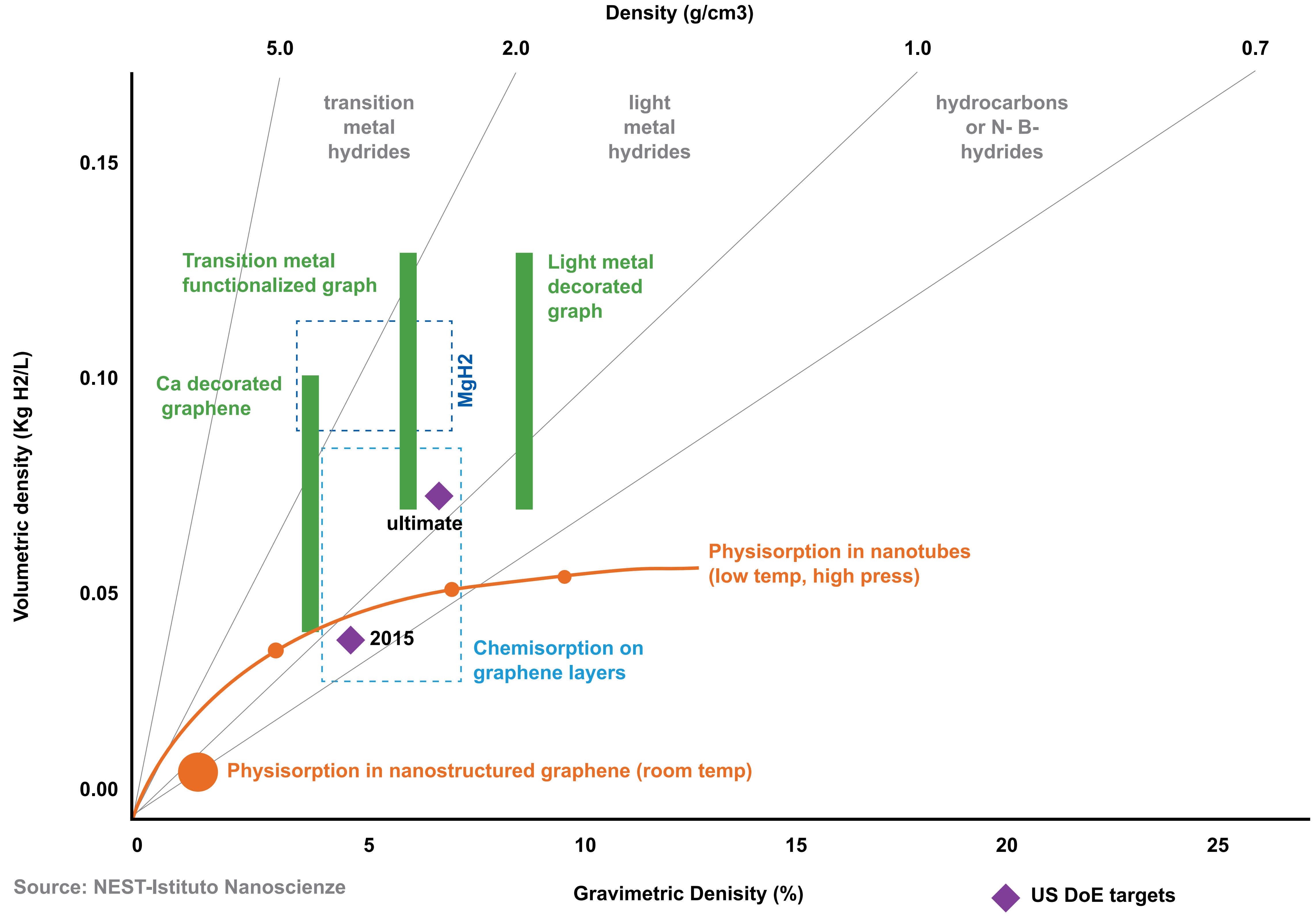
Physisorbtion and Chemisorbtion

Various Metal Hydrides and Graphene based compounds provide an opportunity to chemically absorb hydrogen for later release. Graphene can also absorb hydrogen within its physical structure.

Chemical Conversion to Methanol, Ammonia and Methane

Hydrogen can be used as a feedstock to produce chemicals such as Methanol and Ammonia as an energy storage vector. These chemicals have desirable energy characteristics, but are less desirable in other respects such as lower efficiency and emissions. Alternatively it can be combined with carbon dioxide to produce Methane which can be injected into the natural gas network.

GH2 has lower volumetric energy density than natural gas or other common hydrocarbons, LH2 is cryogenic liquid which loses energy through 'boil off' or cooling demand and chemical sequestration of hydrogen is relatively immature. Achieving maximum storage 'round trip' efficiency, volumetric energy density and input/output response times are key components of the evolving hydrogen landscape.



Source: NEST-Istituto Nanoscienze

End use applications – static fuel cells

Fuel cells are electrochemical devices that convert the chemical energy in Hydrogen into electrical power. The reaction of a fuel cell is exothermic. The heat from the fuel cell reaction can be utilised in combined heat and power (CHP) systems or combined cool, heat and power (CCHP) systems.

Proton Exchange Membrane FC (PEMFC)

These polymer electrolyte based fuel cells systems are used in transport and portable applications. They are able to flex their power output. Current systems use small quantities of Platinum catalyst which are easily poisoned by sulphur and carbon monoxide so they need advanced fuel processing systems.

Solid Oxide FC (SOFC)

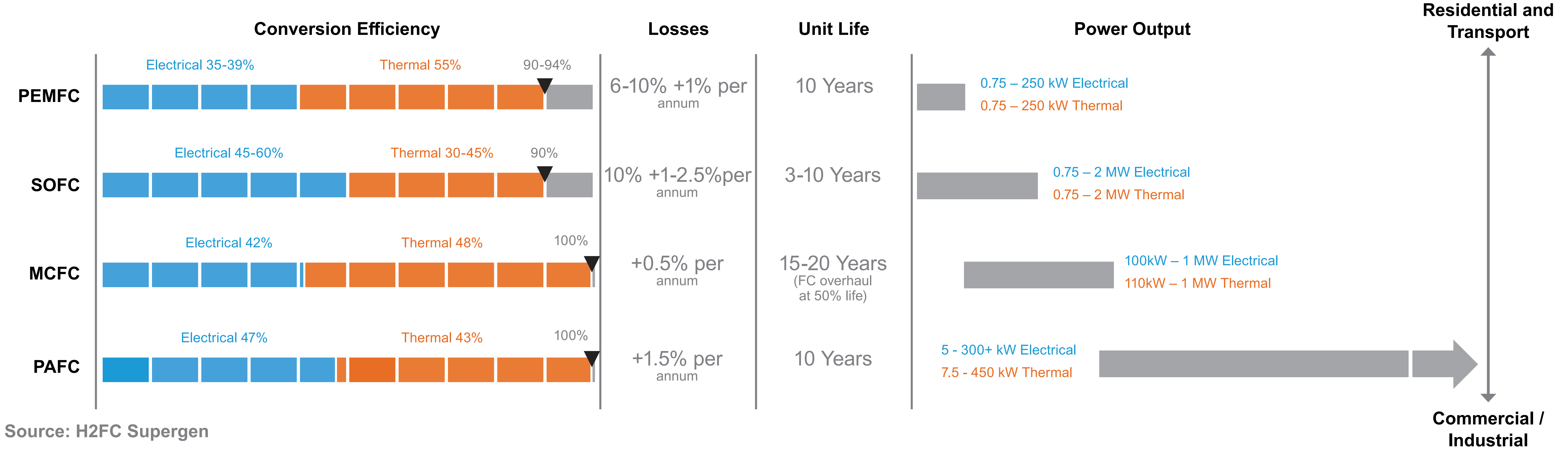
Although these are quite efficient, they operate at high temperatures (500-1000ºC), have long start-up and stop times, therefore considered best suited to stationary applications. They use a solid oxide electrolyte.

Molten Carbonate FC (MCFC)

Molten lithium and potassium carbonate in a ceramic matrix forms the electrolyte operating at ~650ºC. They are large industrial systems with low power density. They are considered for stationary power generation combined with carbon capture.

Phosphoric Acid FC (PAFC)

Liquid phosphoric acid at 180-250ºC is used as the electrolyte in conjunction with platinum catalyst (40x more than PEMFC).

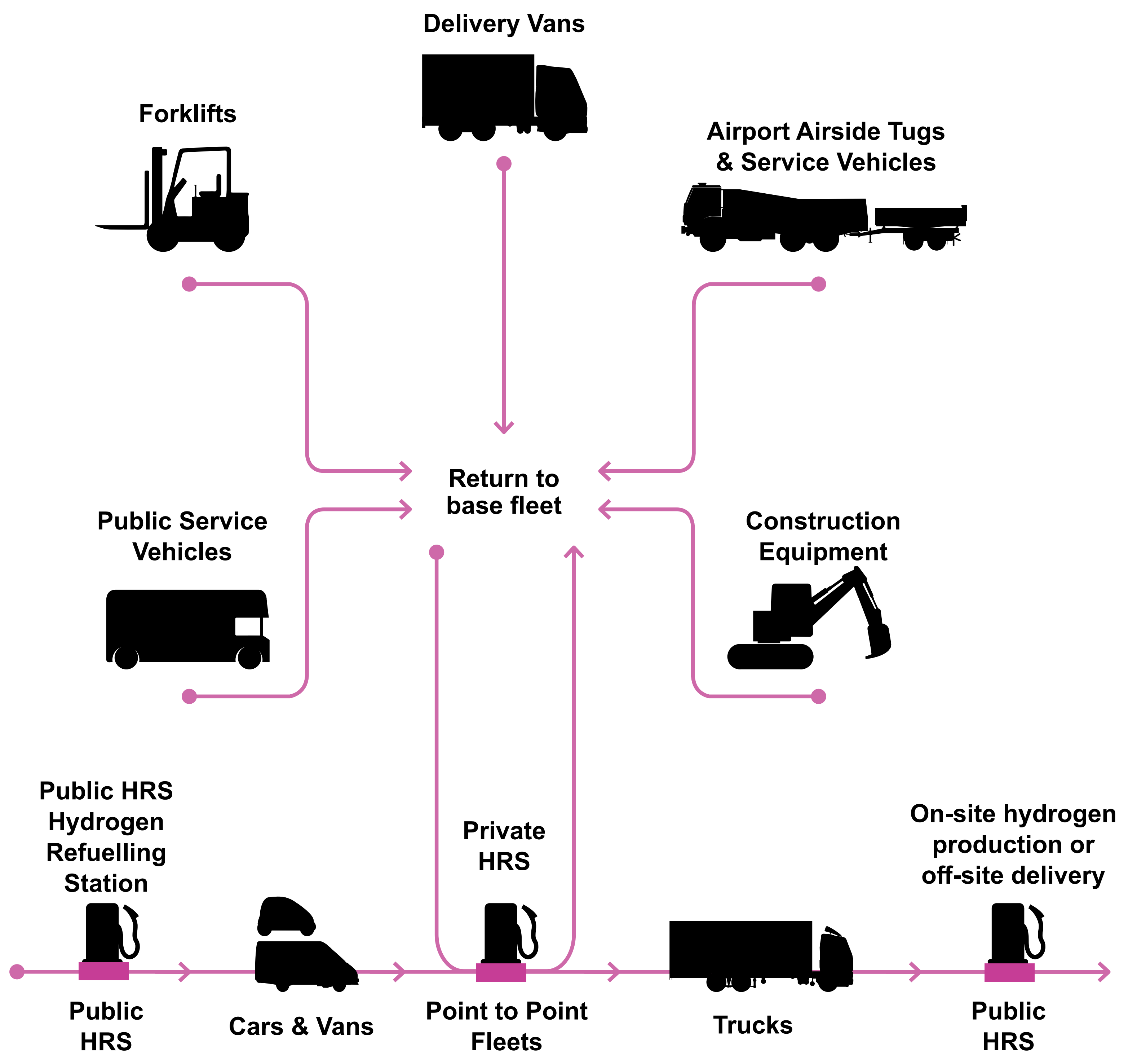


	Conversion Efficiency			Losses	Unit Life	Power Output
PEMFC	Electrical 35-39%	Thermal 55%	90-94%	6-10% +1% per annum	10 Years	0.75 – 250 kW Electrical 0.75 – 250 kW Thermal
SOFC	Electrical 45-60%	Thermal 30-45%	90%	10% +1-2.5%per annum	3-10 Years	0.75 – 2 MW Electrical 0.75 – 2 MW Thermal
MCFC	Electrical 42%	Thermal 48%	100%	+0.5% per annum	15-20 Years (FC overhaul at 50% life)	100kW – 1 MW Electrical 110kW – 1 MW Thermal
PAFC	Electrical 47%	Thermal 43%	100%	+1.5% per annum	10 Years	5 - 300+ kW Electrical 7.5 - 450 kW Thermal

Source: H2FC Supergen

Hydrogen in transport

Hydrogen vehicles have near zero tail pipe emissions other than water vapour and trace NOx. Range and refuelling time are comparable to hydrocarbon fuelled vehicles


Delivery Vans

Forklifts

Airport Airside Tugs
& Service Vehicles

Return to
base fleet

Public Service
Vehicles

Construction
Equipment

Public HRS
Hydrogen
Refuelling
Station

Private
HRS

On-site hydrogen
production or
off-site delivery

Public
HRS

Cars & Vans

Point to Point
Fleets

Trucks

Public
HRS

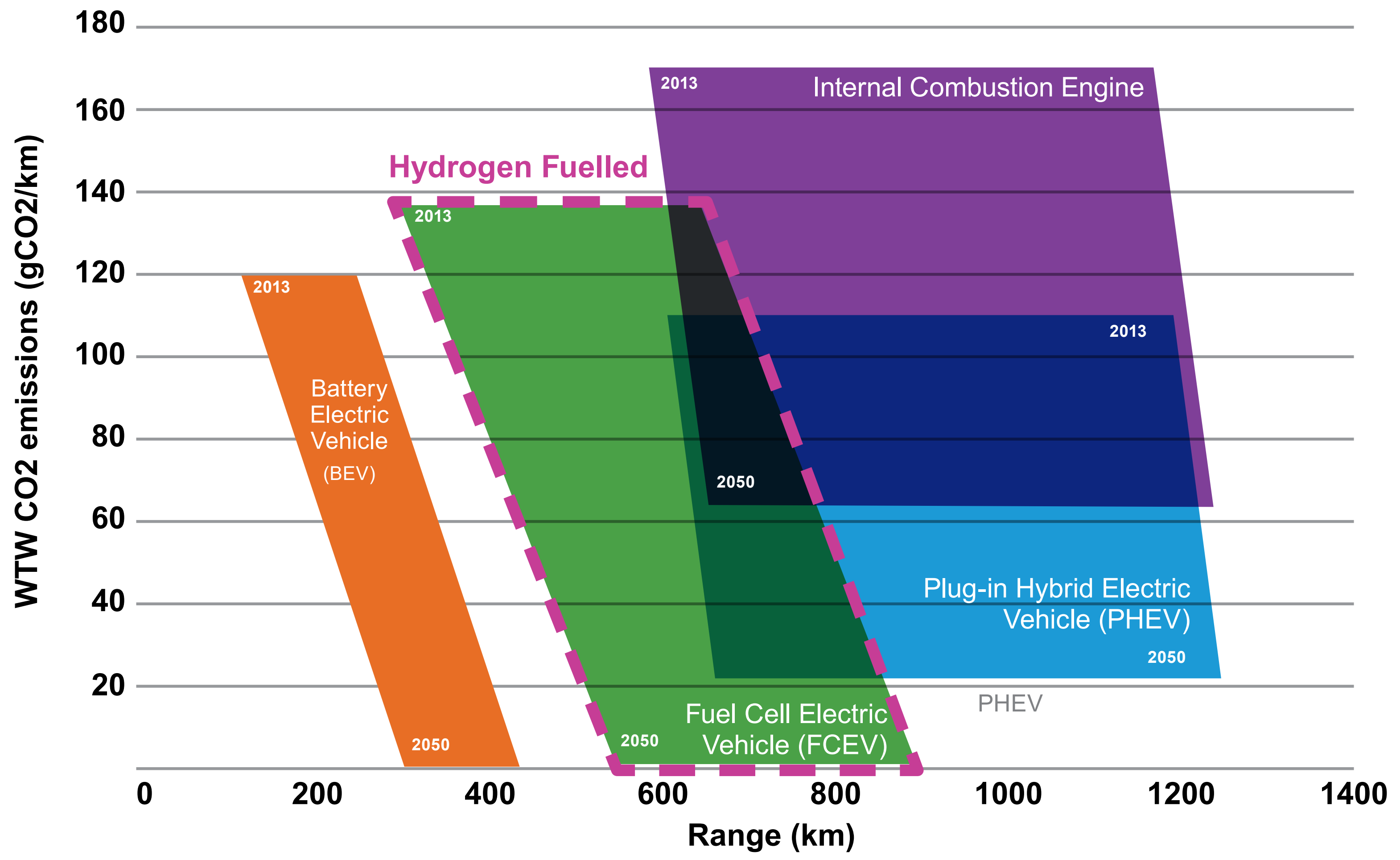
As hydrogen vehicle technologies improve in both efficiency (supply and fuel cells) and capacity (mobile storage) they hold potential to satisfy the medium range requirements between that which is provided by battery electric vehicles and plug-in hybrid electric vehicles.

Fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) have a comparable drive train and high torque performance at low speeds, while also delivering significant range.

Refuelling of hydrogen vehicles is much more rapid than recharging battery electric vehicles meaning that they are well suited to commercial fleets which do not have long periods of downtime in their duty cycle (eg: forklifts operating in a 24hr warehouse).

On-site production of hydrogen from sources of renewable distributed generation is able to accommodate fluctuating power input or draw off-peak electricity from the grid.respects. Alternatively it can be combined with carbon dioxide to produce Methane which can be injected into the natural gas network.

Well to Wheel (WTW) Emissions vs Vehicle range and projected performance improvement to 2050



Source: IEA Technology Roadmap

Hydrogen in stationary applications

Hydrogen can be used to decarbonise heat and industrial processes. Boilers, combined heat and power and industrial furnaces are being developed to be hydrogen ready for the future.

Hydrogen Boilers

Hydrogen can replace natural gas in homes for heating and cooking purposes. Home appliances currently used can take up to 20% hydrogen blend in the natural gas feed. Due to the properties of hydrogen, higher concentration of hydrogen in the gas feed require the change of appliances and boilers connected to the gas grid.

New boilers, gas burners and cookers have been developed to operate with 100% H_2 feed in preparation for the conversion of the gas networks to hydrogen.

Combined Heat and Power (CHP)

Hydrogen can be used to produce both heat and power for residential and commercial buildings. The current fuel cell micro-CHPs include a natural gas reformer and therefore can be connected directly to the gas grid. The reformer can be omitted once the gas grid is converted to hydrogen.

Larger CHP can be employed to provide heat and power for commercial buildings or feed into district heating systems.