Hydrogen

Source of future energy

Energy Transition

- World is going through a major transition period in energy sourcing.
- Consequently, energy driven geopolitics is also changing.
- Carbon dioxide concentration in air has increased from 280 ppm to over 420 ppm.
- Average global temperatures are higher than 1 degree above the pre industrial level
- Efforts are to maintain average global temperatures within 1.5 degree of the pre-industry level.

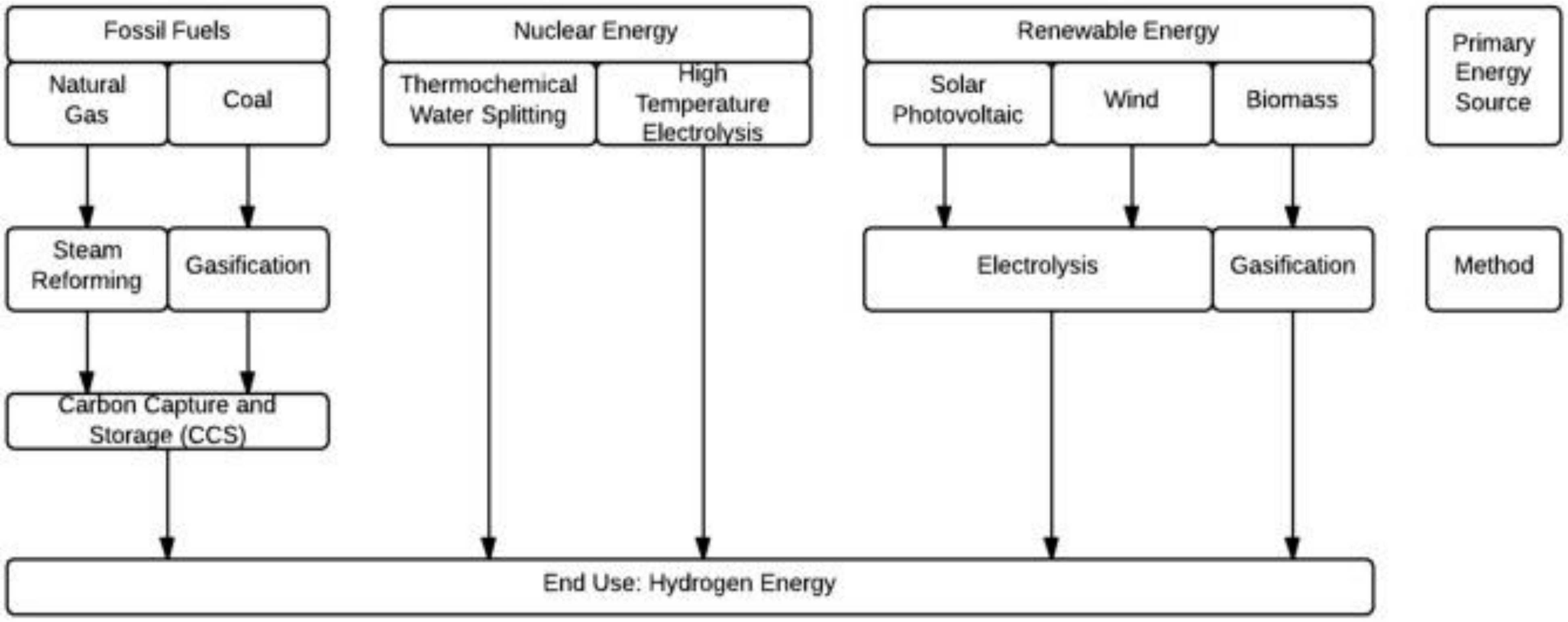
Cond

- This calls for a major shift in the type of energy we are accustomed to.
- Will have to give up fossil fuel and seek renewable sources like solar, wind and hydrogen as our sources of energy besides nuclear and hydropower.
- Solar and Wind driven electric cars(Li -ion battery) are efficient but can not be used for heavy vehicles nor power generation
- Hydrogen burnt with air produces water and energy which is proving to be the ideal replacement of fossil fuel.

Electric vehicle

- Renewable driven electric vehicles uses Li- Ion batteries
- They have proved to be more energy efficient and are cheaper as compared to hydrogen fuel cell (FCV).
- Eight percent of the energy is lost before the electricity is stored in the vehicle's batteries.
- When the electrical energy is converted to drive the electric motor, another 18 percent is lost.
- Depending on the model, the battery-powered e-car thus achieves an efficiency of between 70 to 80 percent."
- The hydrogen fuel cell requires 2-3 times more energy to drive the same distance as a battery powered vehicle, as the overall Well-to-Wheel efficiency is from 25-35%.
- However, renewable driven batteries cannot be used for transportation of heavy vehicles.
- They will need continuous charging and have longer charging time as compared to hydrogen fuel cells .

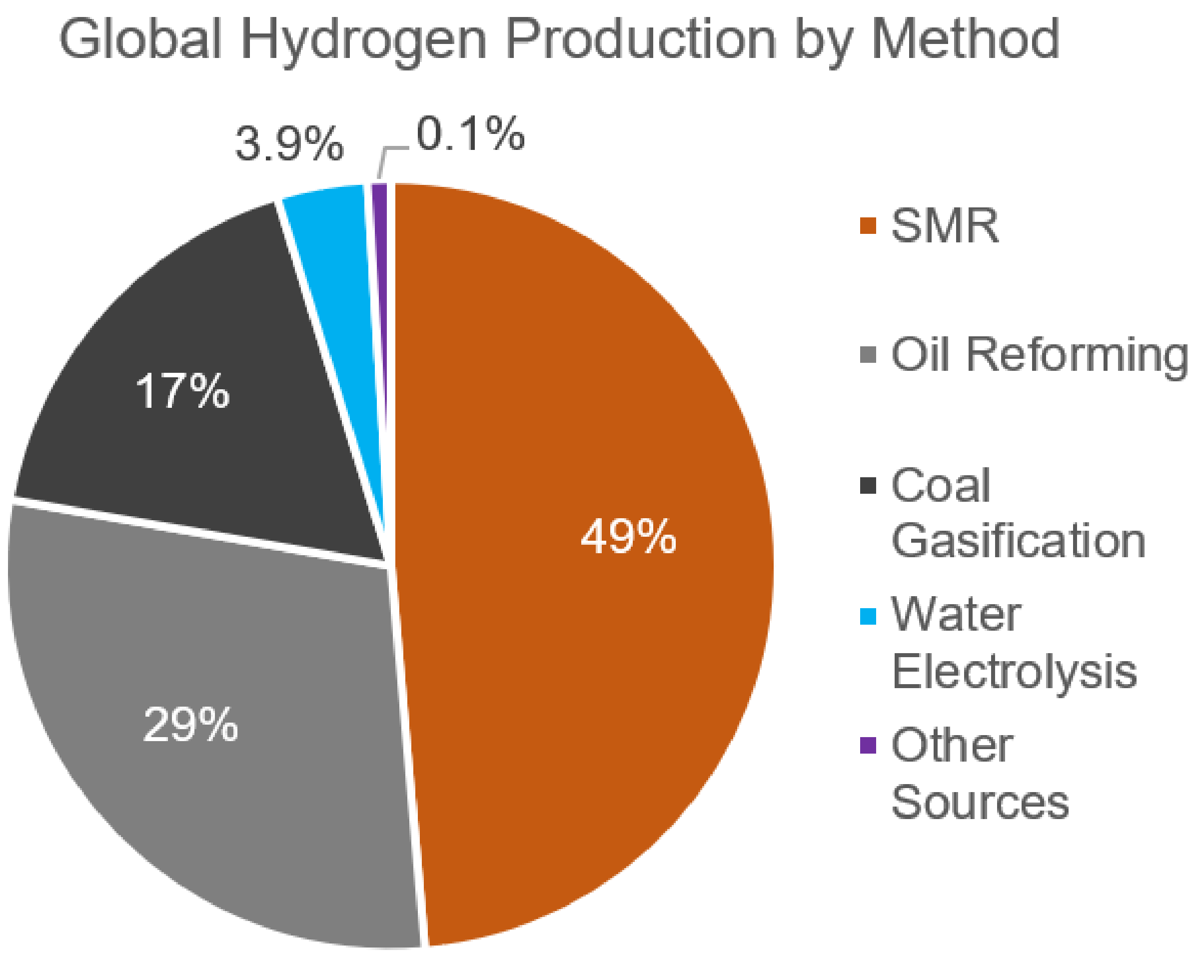
Hydrogen production



Hydrogen production

- Grey hydrogen is generated from natural gas, or methane, through a process called “steam reforming". Generates less CO_2 emission than Black or brown hydrogen, which uses black (bituminous) or brown (lignite) coal in the hydrogen-making process.
- Blue hydrogen is generated by steam reforming as above and CO_2 generated is captured and stored underground through carbon capture and storage (CSS).
- Green hydrogen – also referred to as “clean hydrogen” – is produced by using renewable energy sources, such as solar or wind power, to split water into two hydrogen atoms and one oxygen atom through electrolysis and is produced in a climate-neutral manner

Method



(Dincer & Acar, 2015)

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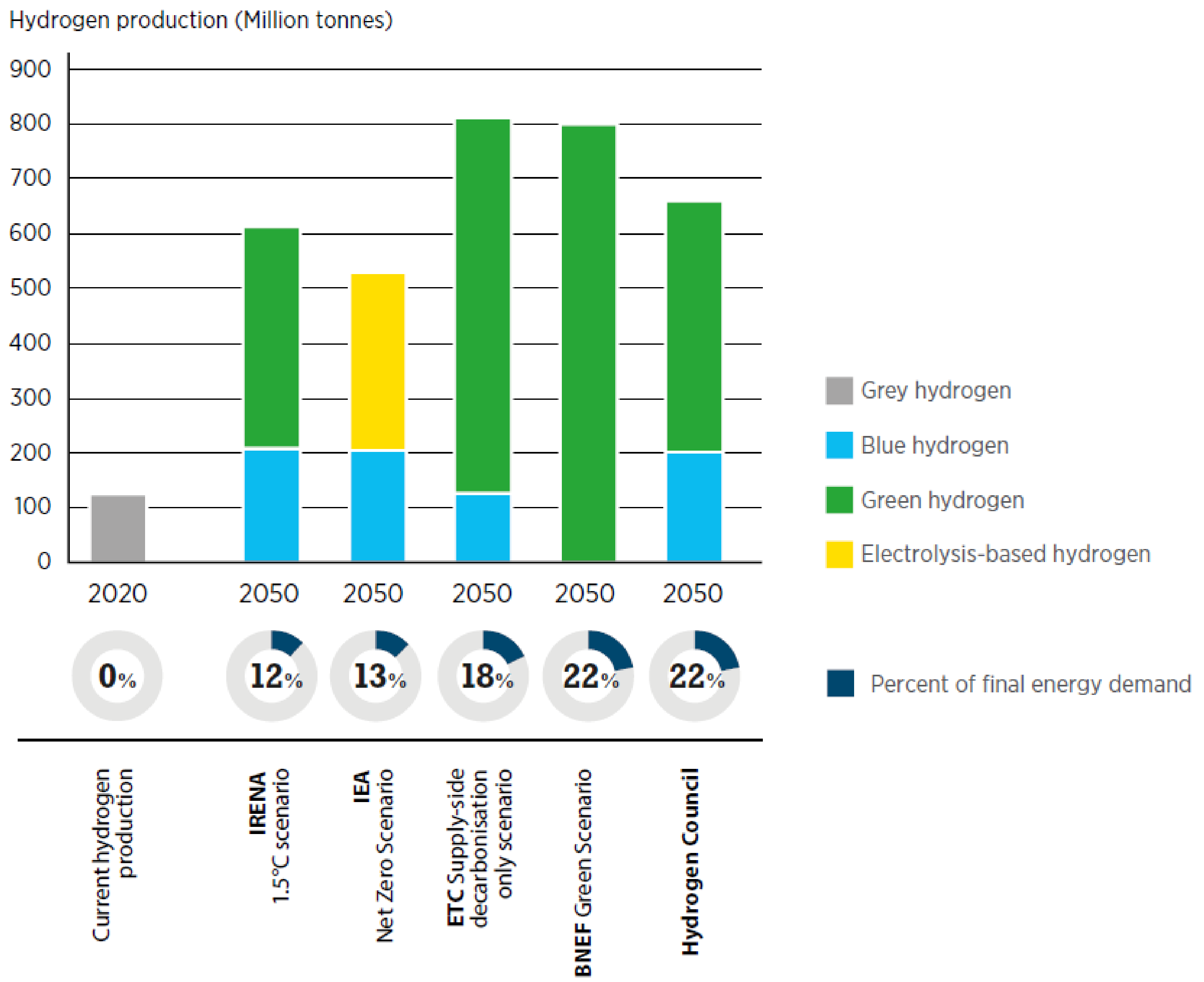


Hydrogen production (Million tonnes)
900
800
700
600
500
400
300
200
100
0
2020
2050
2050
2050
2050
2050
0%
12%
13%
18%
22%
22%
Current hydrogen production
IRENA 1.5°C scenario
IEA Net Zero Scenario
ETC Supply-side decarbonisation only scenario
BNEF Green Scenario
Hydrogen Council
Grey hydrogen
Blue hydrogen
Green hydrogen
Electrolysis-based hydrogen
Percent of final energy demand

Photo Catalytic water Splitting

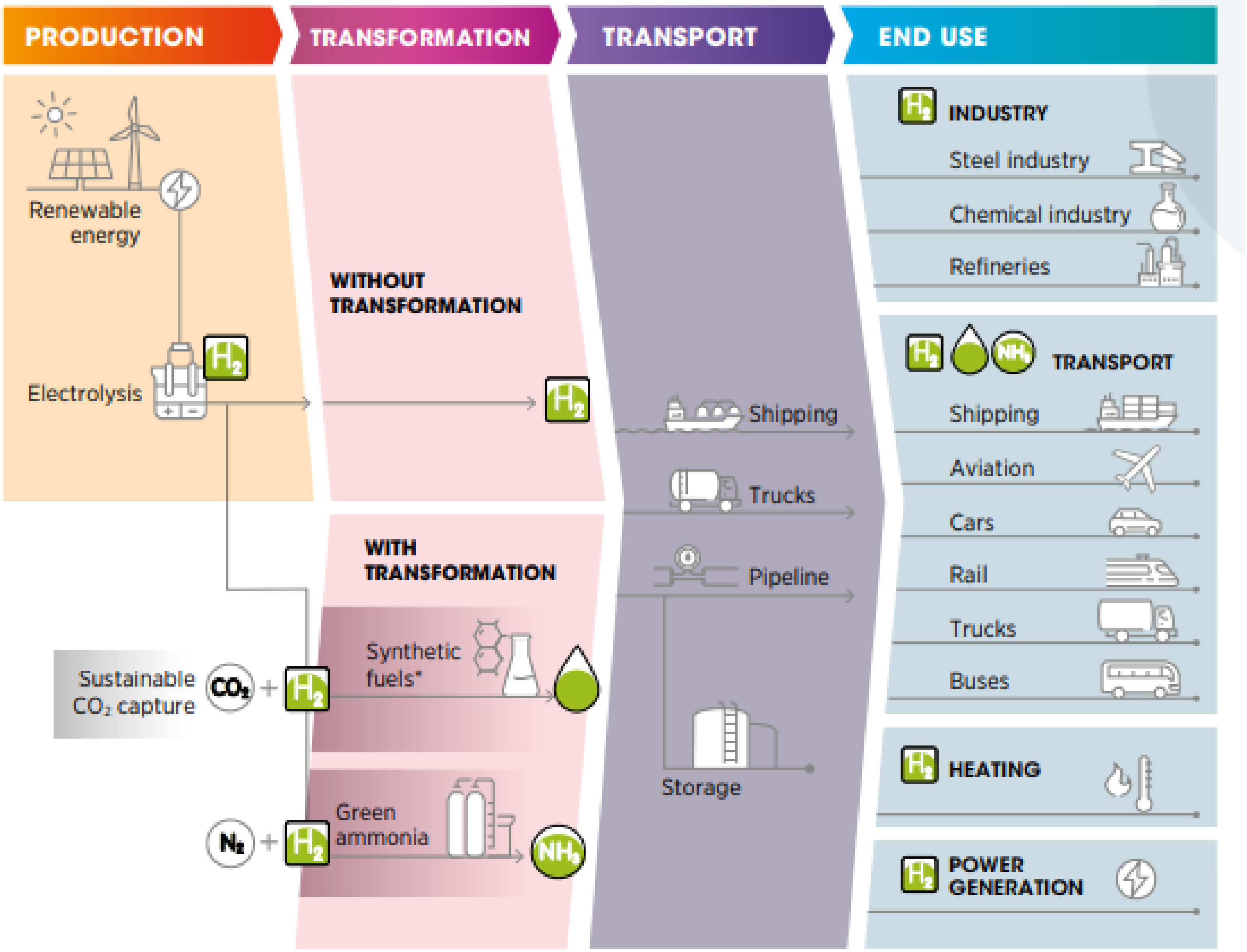
- Photocatalytic water splitting into hydrogen and oxygen using a semiconductor catalyst.
- Recently, photocatalytic water splitting has been employed in industrial effluent treatment and has attracted considerable attention.
- The mechanism basically involves 4 main steps,

The generation of electron–hole pairs from light irradiation on the photo-anode

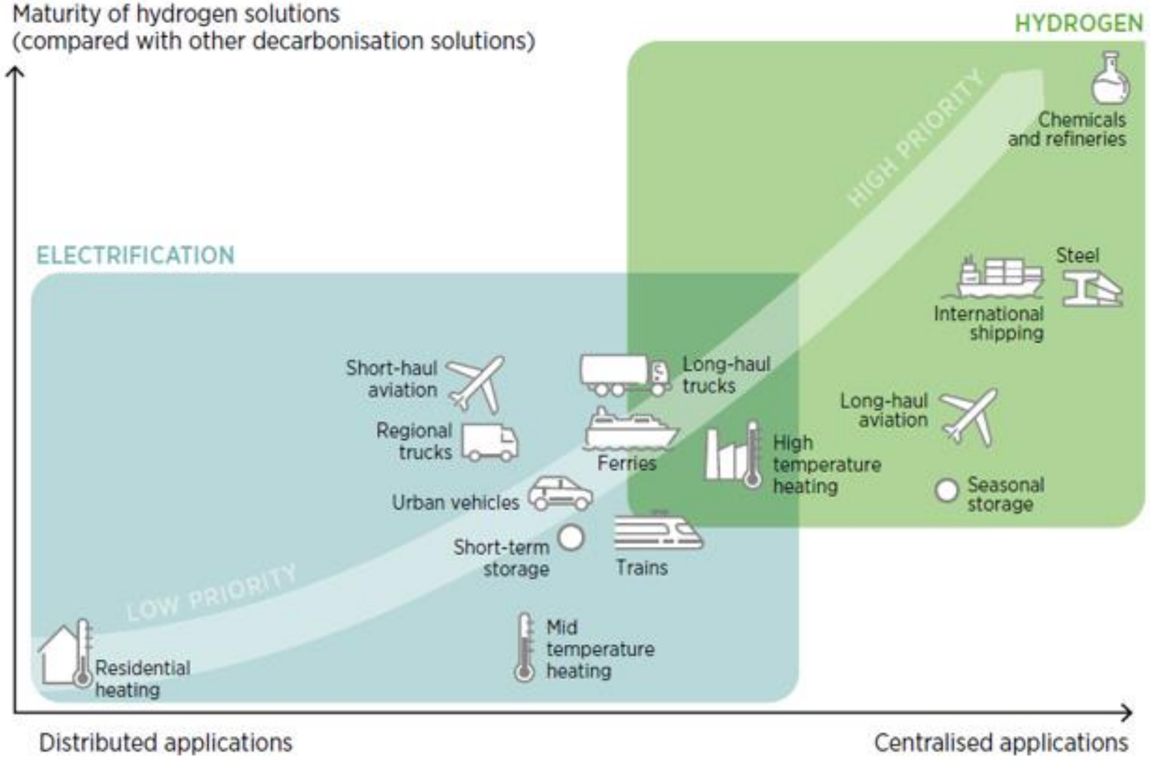
The oxidation of water by photo-generated holes on the photo-anode surface to produce O2 and H+

The transfer of photo-generated electrons through an external circuit to the cathode and the

Reduction of H+ by photo-generated electrons on the cathode surface to produce H2

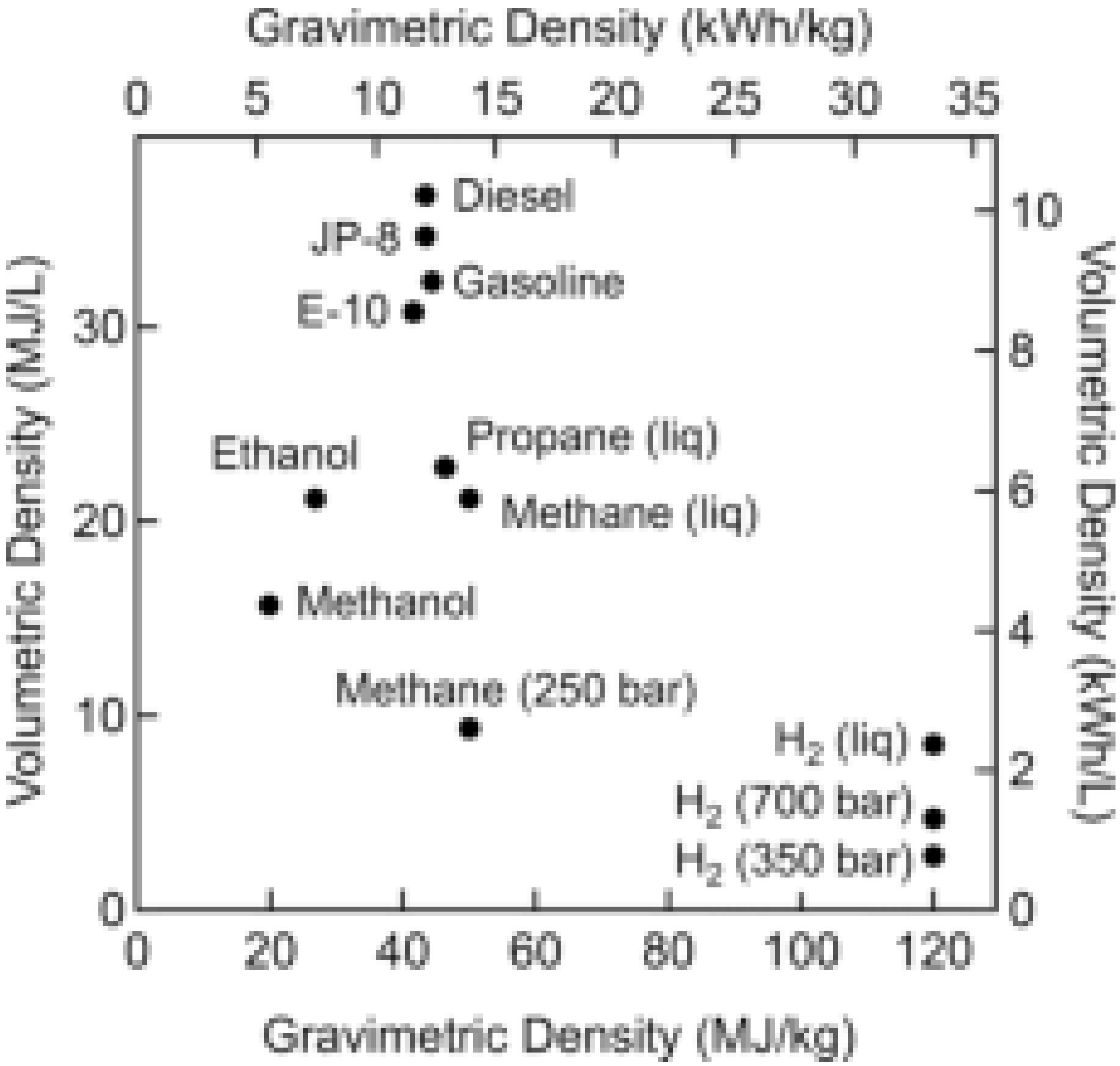

PRODUCTION
TRANSFORMATION
TRANSPORT
END USE
Renewable energy
Electrolysis
WITHOUT TRANSFORMATION
WITH TRANSFORMATION
Sustainable CO₂ capture
Synthetic fuels*
Green ammonia
Shipping
Trucks
Pipeline
Storage
INDUSTRY
Steel industry
Chemical industry
Refineries
TRANSPORT
Shipping
Aviation
Cars
Rail
Trucks
Buses
HEATING
POWER GENERATION

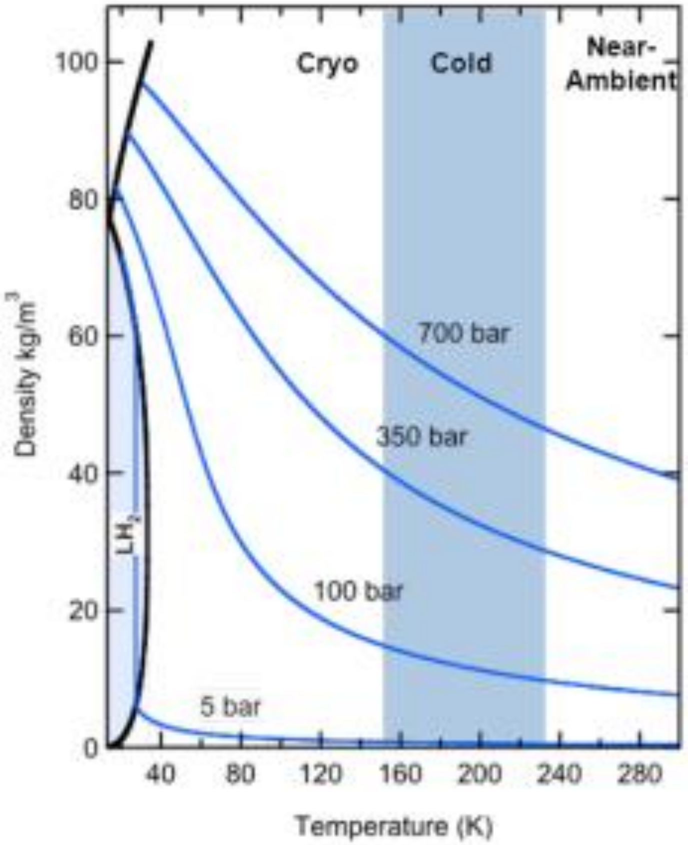
Clean hydrogen policy priorities



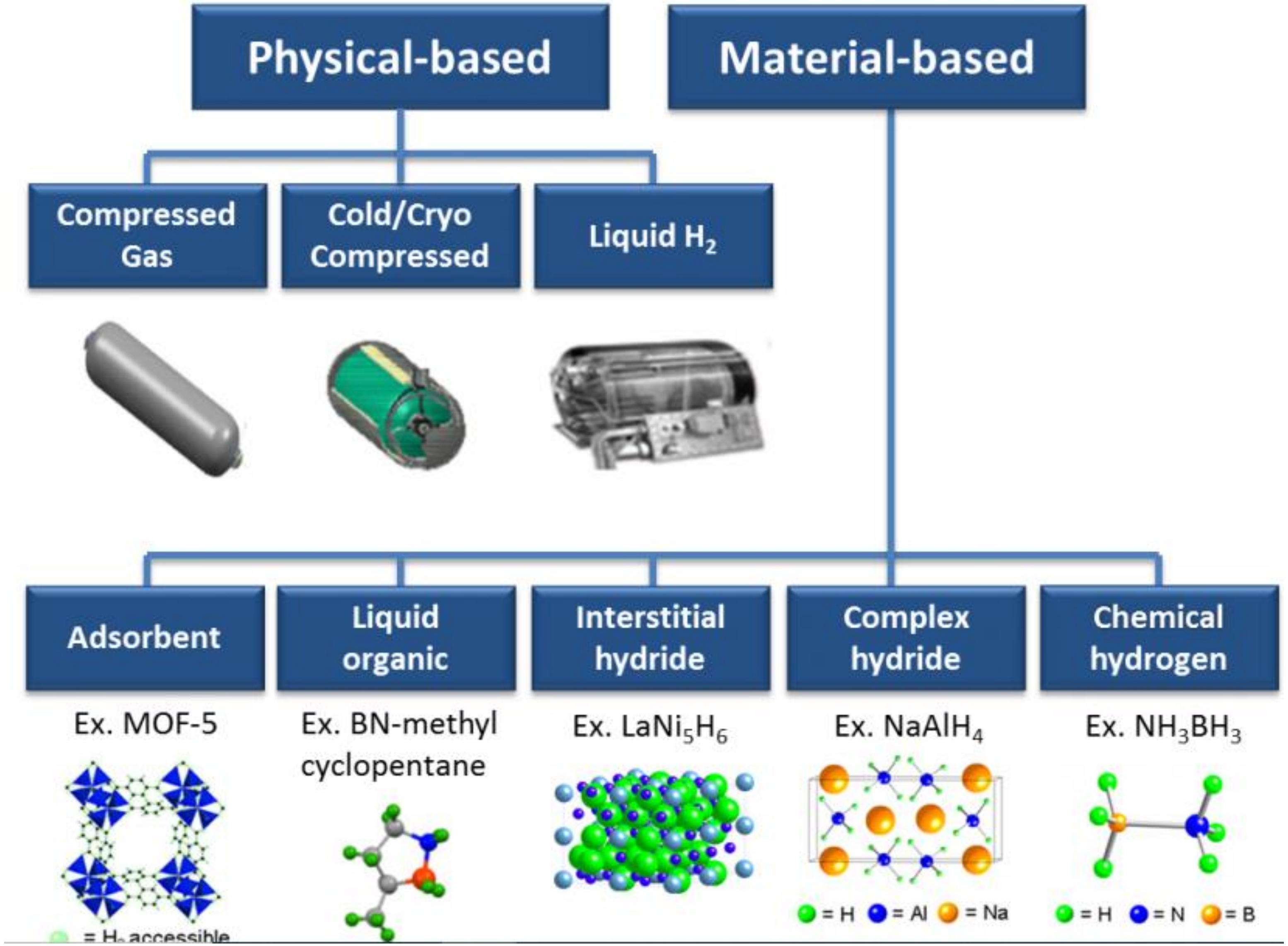
Hydrogen Storage

- Hydrogen has a low energy density. While the energy per mass of hydrogen is substantially greater than most other fuels, its energy by volume is much less than liquid fuels like gasoline.
- For a 300 mile driving range, an Fuel Cell Electric Vehicle will need about 5 kg of hydrogen. At 700 bar (~10,000 psi) a storage system would have a volume of about 200 liters or 3-4 times the volume of gasoline tanks typically found in cars.
- A key challenge, therefore, is how to store sufficient quantities of hydrogen onboard without sacrificing passenger and cargo space.
- Much of the effort of the Hydrogen Storage program is focused on developing cost-effective hydrogen storage technologies with improved energy density.
- Research and development efforts include high pressure, low temperature compressed storage and materials-based storage technologies


Gravimetric Density (kWh/kg)
Volumetric Density (MJ/L)
Volumetric Density (kWh/L)
Gravimetric Density (MJ/kg)
Diesel
JP-8
Gasoline
E-10
Ethanol
Propane (liq)
Methane (liq)
Methanol
Methane (250 bar)
H2 (liq)
H2 (700 bar)
H2 (350 bar)


Cryo
Cold
Near-Ambient
Density kg/m3
LH2
700 bar
350 bar
100 bar
5 bar
Temperature (K)

How is hydrogen stored?



Solid state storage; Chemisorption

- Hydrogen can also be densely stored in materials at low pressures.
- Atomic hydrogen can bind with other elements to form compounds or solid solutions
- Two types of metal hydrides investigated as reversible

    Intermetallic (or interstitial) hydrides where hydrogen occupies interstitial spaces within metal alloys (e.g., $LaNi_5H_6$)

    Complex hydrides where hydrogen covalently bonds to a metal to form multi-element anion that combines with another metal(s) through ionic interactions (e.g., $Na(AlH_4)$)

- Hydrogen is released from chemical hydrogen storage materials through non-equilibrium processes so the now-depleted materials have to be removed and chemically processed to regenerate the original hydrogen containing material.

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- Metallic vs complex Hydrides: The principal difference between them is the transition of metals to ionic or covalent compounds on absorbing hydrogen.
- Metal hydrides are composed of two elements. The ‘A’ element is ordinarily a rare earth or an alkaline earth metal. Nickel is frequently used as B element for it is a catalyst for the hydrogen dissociation.
- The formation of metallic hydrides is an exothermic response
- Extra stable the hydride is, more heat is needed to desorb hydrogen
- Complex hydrides: Group I, II, and III factors, e.g. Li, Mg, B, Al, build a giant kind of steel–hydrogen complexes.
- The number of hydrogen atoms per metallic atom is 2 in many circumstances.
- High volumetric and gravimetric density, at room temperature and normal pressure and reversibility are the guidelines eg $NaAlH_4$ can reversibly soak up/desorb hydrogen at reasonable temperatures.
- Mg hydrides in contemporary years, is also another area of research where hydrogen can be released using light .

Physisorption

- Molecular hydrogen can adsorb onto the surface of porous solids, providing the potential for higher storage densities at significantly lower pressures.
- Hydrogen sorbents are high-surface area, micro-porous solids (e.g., activated carbons or metal-organic frameworks (MOFs)) where the diatomic hydrogen molecule adsorbs onto the surface through van der Waals interactions.
- The challenge for all hydrogen storage material development efforts is to develop cost effective materials with high hydrogen density by volume and mass.
- Moreover, these materials must be capable of fast charge/discharge rates within the temperature and pressure ranges of fuel cell operation .
- Able to undergo sufficient charge/ discharge cycles to last the lifetime of the FCEV.

Metal –organic-framework (MOF s)

- MOF s are porous crystals made of metal ions ,where large pores within crystal can store hydrogen gas.
- MOF s have high surface areas and hydrogen adsorption capacities where hydrogen molecules cling to the surface of Mof s cavities .
- MOF s can also store liquid hydrogen and are cost competitive
- They have a simple charge / discharge mechanism ,allowing stored hydrogen to be released without any chemical reaction.
- As per Berkley lab MOF s could be cost competitive as a 10 MW microgrid back up.
- Mof s are still in the R and D realm .

Chemisorption vs Physisorption

Physisorption	Chemisorption
It is due to the formation of van der Waals forces.	It is due to the formation of chemical bonds.
It is reversible in nature.	It is irreversible in nature.
Physisorption is not specific in nature.	It is very specific in nature.
It has low adsorption enthalpy nearly 20 to 40 kJ/mol.	Chemisorption has high adsorption enthalpy nearly to 240 kJ/mol.
It favours low temperature.	It favours high temperature.
Physisorption decreases with increase in temperature.	Chemisorption increases with increase in temperatu
It results in a multimolecular layer.	It results in a unimolecular layer.
Activation energy is less in physisorption.	Activation energy is high in chemisorption.

Summarising

- Storage of hydrogen in a pressurized cylinder is not likely to be applied in the future due to the low density and high cost at high pressures.
- Liquid hydrogen could be applied if the unit cost becomes comparable with gasoline, yet the inevitable boiling-off of liquid might be of concern.
- Metallic hydrides of heavy metals cannot get rid of the constraint of gravimetric density, and the relatively high temperature of ab- and desorption and the large amount of energy required for releasing hydrogen remain the barriers for the light metal hydrides.
- Complex hydrides are still in the domain of research and development.

Cond

- Physisorption of hydrogen on nanotubes/nanofibers of any materials seems hopeless for enhancing the hydrogen density due to the small surface area.
- Cry adsorption of hydrogen on super activated carbon of abundant slit-like micro-pores (<2 nm) is presently promising because it reaches the gravimetric density of more than 10 wt% and a reasonable volumetric density of 41 kg/m3 at relatively low cost.
- However, to find out better technique of hydrogen storage remains a challenge facing us

Areas of Concern

- High Production cost of fuel from green hydrogen

Vehicles with fuel cells and hydrogen tanks cost at least 1.5 to 2 times more than their fossil fuel counterparts .Synthetic fuels for aviation are today, even at the best sites in the world, up to eight times more expensive than fossil jet fuel.

- Lack of Infrastructure for green hydrogen

There are only about 5000 kms of hydrogen transmission pipelines around the world compared with more than 3 million kms for natural gas. There are 470 hydrogen refuelling stations around the world), compared with more than 200000 petrol and diesel refuelling stations in the United States and the EU

ENERGY LOSSES

About 30-35% of the energy used to produce hydrogen through electrolysis is lost .In addition, the conversion of hydrogen to other carriers can result in 13-25% energy loss, and transporting hydrogen requires additional energy inputs, which are typically equivalent to 10-12% of the energy of the hydrogen itself Using hydrogen in fuel cells can lead to an additional 40-50% energy loss.

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The key issue is whether the annual pace of development of the solar and wind potential will be fast enough to meet the needs for both the electrification of end uses and the development of a global supply chain in green hydrogen, and the cost that this additional capacity will entail.

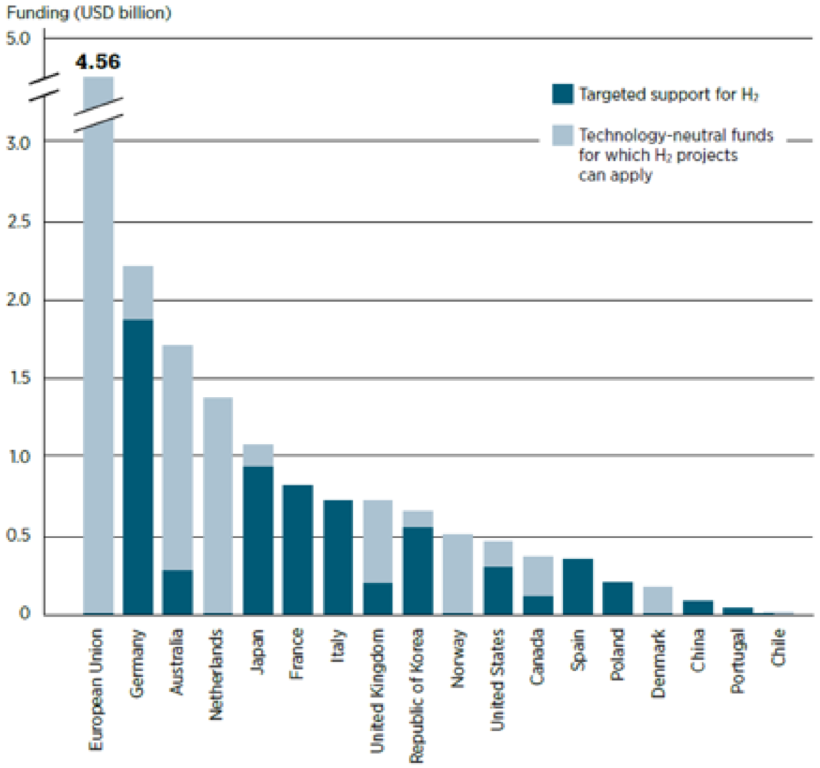
LACK OF VALUE RECOGNITION

There is no green hydrogen market, no green steel, no green shipping fuel and basically no valuation of the lower GHG emissions that green hydrogen can deliver. Hydrogen is not even counted in official energy statistics of total final energy consumption, and there are no internationally recognized ways of differentiating green from grey hydrogen. This limits the demand for green hydrogen.

NEED TO ENSURE SUSTAINABILITY

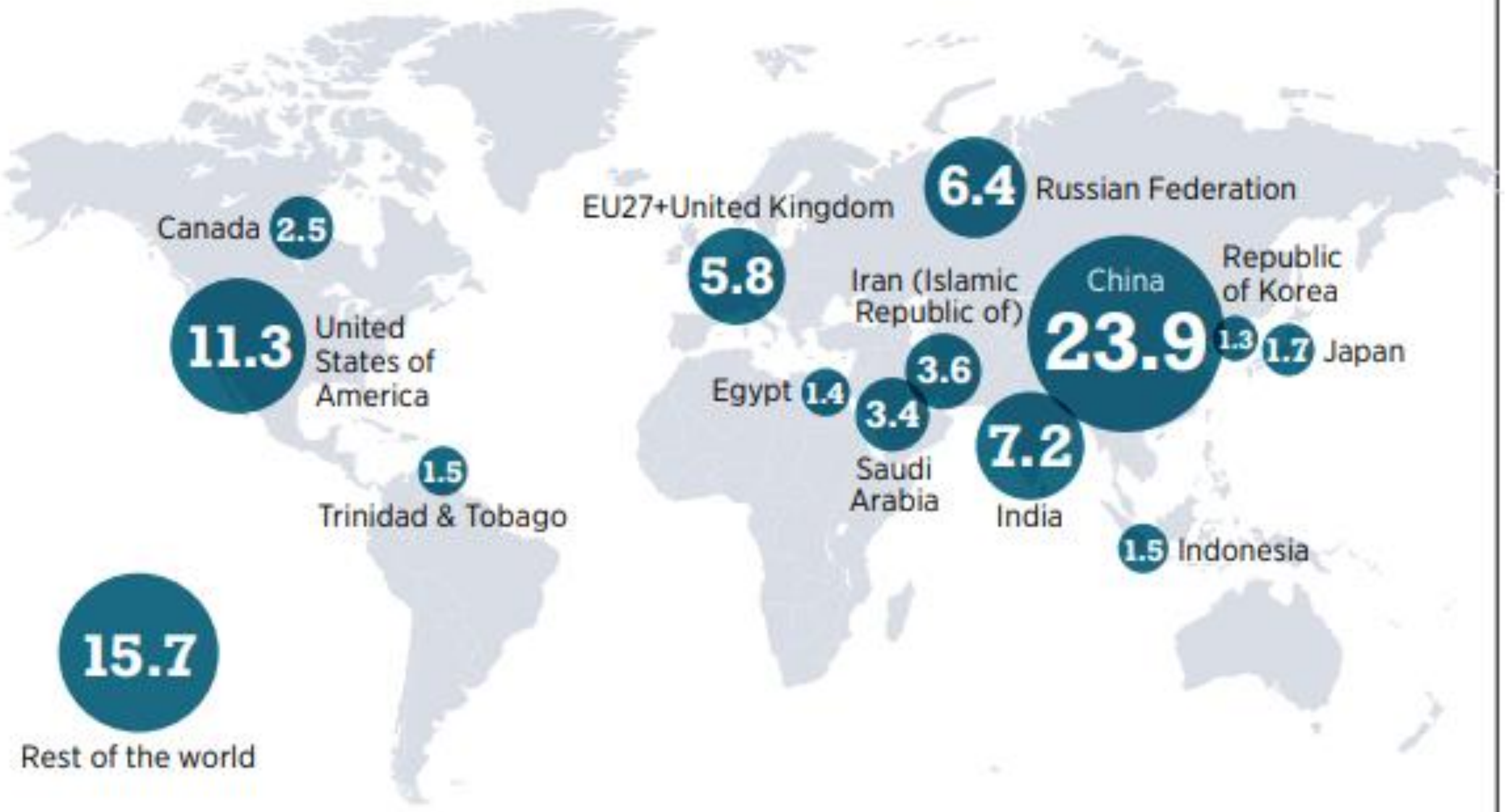
For hydrogen from electrolysis to have lower overall emissions than grey hydrogen, CO2 emissions per unit of electricity need to be lower than 190 grams of CO2 per kilowatt-hour (Reiter and Lindorfer, 2015). Only a few countries (mostly benefiting from hydropower) have average CO2 emissions per kWh below that threshold and thus can ensure the sustainability of electrolytic hydrogen. Most other countries are currently above that threshold.

Average annual funding potentially available for hydrogen projects, 2021-2030



As of August 2021

Hydrogen Consumption in Mt per anumn

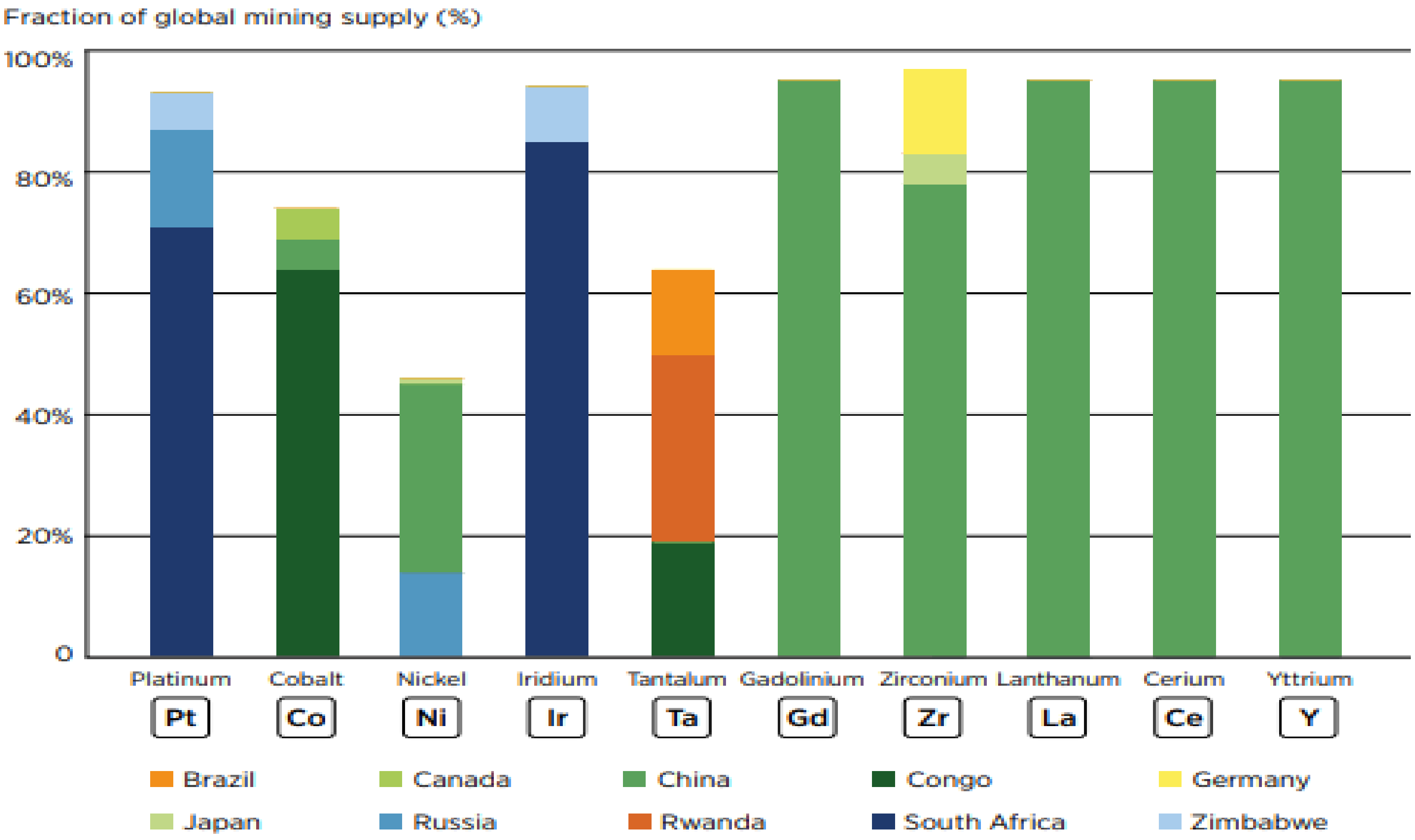


Map source: Natural Earth, 2021

Note: Values are derived from current production of ammonia, methanol, refining and direct reduced iron for steel.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

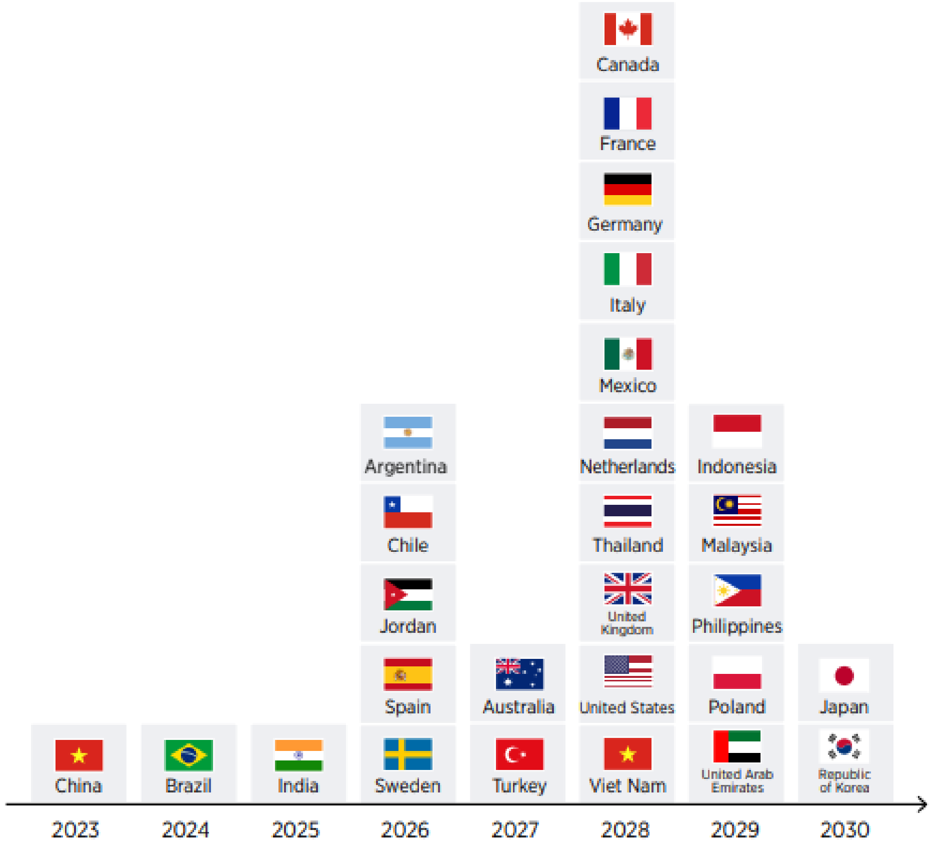
Producers of critical materials for electrolyser



Source: IRENA (2020a).

Countries in which green hydrogen could possibly become cheaper than blue hydrogen, by year

- 2.5 dollars per kg by 2025 and 1 $ by 2030 as per Niti Ayog ,and formation of global carbon markets.



Source: BloombergNEF (2021d).

Circular economy

- Advance technology and improve policy for reuse
- Broken solar panels release toxic pollutants, like Ag, Pb ,Ar, Cd, Ga ,Si dust etc 250,000 MT est of IRENA in 2018 .
- Batteries also generate waste like Li , Co ,Ni, Mn, Cu, Al, steel and Plastic
- Waste to energy plants ,renewable energy waste to electricity, a viable solution , even fossil fuel derived products like plastics release half the carbon dioxide of a coal based plant.
- Food waste when incinerated produce carbon dioxide ,sustainability an issue type of waste matters
- Challenges are financial for disposal of waste costs more than the waste, but landfill is hazardous
- Technology can help in selecting materials with less waste like limiting silicon in solar panels and elements which are recyclable.

- Thank You

Storage Media		Volume	Mass	Pressure	Temperature	
	molecular H_2	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
		20 kg $H_2 \cdot m^{-3}$	4 mass%	70 bar	65 K	Physisorption
	atomic H	max. 150 kg $H_2 \cdot m^{-3}$	2 mass%	1 bar	298 K	Metalhydrides
		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

	GREY HYDROGEN	BLUE HYDROGEN	GREEN HYDROGEN
Process	Reforming or gasification	Reforming or gasification with carbon capture	Electrolysis
Energy source	Fossil fuels	Fossil fuels	Renewable electricity
Estimated emissions from the production process[a]	Reforming: 9 – 11[b] Gasification: 18 – 20	0.4-4.5[c]	0

Note: a) $CO_{2\text{-eq}}$/kg = carbon dioxide equivalent per kilogramme; b) For grey hydrogen, 2 kg $CO_{2\text{-eq}}$/kg assumed for methane leakage from the steam methane reforming process. c) Emissions for blue hydrogen assume a range of 98% and 68% carbon capture rate and 0.2% and 1.5% of methane leakage.

Physisorption vs Chemisorption

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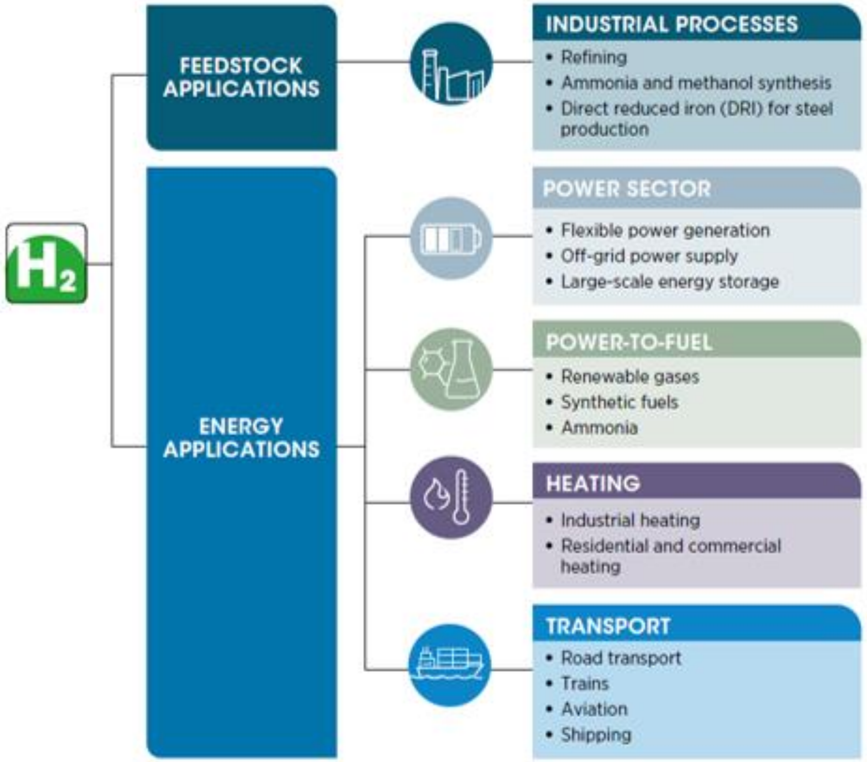
It is reversible in nature.	It is irreversible in nature.
Physisorption is not specific in nature.	It is very specific in nature.
It favours low temperature and low activation energy.	It favours high temperature and high activation energy.
In Physisorption, enthalpy change is low that is nearly 20 to 40 kJ/mol.	In Chemisorption, enthalpy change is high that is nearly 80 to 240 kJ/mol.


H2
FEEDSTOCK APPLICATIONS
ENERGY APPLICATIONS
INDUSTRIAL PROCESSES
• Refining
• Ammonia and methanol synthesis
• Direct reduced iron (DRI) for steel production
POWER SECTOR
• Flexible power generation
• Off-grid power supply
• Large-scale energy storage
POWER-TO-FUEL
• Renewable gases
• Synthetic fuels
• Ammonia
HEATING
• Industrial heating
• Residential and commercial heating
TRANSPORT
• Road transport
• Trains
• Aviation
• Shipping