Hydrogen – a Viable Fuel for the Future?

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In 2021, World's hydrogen demand reached 94 million tonnes, mostly due to increased traditional usage in petroleum refining and industry.

Demand for new uses grew to about 40 thousand tonnes, a miniscule amount.

Most of the increase was met by unabated fuels, meaning there was no supposed benefit for mitigating for so called "climate change".

In 2021, the production of low emission hydrogen was less than 1 million tonnes, almost all of it from plants using fossil fuels with carbon capture, utilisation and storage (CCUS).

Let's now look at Hydrogen and it's production, transport and cost in some detail.

Properties of Hydrogen

Discovery date : 1786

Discovered by : Henry Cavendish

Origin of Name : The name is derived from the Greek " hydro" and "genes" meaning water forming

Atomic Number : 1

Abundance : the most abundant element on earth

Melting Point : -259.18 deg C

Boiling Point : - 252.879 deg C

Density : 0.000082 g/cc

Isotopes: H^1 (Protium) 99.99%, H^2 (Deuterium) 0.01% and H^3 (Tritium) 10^{-15}%

Colour: colourless gas

PROPERTIES OF SELECTED FUELS

Fuel	Density		Higher Calorific Value (GCV)			Lower Calorific Value (NCV)		
	kg/m3	kg/Litre	MJ/kg	MJ/m3	MJ/Litre	MJ/kg	MJ/m3	MJ/Litre
Hydrogen	0.09		141.7	12.7		120	10.8	
Natural Gas (USA)	0.777		52.2	40.6		47.1	36.3	
LNG		0.428	55.2		23.6	48.6		20.8
LPG		0.537	49.3		26.5	45.5		24.4
Biodiesel		0.92	40.5		35.7	37.5		33.3
Methanol		0.781	23		18.2	19.9		15.8
Bituminous Coal			30.2			29		
Wood (dry)			16.2			15.4		

The Colours of Hydrogen

Courtesy of CS Energy Web Site

Hydrogen Production Processes

Thermochemical Processes

- Natural gas reforming (also called steam methane reforming or SMR)
- Biomass gasification
- Biomass-derived liquid reforming
- Solar thermochemical hydrogen (STCH).

Electrolytic Processes

Direct Solar Water Splitting Processes

- Photoelectrochemical (PEC)
- Photobiological.

Biological Processes

- Microbial biomass conversion
- Photobiological.

Hydrogen Production: Natural Gas Reforming (1)

- Mature production process by which ~95% of Hydrogen is produced today
- Main process is steam-methane reforming of natural gas by steam at 700 -1000 deg C and 3 – 25 bar pressure
- Reaction is endothermic and heat must be supplied for the reaction to proceed
- $CH_4 + H_2O$ (+heat) $\Longrightarrow$ $CO + 3H_2$
- The CO is then reacted with steam and a catalyst to form more H_2. This is the "water-shift gas reaction"
- $CO + H_2O \Longrightarrow CO_2 + H_2$ (+ a small amount heat)
- The final step is called "pressure – swing adsorption" where CO_2 and other impurities are removed.

Hydrogen Production : Partial Oxidation (2)

- In partial oxidation, the hydrocarbons in natural gas react with a limited amount of oxygen so that the hydrocarbons do not form H_2O and CO_2
- The CO is then reacted with water to produce more hydrogen and CO_2
- Partial oxidation is an exothermic reaction and much faster
- $CH_4 + 1/2O_2 \Longrightarrow CO + 2H_2$ (+heat)
- $CO + H_2O \Longrightarrow CO_2 + H_2$ (+ small amount of heat)

Hydrogen Production – Biomass Gasification

- Biomass gasification is a mature technology that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products, without combustion.

- Biomass, a renewable organic resource, includes agriculture crop residues, forest residues, special crops grown specifically for energy use, organic municipal solid waste, and animal wastes.

- Gasification converts organic materials at high temperatures (>700°C), without combustion, with a controlled amount of oxygen and/or steam into carbon monoxide, hydrogen, and carbon dioxide.

- Simplified example reaction - $C_6H_{12}O_6$ (glucose)+ $O_2 + H_2O \rightarrow CO + CO_2 + H_2$ + other species

- Water-gas shift reaction - $CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

- In general, biomass does not gasify as easily as coal, and it produces other hydrocarbon compounds in the gas mixture exiting the gasifier. As a result, typically an extra step must be taken to reform these hydrocarbons with a catalyst to yield a clean syngas mixture of hydrogen, carbon monoxide, and carbon dioxide.

- Hydrogen produced is then separated and purified

- In the United States, up to 1 billion dry tons of biomass could be available for energy use annually.

Hydrogen Production: Biomass – Derived Liquid Reforming

* Liquids from biomass such as ethanol and bio-oils can be reformed to produce hydrogen by a process similar to natural gas reforming

* Steam reforming reaction (ethanol) - $C_2H_5OH + H_2O$ (Heat) $\Longrightarrow$ $2CO + 4H_2$

The liquid fuel is reacted with steam at high temperature to produce a gas, mostly of H_2, CO and some CO_2

Additional H_2 and CO_2 can be produced by reacting the CO so produced with high temperature steam, "water gas shift reaction"

Finally, the hydrogen is separated and purified

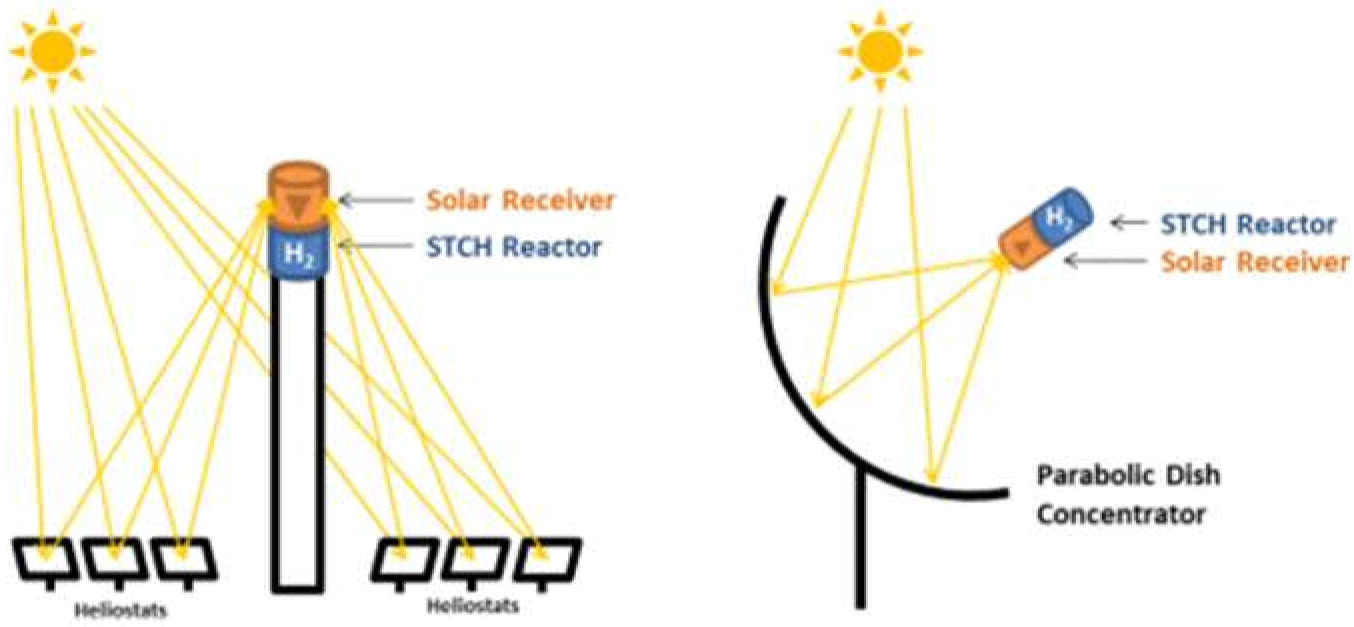
Water-gas shift reaction: $CO + H_2O \Longrightarrow CO_2 + H_2$ (+ small amount of heat)

Hydrogen Production: Thermochemical Water Splitting

Thermochemical water splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen.

The necessary high temperatures can be generated in the following ways:

- Concentrating sunlight onto a reactor tower using a field of mirror "heliostats"
- Using waste heat from advanced nuclear reactors.



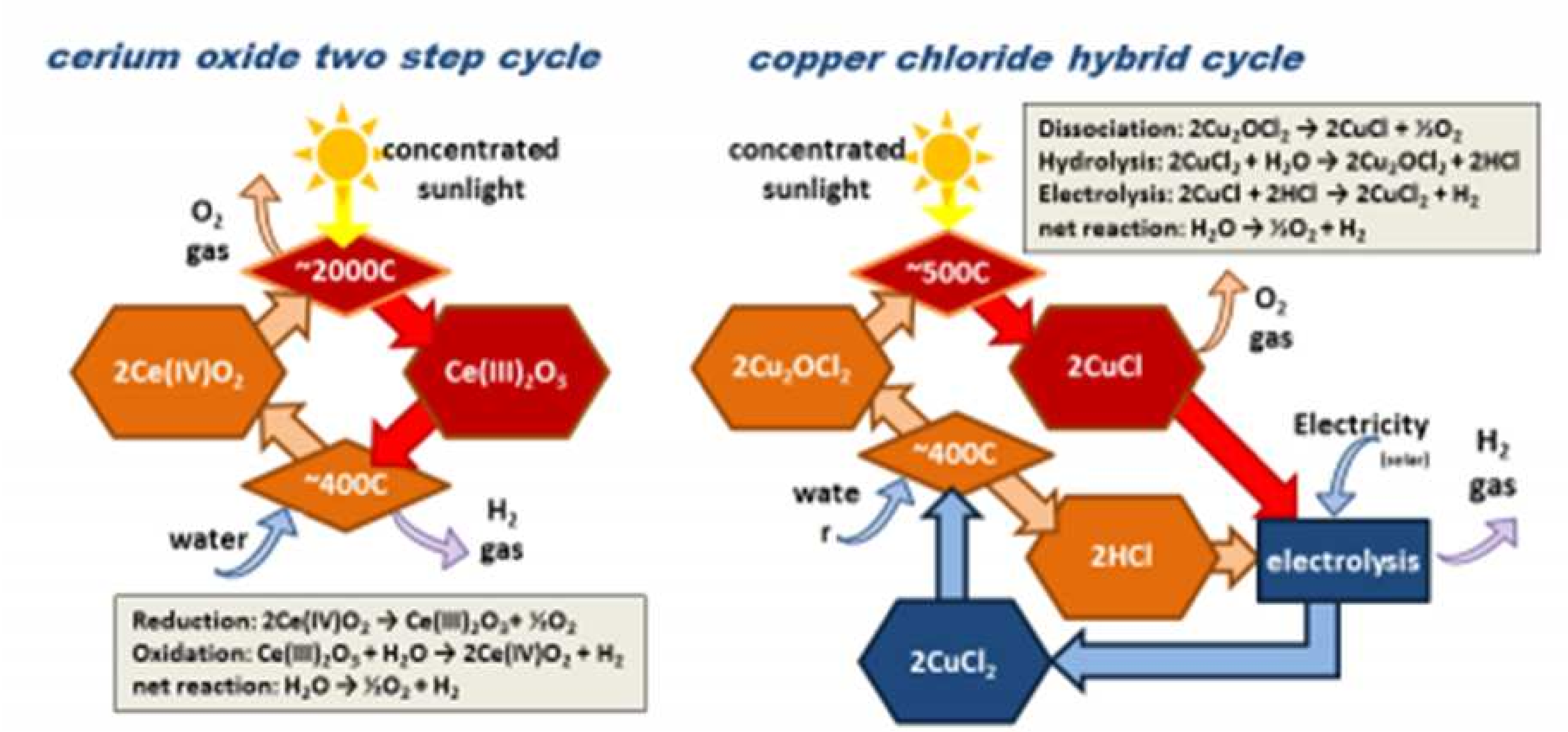
(a) Central receiver/reactor tower with heliostats

(b) Modular dish-mounted receiver/reactor

- Two examples of thermochemical water splitting cycles, the "direct" two-step cerium oxide thermal cycle and the "hybrid" copper chloride cycle

- Typically direct cycles are less complex with fewer steps, but they require higher operating temperatures compared with the more complicated hybrid cycles.

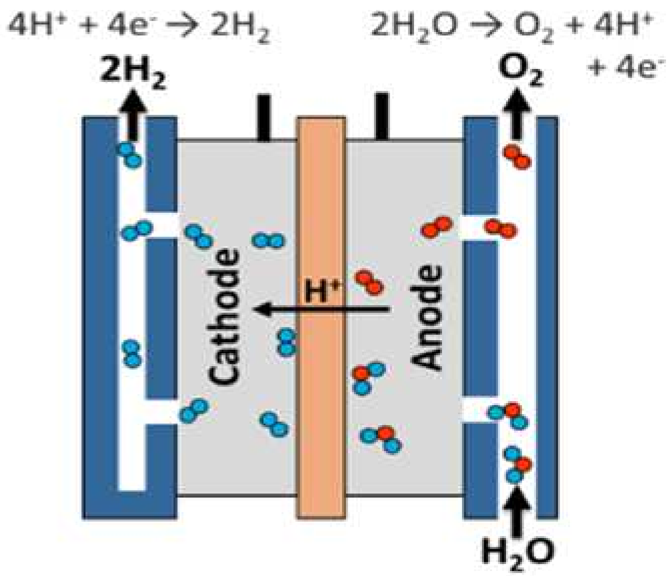
- Solar high-temperature thermochemical water-splitting cycles produce hydrogen with near-zero greenhouse gas emissions using water and sunlight.



Hydrogen Production: PEM Electrolysis

* Electrolysis is the process of using electricity to split water into hydrogen and oxygen

* Electrolysers consist of an anode and a cathode separated by an electrolyte



* In a polymer electrolyte membrane (PEM) electrolyser the electrolyte is a solid specialty electrolyte

* Water reacts at the anode to form O2 and +vely charged hydrogen ions (protons)

* The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode

* At the cathode, the hydrogen ions combine with electrons from the external circuit to form H2 gas

* Anode reaction: 2H2O $\Longrightarrow$ O2 + $4H^+ + 4e^-$

* Cathode reaction: $4H^+ + 4e^-$ $\Longrightarrow$ 2H2

PEM high pressure electrolyzer system

PEM Electrolyser

- As of 2021, the largest PEM electrolyser is 2
- PEM electrolysis has an electrical efficiency about 80% in working application, in terms hydrogen produced per unit of electricity use drive the reaction
- As the process operates at 80 °C for PEM electrolysers the waste heat can be redirecte through the system to create the steam, resu in a higher overall electrical efficiency
- Operates under pressures up to 30 bar

Alkaline Electrolysers

- These work via the transport of hydroxide ions (OH^-)through the electrolyte from cathode to anode
- Use typically a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte
- New approach is to use solid alkaline membranes (AEM) as the electrolyte and being tested on a lab scale

Solid Oxide Electrolysers

- Use ceramic material as the electrolyte that selectively conducts negatively charged ions (O^{2-}) at elevated temperatures
- Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions
- The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit
- Must operate at high temperature for the solid state membranes to function (700 – 800 C, compared with PEM at 70 – 80 C)
- Can effectively use heat available from external sources (e.g. nuclear reactor) to decrease the electrical energy needed as heat

Direct Solar Water Splitting Processes

Photobiological Process

- The photobiological hydrogen production process uses microorganisms and sunlight to turn water, and sometimes organic matter, into hydrogen.

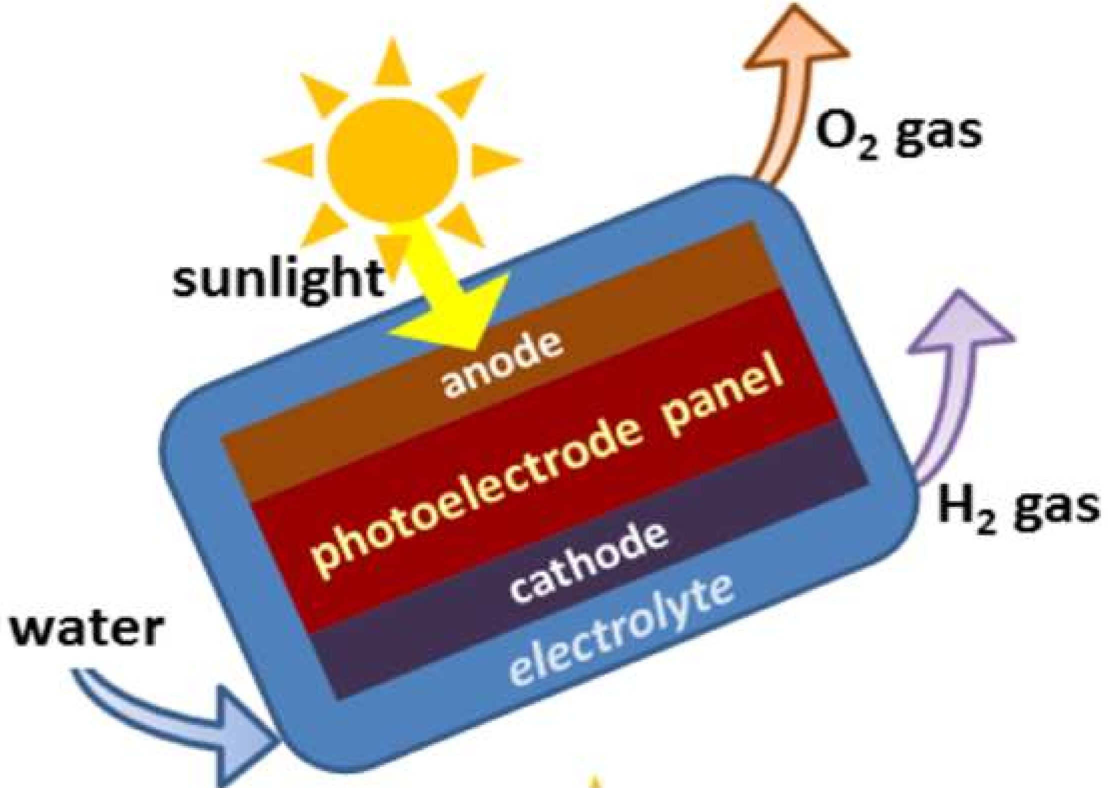
- In photolytic biological systems, microorganisms—such as green microalgae or cyanobacteria—use sunlight to split water into oxygen and hydrogen ions. The hydrogen ions can be combined through direct or indirect routes and released as hydrogen gas

- Challenges for this pathway include low rates of hydrogen production and the fact that splitting water also produces oxygen, which quickly inhibits the hydrogen production reaction and can be a safety issue when mixed with hydrogen in certain concentrations.

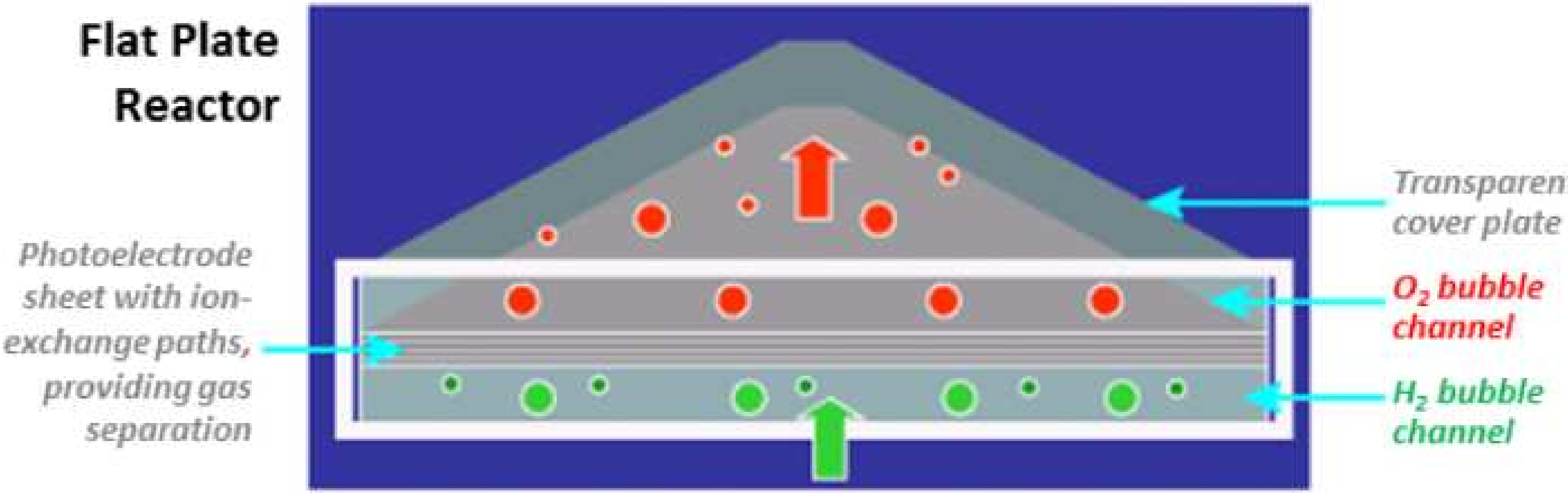
Direct Solar Water Splitting Processes (2)

Photoelectrochemical (PEC)

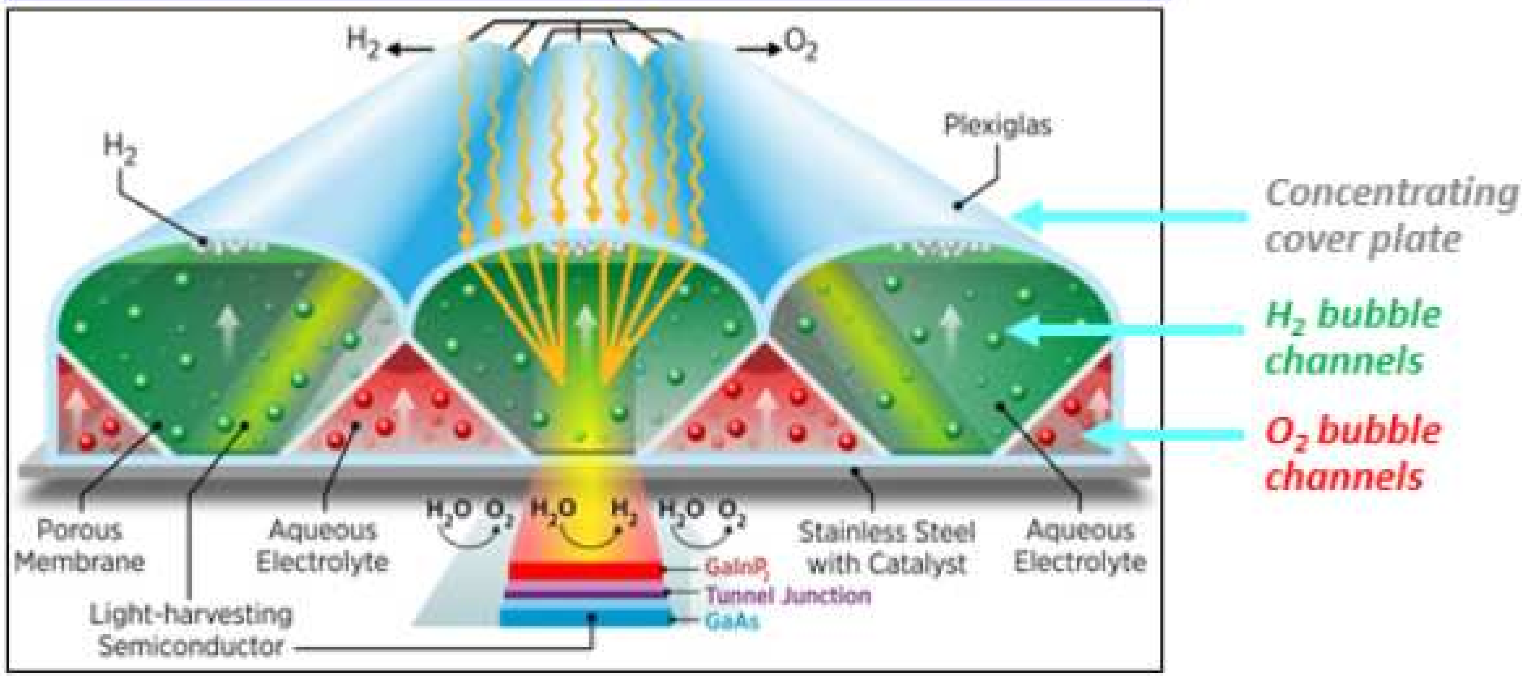
- Hydrogen is produced from water using sunlight and specialized semiconductors called photoelectrochemical materials, which use light energy to directly dissociate water molecules into hydrogen and oxygen
- The PEC water splitting process uses semiconductor materials to convert solar energy directly into chemical energy in the form of hydrogen
- The semiconductor materials used in the PEC process are similar to those used in photovoltaic solar electricity generation, but for PEC applications the semi conductor is immersed in water-based electrolyte, where sunlight energies the water-splitting process



Flat Plate Reactor



Tubular Reactor



Biological Process

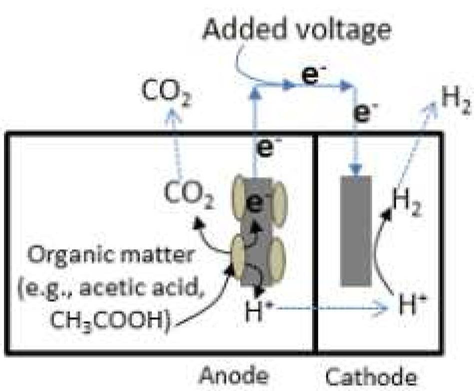
Microbial Biomass Conversion

- In fermentation-based systems, microorganisms, such as bacteria, break down organic matter to produce hydrogen

- The organic matter can be refined sugars, raw biomass sources, and even wastewater

- Researchers are studying how to make fermentation systems produce hydrogen faster (improving the rate) and produce more hydrogen from the same amount of organic matter (increasing the yield)

- Microbial electrolysis cells (MECs) are devices that harness the energy and protons produced by microbes breaking down organic matter, combined with an additional small electric current, to produce hydrogen



Bulk Storage of Hydrogen

Salt Caverns

- Already in use at Teeside (UK) since 1972 and along the Gulf Coast of Texas since 1983
- Projects in France, Germany , Netherlands and Portugal

Depleted Natural Gas Fields

- None currently in use
- Projects in Germany, Austria and Argentina

Aquifers

- Not necessarily as tight as gas fields and none in use
- Have been used for town gas in the past

Lined Hard Rock Caverns

- None in use but could be used for both gaseous hydrogen and liquid hydrogen
- Demonstration facility (100 m3, <250 bar) to store hydrogen in lined hard rock caverns at Luleå.
- At a later stage, a full-scale facility of around (100 000 m3) could be constructed.

Storage of Hydrogen

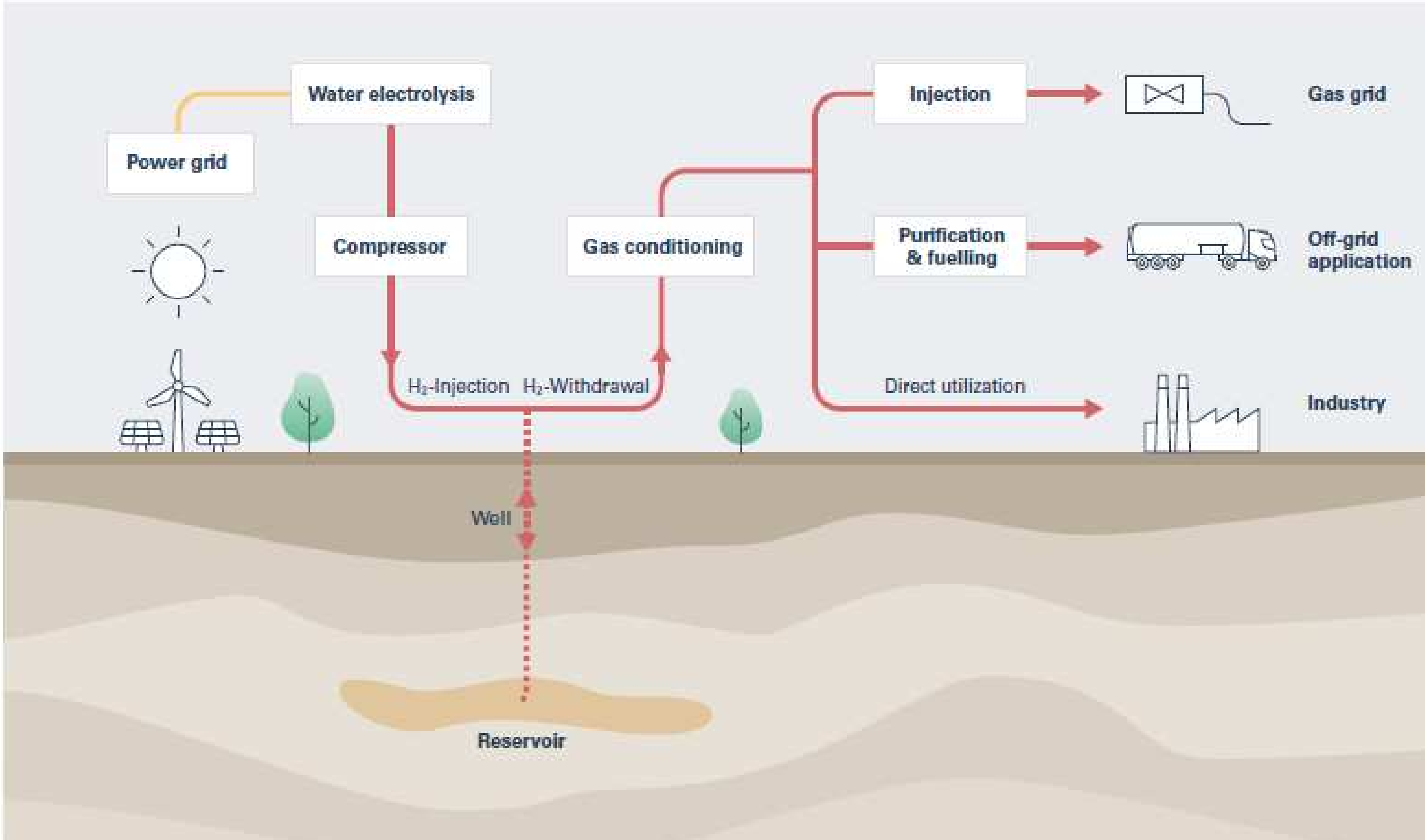
- **Underground natural gas storage plays a key role in meeting gas supply flexibility requirements. Current global storage capacity is close to 430 billion cubic metres (bcm), about 10% of global natural gas demand**
- **Balancing fluctuations in supply from electrolysers using variable renewable electricity and some seasonality in hydrogen demand.**
- **Providing energy security in case of supply disruptions, such as trade conflicts, unforeseen outages, natural disasters, and reducing related price volatility**

Characteristics of hydrogen underground storage types

	Salt cavern	Depleted gas field	Aquifer	Lined hard rock cavern
Specific investment	Medium	Low	Low	High
Levelised cost of storage	Low	Medium	Medium	Medium
Cushion gas*	25-35%	45-60%	50-70%	10-20%
Capacity	Medium	Large	Large	Small
Annual cycles	Multiple	Few	Few	Multiple
Geographic availability	Limited	Variable	Variable	Abundant**

*Cushion gas is the volume of gas required as a permanent inventory in a storage facility. Its goal is to maintain sufficient pressure in the storage to meet withdrawal demands at a high rate, even at low storage levels.

Underground H2 Storage Trial Project



A small former natural gas reservoir in the municipality of Gampern (Upper Austria), under the leadership of RAG Austria AG, is a trial facility initiated in 2023. Useable capacity is 1.3 mNm3.

Transport of Hydrogen (Gas)

- Gaseous hydrogen is compressed to pressures of 180 bar (~2,600 psig) or higher into long cylinders that are stacked on a trailer that the truck hauls. This gives the appearance of long tubes, hence the name tube trailer.
- Tube trailers are currently limited to pressures of 250 bar by U.S. Department of Transportation (DOT) regulations
- Steel tube trailers are most commonly employed and carry approximately 380 kg onboard; their carrying capacity is limited by the weight of the steel tubes
- Composite storage vessels have been developed that have capacities of 560–900 kg of hydrogen per trailer

Transport of Hydrogen (Gas)

Pipeline

- Hydrogen is transported through pipelines much the same way natural gas is today. Currently about 2 600 kilometres (km) of hydrogen pipelines are operating in the United States and in Europe the estimate is around 2 000 kms

- These pipelines are located where large hydrogen users, such as petroleum refineries and chemical plants, are concentrated.

- Repurposing natural gas networks to hydrogen, however, will require more significant reconfiguration and adaptation

- Centrifugal compressors, which are the compressors of choice for H2, rotate a turbine at very high speeds to compress the gas. Hydrogen centrifugal compressors must operate at tip speeds 3 times faster than that of natural gas compressors to achieve the same compression ratio because of the low molecular weight of hydrogen

- Hydrogen specific codes, such as ASME B31.12 for inland hydrogen pipelines, however, tend to be more restrictive than their natural gas equivalents, as hydrogen may reduce ductility, fracture toughness and increase fatigue growth rate compared to natural gas. Due to differences in chemical properties, hydrogen can accelerate pipe degradation through a process known as hydrogen embrittlement, whereby hydrogen induces cracks in the steel

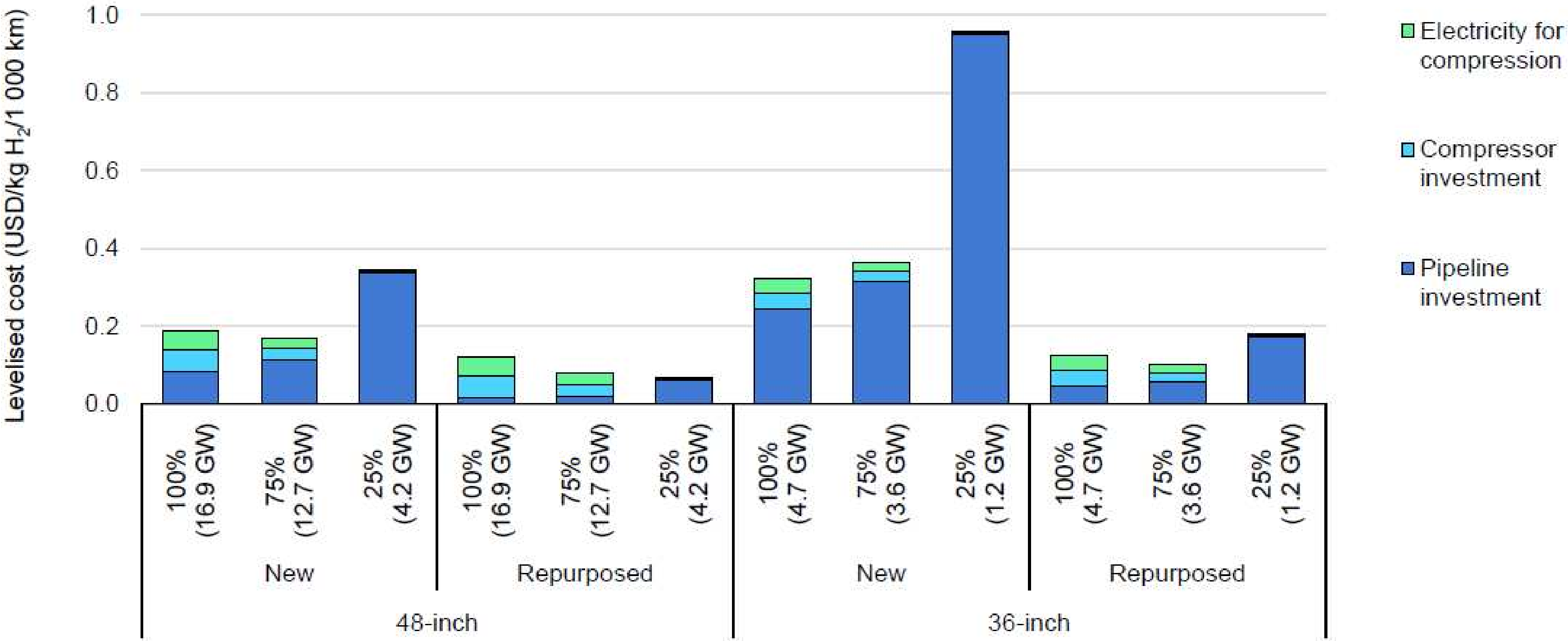
Transport of Hydrogen (2)

Blending in Natural Gas Pipelines

- Blending is the injection of hydrogen into existing natural gas pipelines
- Blending is feasible in existing pipelines up to 10% with only minor upgrading
- Blending at 20% would appear to be the upper limit but would require retrofitting compressors
- Blending is underway in UK, Slovakia, Greece and Korea up to the 20% limit
- De-blending will be required for some applications such as refuelling vehicles but that technology is not commercially available
- However, practical experience with 100% repurposed pipelines is limited and only example is 12km pipeline in the Netherlands

Optimise compression needs and throughput capacity of new and repurposed hydrogen pipelines to minimise transmission costs

Levelised cost of hydrogen transmission based on pipeline diameter and throughput capacity



Notes: A 100% throughput capacity means that the pipeline is designed to operate at 100% of the theoretical maximum throughput capacity, e.g. a 48-inch pipeline would have a theoretical maximum capacity of 16.9 GW of hydrogen. Analogously, a 75% throughput capacity means that the pipeline is designed to operate at 75% of the theoretical maximum throughput capacity, i.e. 75% of 16.9 GW, so the maximum throughput capacity would be 12.7 GW of hydrogen. Compressors use electricity from the grid (electricity price is assumed to be EUR 50 per megawatt-hour [MWh] [USD 59 /MWh]). Inland pipelines are modelled.

Source: IEA calculations based on data from Guidehouse (2021).

Transport of Hydrogen (Liquid)

- Hydrogen liquefaction is an energy-intensive process as it has to be cooled to -253deg C. The most recent hydrogen liquefaction plants have average electricity consumption of approximately 10 kilowatts per kilogram (kWh/kg), equivalent to around 30% of the energy content (lower heating value) of hydrogen.

- Today, large-scale liquid hydrogen storage technology is relatively similar to that of the 1960s, with the largest facility at NASA's Kennedy Space Center (Florida, United States). It is a double-walled vacuum insulated sphere, used for space applications, with a capacity of 3 200 m3 (230 tonnes)

- Conceptual design for a 60,000m3 storage tank has been completed and designs for up to 100,000m3 tanks are underway

Transport of Hydrogen by Ship

Liquefied hydrogen

- Hydrogen liquefaction and storage are mature technologies that have been used for decades, mostly for space applications and petrochemicals; however, at relatively modest levels compared with the LNG industry
- Ships for transporting LH2, however, are not yet commercially available.

Compressed hydrogen

- A 430 tonne cargo capacity at 250 bar (26 000 m3) tanker is being considered at present and as well as plans for a full-scale 2 000 tonne tanker. Hydrogen would be stored in the hull in the cargo hold and used as fuel.
- Several projects in Australia are assessing the needs for compressed hydrogen storage and loading facilities at ports, specifically in the Gascoyne region (HyEnergy) and on the Tiwi Islands and targeting first exports in 2026.

Ammonia

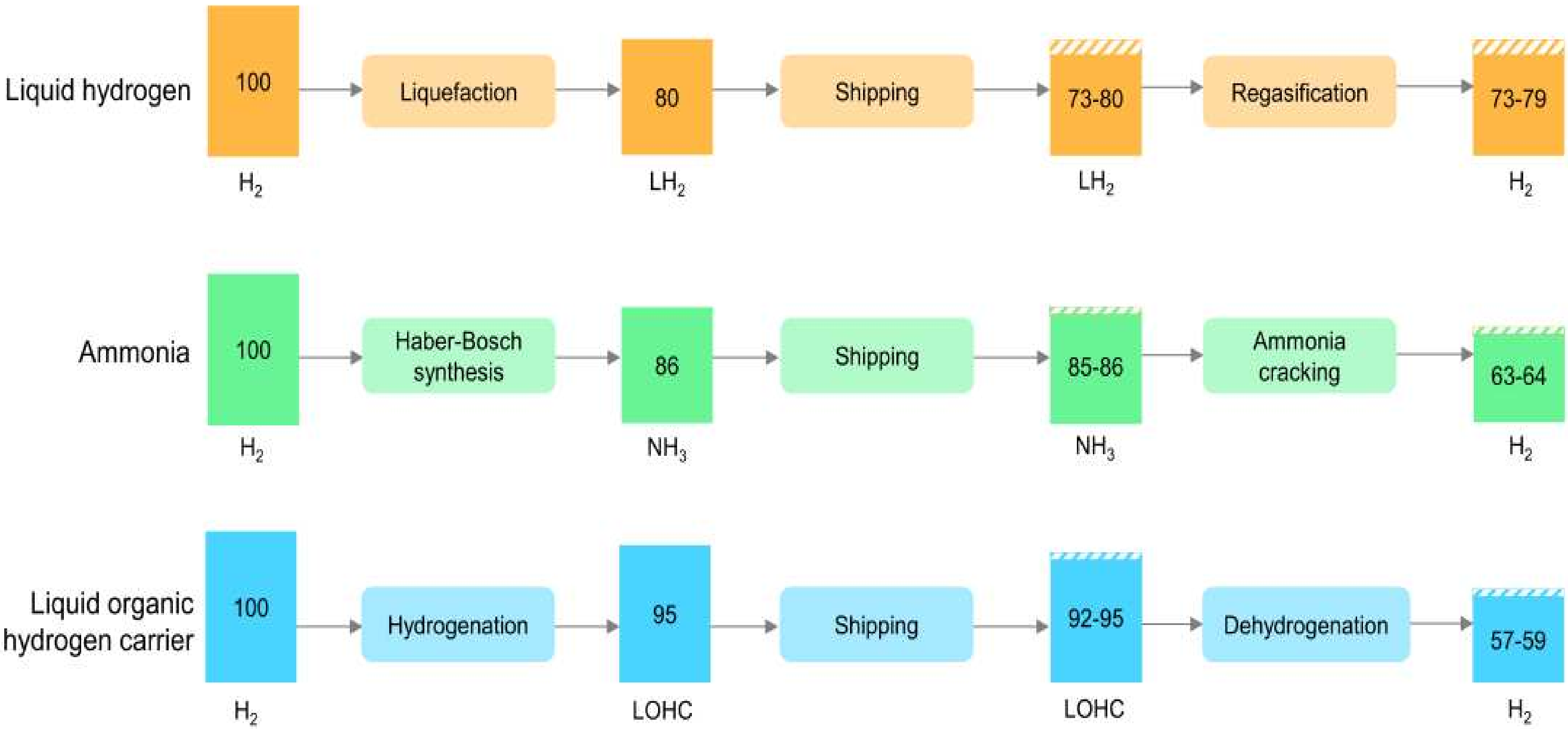
- an established worldwide ammonia infrastructure already exists with significant maritime trading of around 20 million tonnes per year (Mtpa),
- 195 ammonia terminals at over 120 ports.

Liquid organic hydrogen carrier

- Hydrogen can also be incorporated in an organic molecule, resulting in a LOHC with similar properties to oil products.
- At the destination, the hydrogen is extracted from the LOHC

The final use will influence the choice of the shipping option, as energy losses vary between the different hydrogen carriers

Energy available along the conversion and transport chain in hydrogen equivalent terms, 2030



Notes: LH_2 = liquefied hydrogen; NH_3 = ammonia; LOHC = liquid organic hydrogen carrier. Numbers show the remaining energy content of hydrogen along the supply chain relative to a starting value of 100, assuming that all energy needs of the steps would be covered by the hydrogen or hydrogen-derived fuel. The Haber-Bosch synthesis process includes energy consumption in the air separation unit. Boil-off losses from shipping are based on a distance of 8 000 km. For LH_2, dashed areas represent energy being recovered by using the boil-off gases as shipping fuel, corresponding to the upper range numbers. For NH_3 and LOHC, the dashed area represents the energy requirements for one-way shipping, which are included in the lower range numbers.

Hydrogen Energy Supply Chain (HESC) project

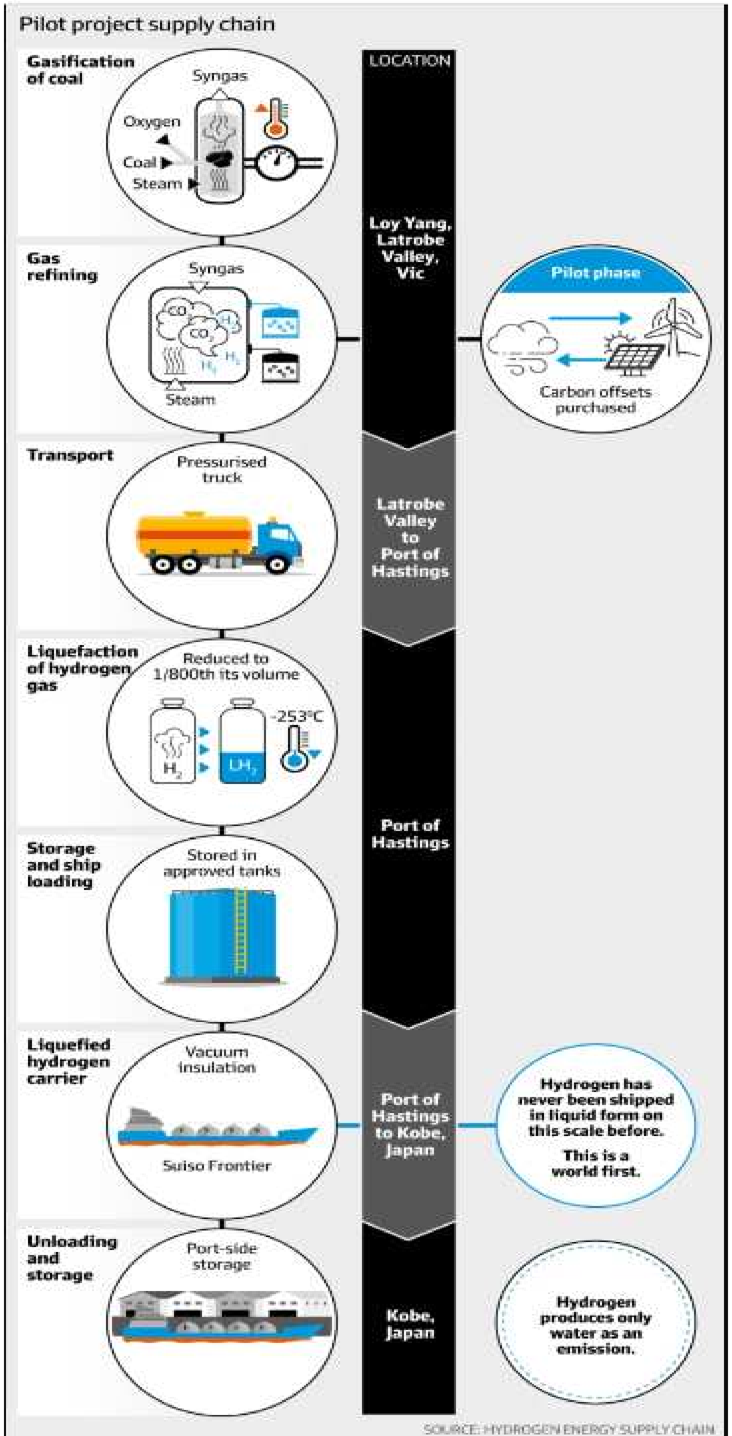
- The Hydrogen Energy Supply Chain (HESC) project in Australia is the first demonstration facility to test liquefied hydrogen shipping. It integrates a hydrogen liquefaction facility (0.25 tpd), a LH2 storage container (41 m3) and a loading facility in Hastings, Victoria.

- LH2 is transported to Japan in the world's first LH2 carrier, Suiso Frontier, with a capacity of 1 250 m3 (75 tonnes of LH2 per trip) and double-shell vacuum insulation tanks.

- The first shipment of LH2 arrived at the receiving terminal HyTouch Kobe in Japan in February 2022

- The terminal is equipped with a 2 500 m3 LH2 tank, a double-shell vacuum insulation and a spherical design to reduce heat transfer

- The HESC project aims to produce 225 kilotonnes per year (ktpa) of liquid hydrogen from a mix of Latrobe Valley coal and biomass, as well as to capture and store CO2.

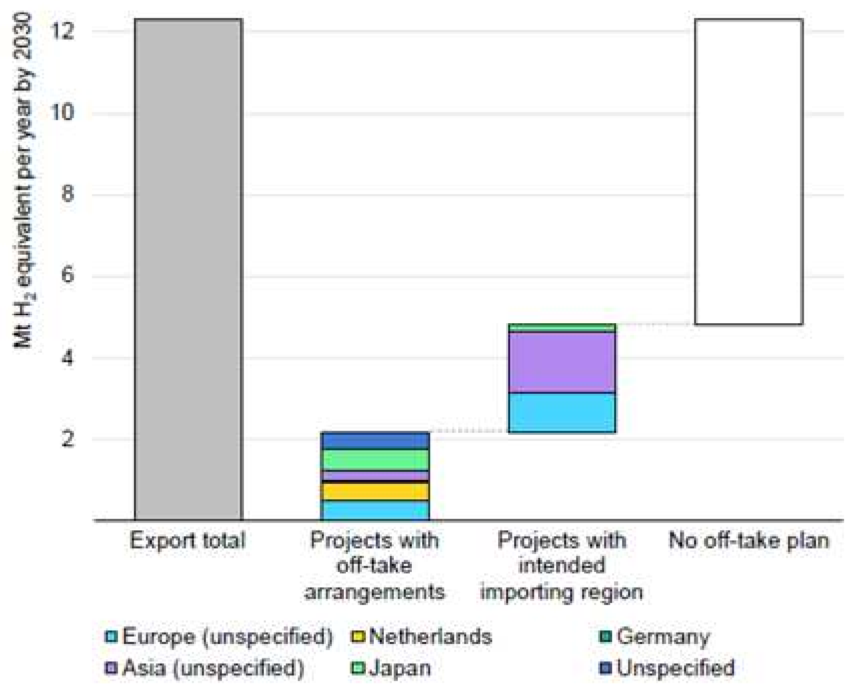

Pilot project supply chain
LOCATION
Gasification of coal
Syngas
Oxygen
Coal
Steam
Loy Yang, Latrobe Valley, Vic
Gas refining
Syngas
CO
CO2
H2
Steam
Pilot phase
Carbon offsets purchased
Transport
Pressurised truck
Latrobe Valley to Port of Hastings
Liquefaction of hydrogen gas
Reduced to 1/800th its volume
-253°C
H2
LH2
Port of Hastings
Storage and ship loading
Stored in approved tanks
Liquefied hydrogen carrier
Vacuum insulation
Suiso Frontier
Port of Hastings to Kobe, Japan
Hydrogen has never been shipped in liquid form on this scale before.
This is a world first.
Unloading and storage
Port-side storage
Kobe, Japan
Hydrogen produces only water as an emission.
SOURCE: HYDROGEN ENERGY SUPPLY CHAIN

The *Suiso Frontier* was built by Kawasaki Heavy Industries, following support by the governments of Japan and Australia. The ship carries liquid hydrogen, the first load of which was extracted from brown coal in Australia and carried to Kobe, Japan. As a prototype, she is planned to lead to a commercial liquid hydrogen carrier sometime in the mid-2020s. She is 8000 Gross Tonnes and carries 75 tonnes of H2.

Hydrogen Trade

- Most projects that have identified a hydrogen carrier molecule have chosen ammonia
- Smaller volumes are planned for synthetic liquid fuels, LOHC, liquefied hydrogen or compressed hydrogen by ship
- Projects accounting for 40% of planned export volumes by 2030 have not yet identified a carrier molecule.
- Electrolytic hydrogen production accounts for 88% of planned export volumes by 2030
- 12% is fossil fuel-based hydrogen production with CCUS

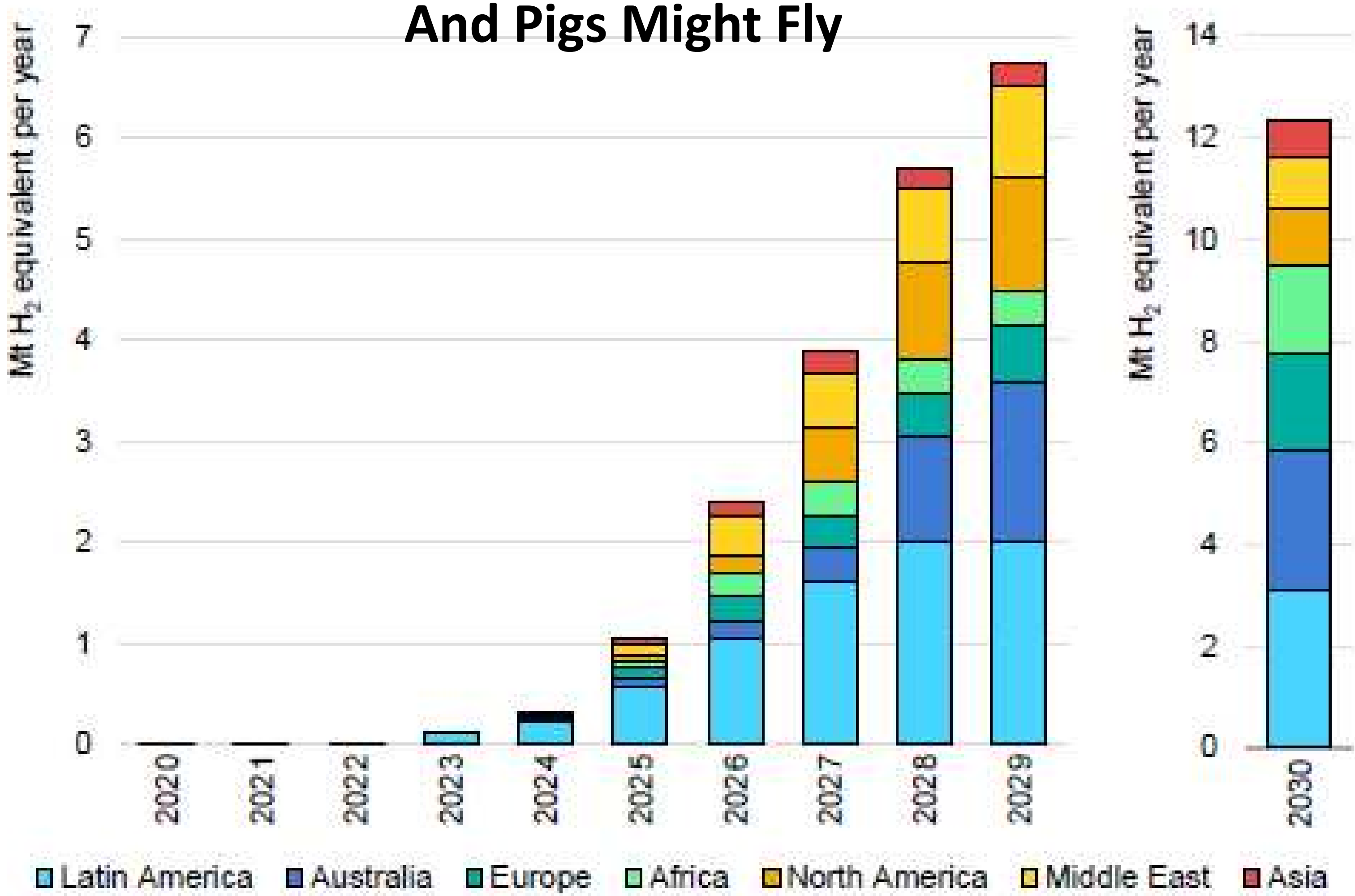
Export volumes from planned projects with off-take arrangements or intended destinations by importing country/region, 2030



Source: IEA analysis based on data from news outlets, press releases and governments.

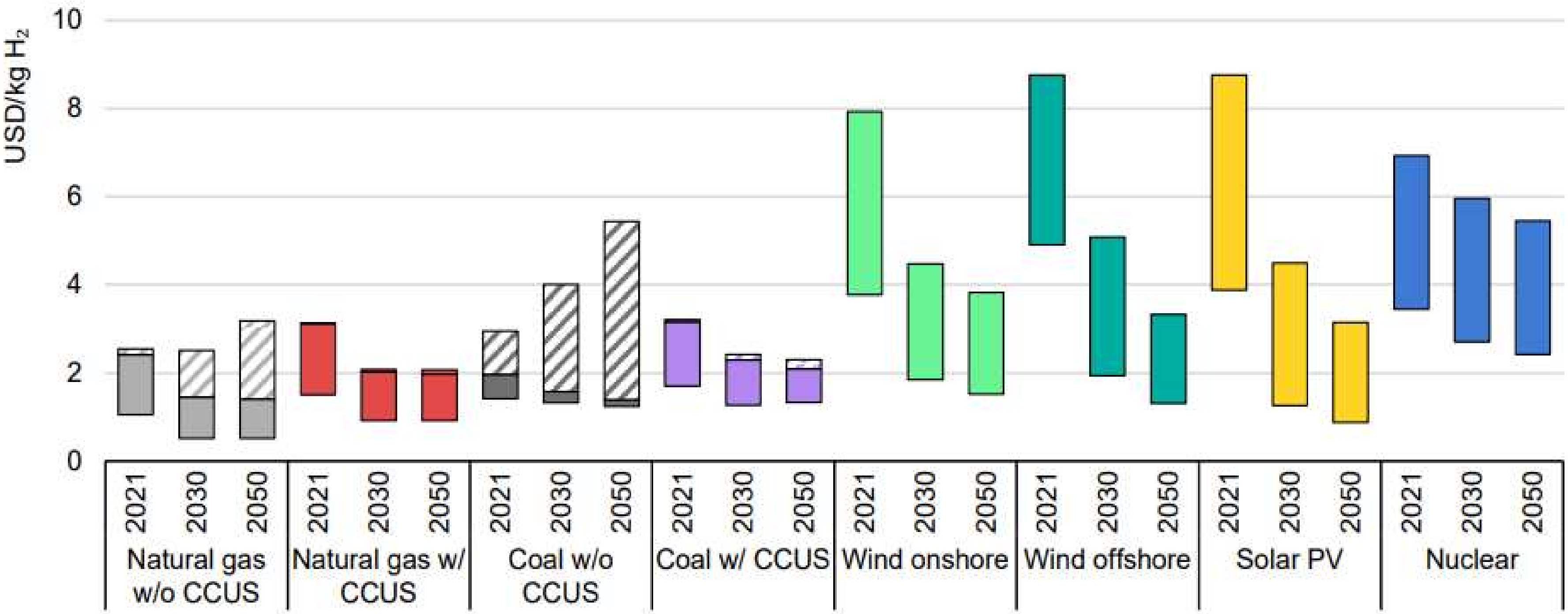
Planned hydrogen exports by region, 2020-2030

And Pigs Might Fly



Opportunities for cost reductions to produce low-emission hydrogen

Levelised cost of hydrogen production by technology in 2021 and in the Net Zero Emissions by 2050 Scenario, 2030 and 2050



Notes: Ranges of production cost estimates reflect regional variations in costs and renewable resource conditions. The dashed areas reflect the CO_2 price impact, based on CO_2 prices ranging from USD 15/tonne CO_2 to USD 140/tonne CO_2 between regions in 2030 and USD 55/ tonne CO_2 to USD 250/ tonne CO_2 in 2050.

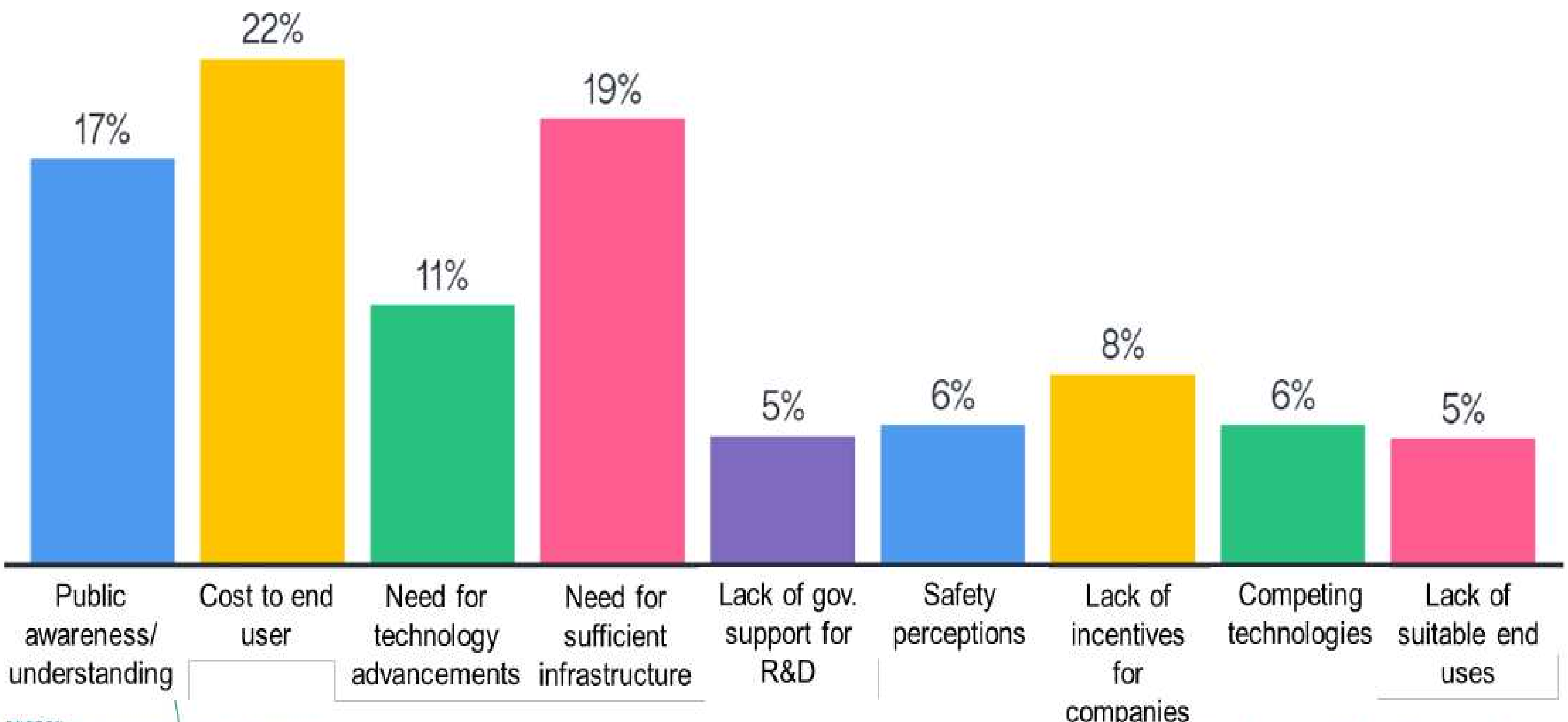
Sources: Based on data from McKinsey & Company and the Hydrogen Council; Council; IRENA (2020); IEA GHG (2014); IEA GHG (2017); E4Tech (2015); Kawasaki Heavy Industries; Element Energy (2018).

This chart is from the DOE meeting themed"111", $1 for 1kg of clean H2 in 1 decade.

DOE Hydrogen Shot Summit Stakeholder Feedback

4,900+ total registrants, 3,200+ participants in Plenary, 33 countries + USA

Responses to: What are the greatest barriers preventing public acceptance of widespread H_2 in the US?



Uses of Hydrogen

Current Uses

- Current common well known uses include by industry for refining petroleum, treating metals, producing fertilizer, and processing foods

Hydrogen Fuel Cells

- NASA was one of the first to use hydrogen fuel cells to power the electrical systems on spacecraft.
- Hydrogen fuel cells produce electricity by combining hydrogen and oxygen atoms
- Small fuel cells can power laptop computers and even cell phones, and military applications
- Large fuel cells can supply electricity to electric power grids, supply backup or emergency power in buildings
- As of the end of October 2021, there were about 166 operating fuel cell electric power generators at 113 facilities in the United States with a total of about 260 megawatts (MW)
- The largest single fuel cell is the Bridgeport (Connecticut) Fuel Cell, LLC with about 16 MW of generation capacity

Generating Electricity

- In the United States, several power plants have announced plans to operate on a natural gas-hydrogen fuel mixture in combustion gas turbines
- One example is the 485 MW Long Ridge Energy Generation Project facility in Ohio with a gas-fired combustion turbine that will run on a 95% natural gas/5% hydrogen fuel blend in a gas turbine with a plan to eventually use 100% *green* hydrogen produced from renewable resources.

Vehicular Fuel

- Hydrogen is considered an alternative vehicle fuel
- A fuel cell may be two to three times more efficient than an internal combustion engine running on gasoline
- The high cost of fuel cells and the limited availability of hydrogen vehicle fueling stations have limited the number of hydrogen-fueled vehicles in use today.
- In the United States, there are about 48 hydrogen vehicle fueling stations and nearly all are in California

Now getting back to the real world!

ATCO Proposed Hydrogen Project

- The project consisted of 10 megawatt electrolyser powered by a wind farm 250 kms north of Perth
- Planned to be one of largest green hydrolyser projects in the World
- Plan to truck the green hydrogen to Perth and inject it into the domestic gas network up to 10%
- The project was granted $28.7 million in public funding by ARENA in 2021
- Energy Policy WA modelled green hydrogen at up to $78.02 / GJ when converted to electricity compared with $5.60/GJ for natural gas
- The project has been cancelled as of 17 August
- Jai Thomas from Energy Policy WA said, “It is going to take a number of years for hydrogen to become commercially equivalent with technologies that exist today or other fuel sources”.
- **HE IS A SUPREME OPTIMIST!**

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Global Hydrogen Review, International Energy Agency, Paris, France

The Engineering Toolbox

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Energy company ATCO says WA gas reservation a factor in hydrogen project cancellation, ABC Midwest and Wheatbelt