Enhancing Sustainable Hydrogen Production: The Role of Carbon Capture Storage in Transitioning from Blue to Green Hydrogen

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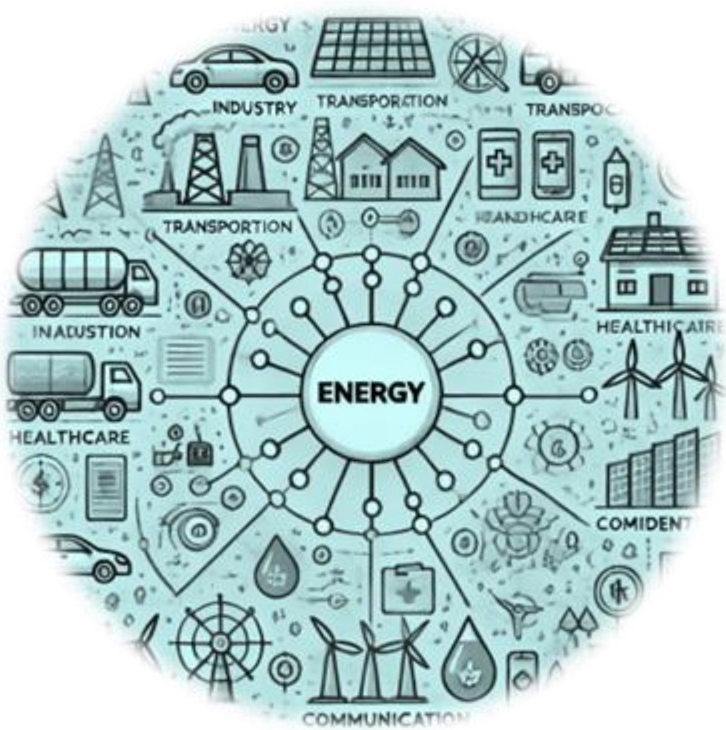
Jules Verne

"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable".

"The Mysterious Island", 1874

Nobody would have believed in 1874, but now the prediction is coming true

Is the Global Energy facing any challenges?

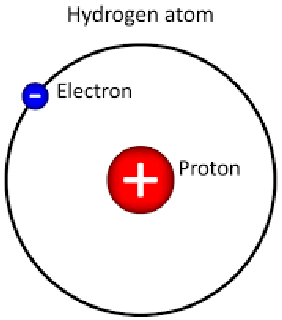


Energy is a foundation of modern life

Headlines

- What is Hydrogen?
- Overview on Hydrogen types
- Overview on the carbon capture and storage technologies
- How blue hydrogen could be a transitional technology to green hydrogen
- Cases highlighting the growing adoption of blue hydrogen
- Challenges facing the adoption of blue hydrogen
- Long-term role of CCS beyond blue hydrogen
- Conclusions

What is Hydrogen?

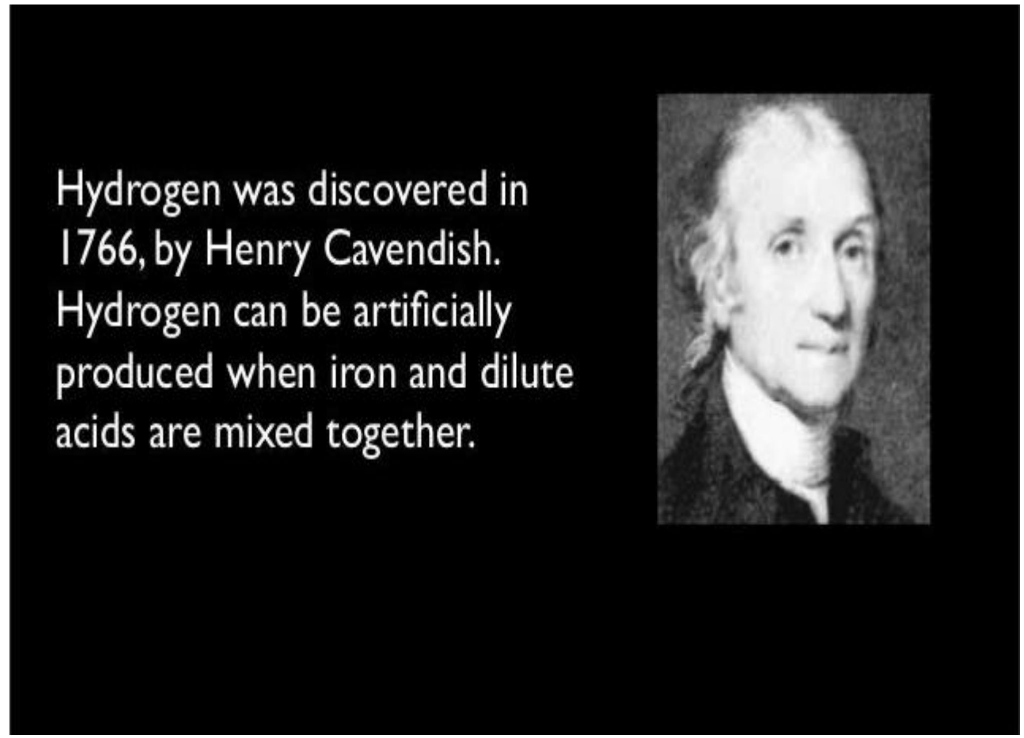


- Hydrogen is the simplest and most abundant element on earth—it consists of only one proton and one electron.
- Hydrogen can store and deliver usable energy, but it doesn't typically exist by itself in nature and must be produced from compounds that contain it.
- Hydrogen is an energy carrier, not an energy source and can deliver or store a tremendous amount of energy.
- Hydrogen can be used in fuel cells to generate electricity, or power and heat.

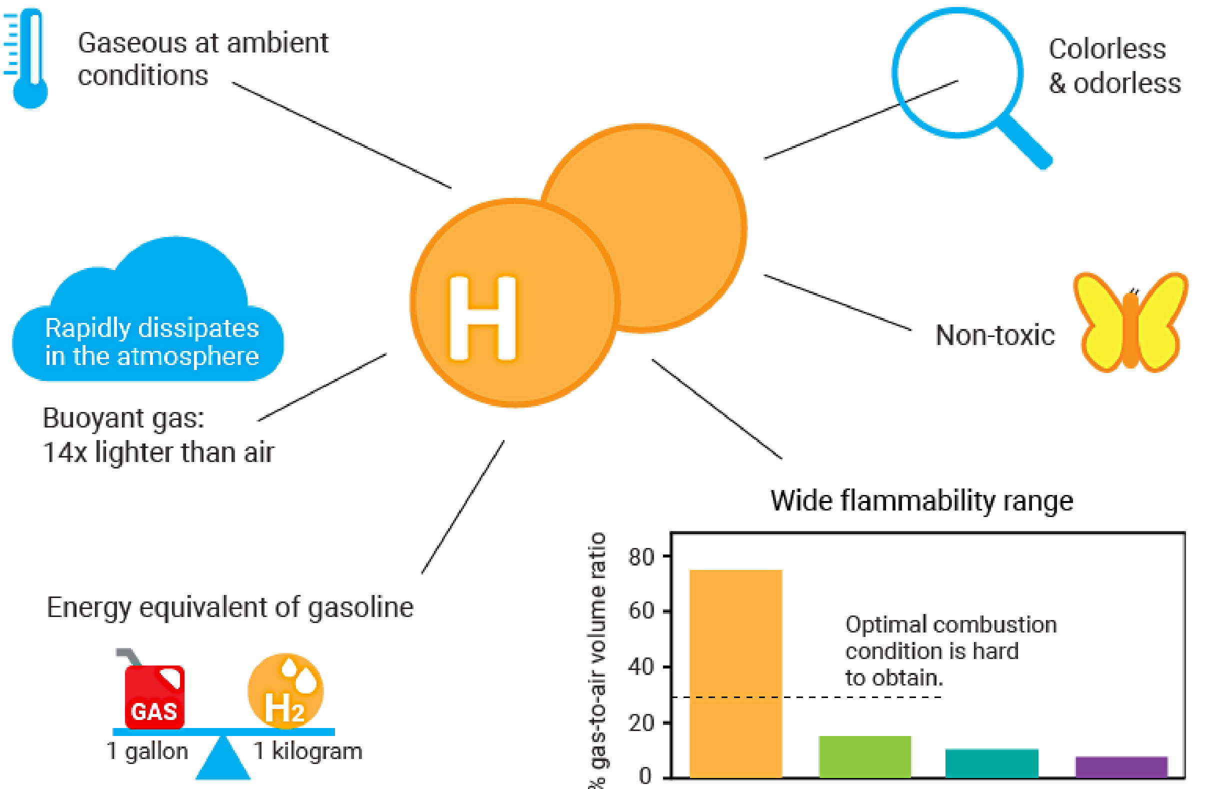
HOW WAS HYDROGEN FOUND?

The name of hydrogen was derived from two Greek words (Gr. Hydro, water, and genes, forming) to mean water forming

- **Ninety three percent of all atoms in the universe are hydrogen**
- **It is half the mass of the Sun and other stars**



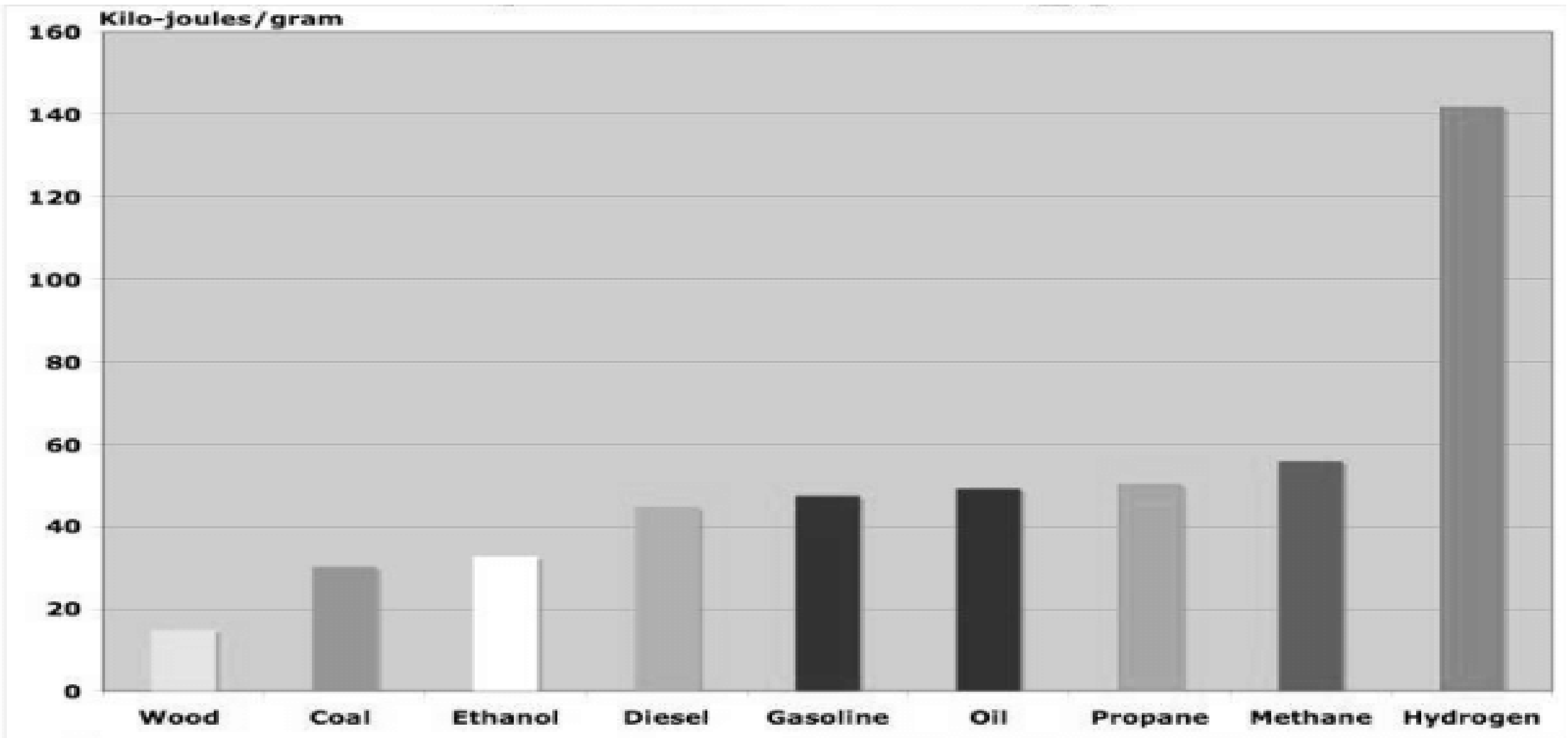
Hydrogen Properties



- Does not conduct electricity and only slightly soluble in water
- Reactive compound that occurs in a variety of compounds

Specific energy of Hydrogen

- Hydrogen has a very high specific energy



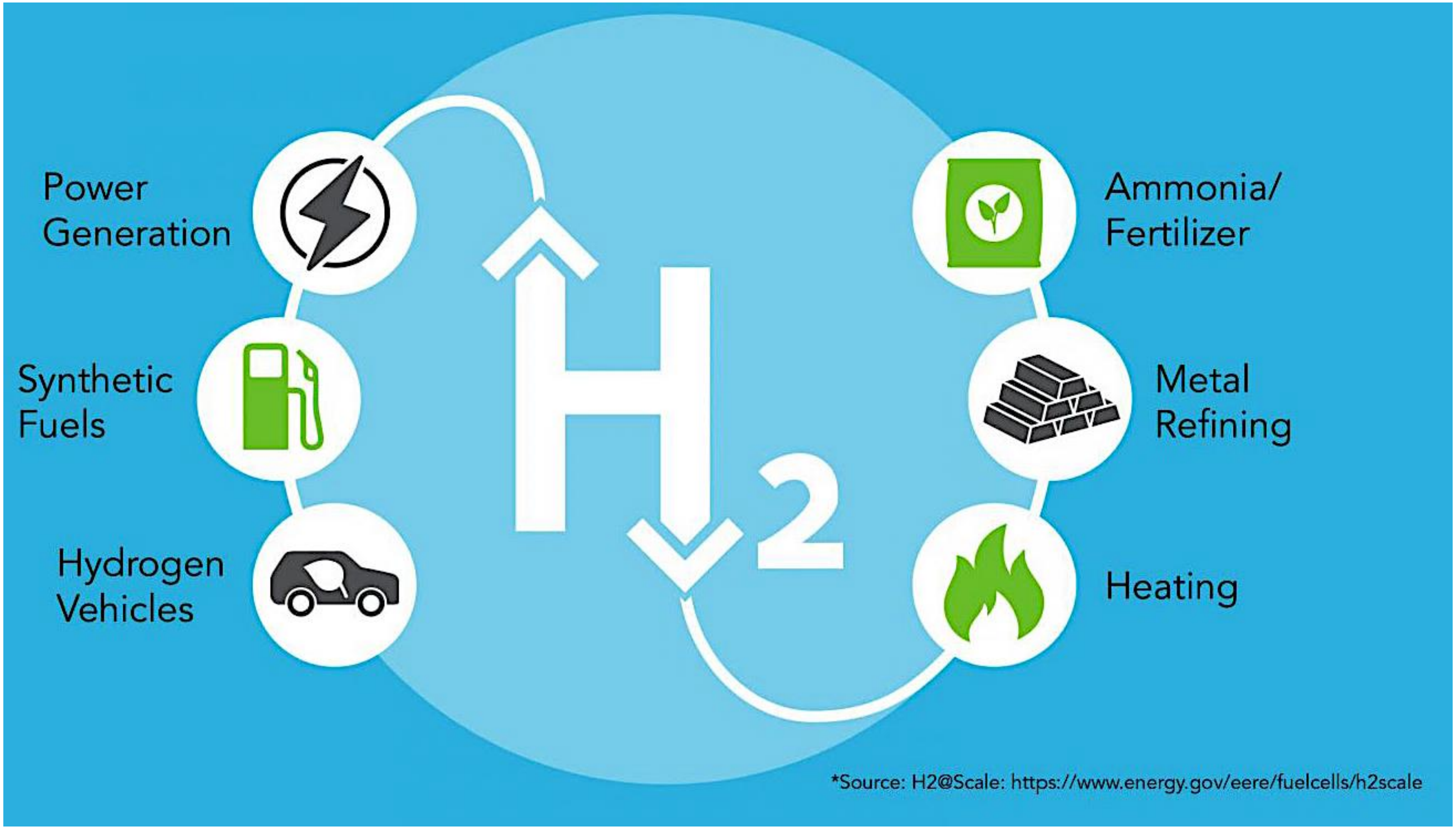
Hydrogen stores approximately 2.6 times the energy per unit mass as gasoline

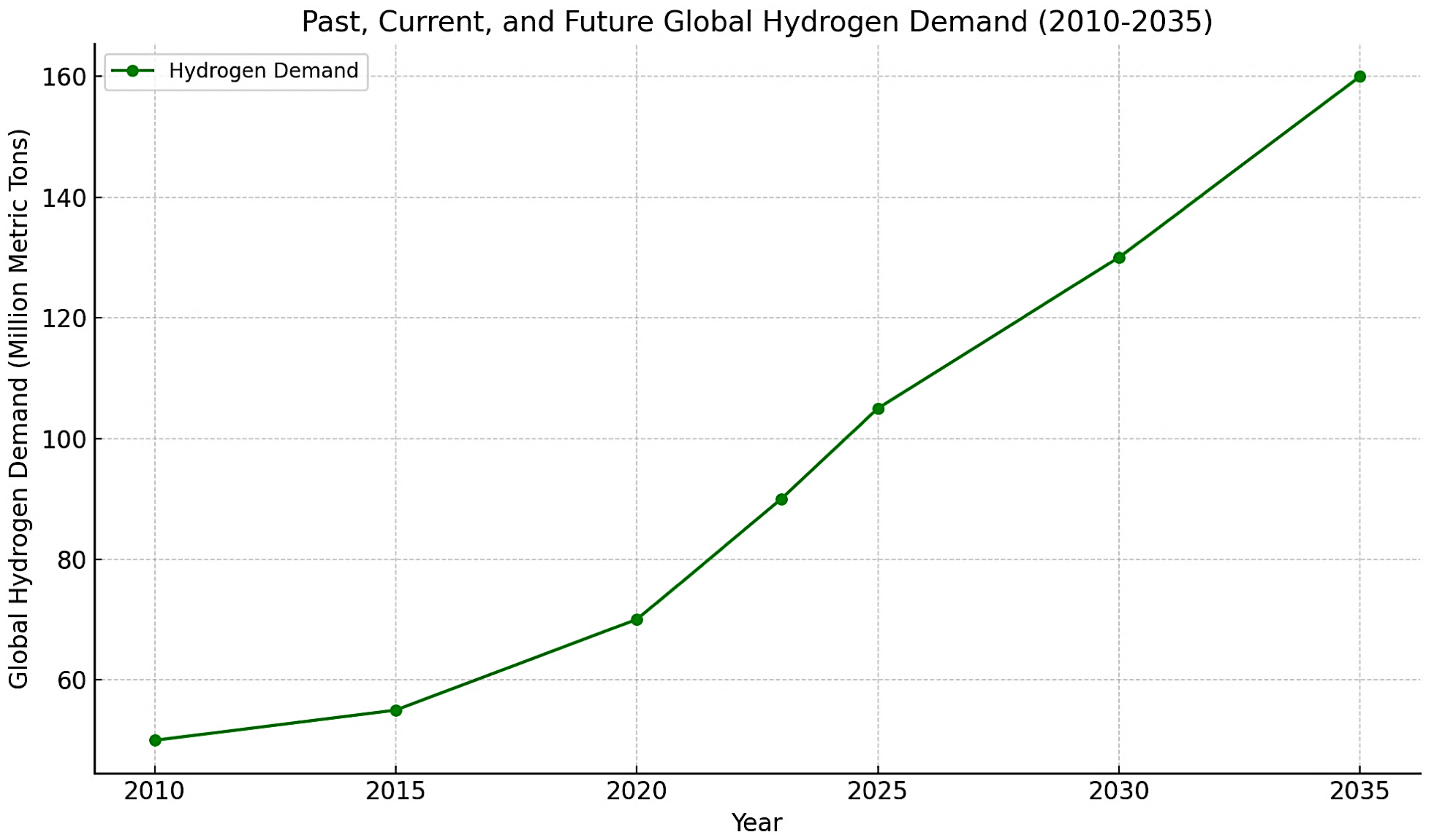
Types of hydrogen

A comparison between the different types of hydrogen

Hydrogen type	Cost range ($/kg)	CO_2 emissions
Grey	$1.00-$2.50	9-12 kg CO_2 per kg H_2
Blue	$2.00-$4.00	1-4 kg CO_2 per kg H_2
Green	$3.00-$7.00	Zero direct CO_2 emission
Yellow	$3.50-$6.50	variable
Pink	$3.00-$6.50	Zero direct CO_2 emission
Brown	$1.00-$2.50	15-20 kg CO_2 per kg H_2

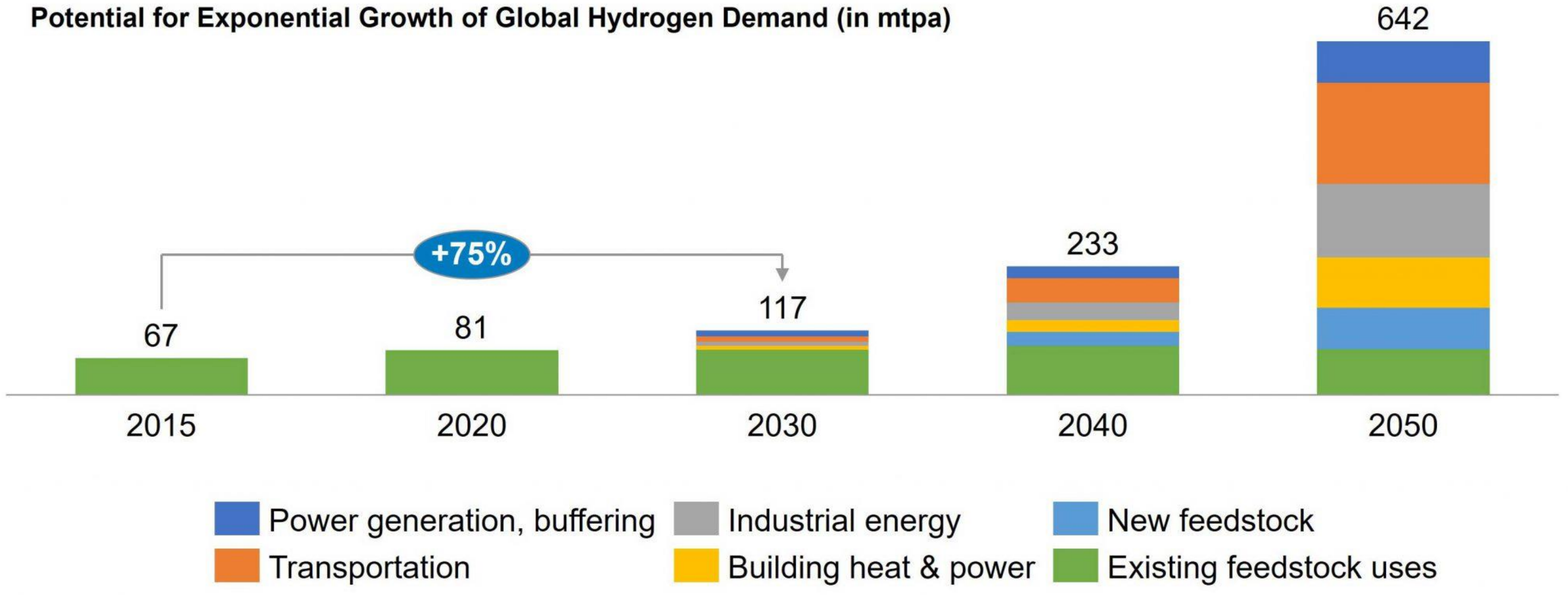
Uses of hydrogen





Source: IEA Global Hydrogen Review 2024

Hydrogen uses



Source: Hydrogen Council

Saudi Arabia Hydrogen Strategy: 2030 Vision

- **Saudi Arabia is exploring ways to become the top supplier of hydrogen in the world and has clean hydrogen production targets of 2.9 million tons per year (t/yr) by 2030 and 4 million t/yr by 2035.**
- **NEOM has signed a $5 billion deal with U.S. gas and chemicals company Air Products and the Saudi group ACWA Power to build a "world-scale green hydrogen-based ammonia production facility powered by renewable energy."**

Projected site of Neom development

Technologies used to generate blue hydrogen

Blue hydrogen generation

- **Steam Methane reforming**
  Feedstock: Natural gas and water
- **Auto-thermal reforming.**
  Feedstock: Natural gas, oxygen, and water

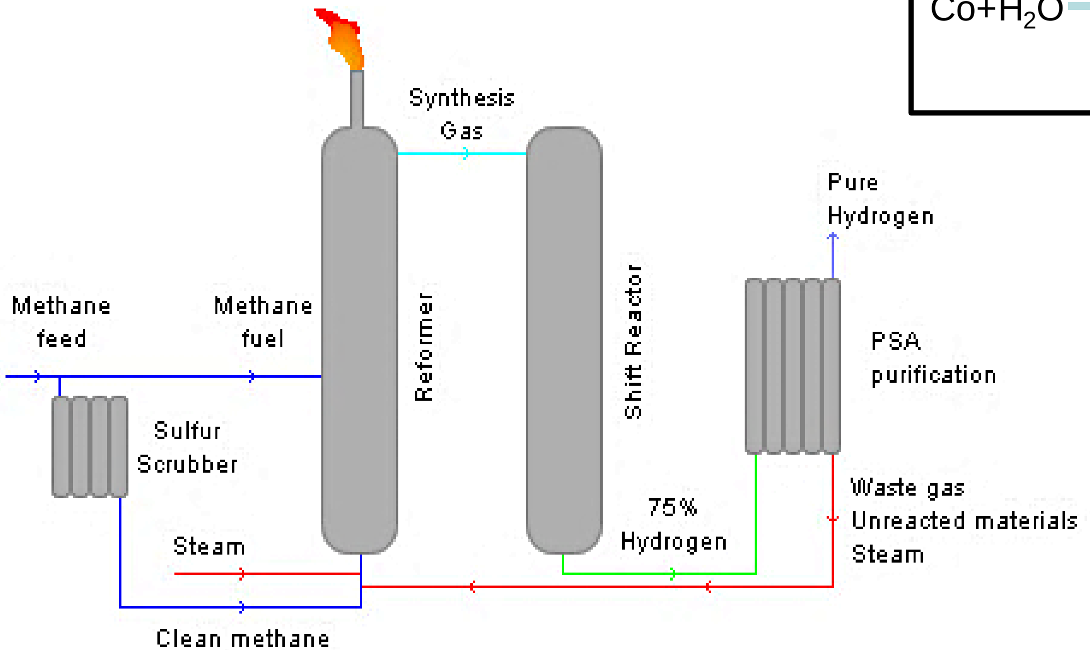
- Steam methane reforming

Steam reforming is a hydrogen production process from natural gas. The process consists of heating the gas to between 800 – 900 ° C at moderate pressures (15-30 bar) in the presence of steam and a nickel catalyst.

<u>Steam-methane reforming reaction</u>

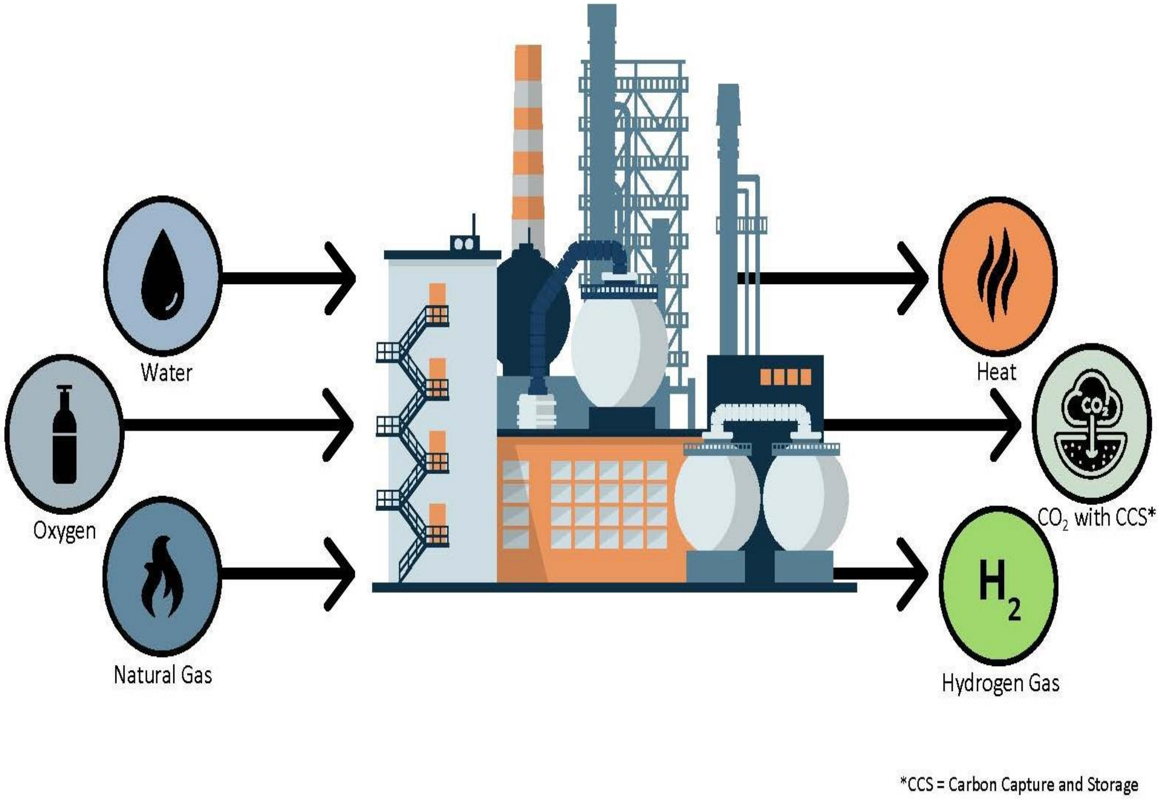
$CH_4 + H_2O + heat \rightarrow Co + 3H_2$

$Co + H_2O \rightarrow CO_2 + H_2$ + small amount of heat



- Auto-thermal reforming

ATR is a process that combines partial oxidation and steam reforming in a single reactor, allowing for the simultaneous production of hydrogen and synthesis gas



1. **Steam Reforming Reaction:**

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

2. **Partial Oxidation Reaction:**

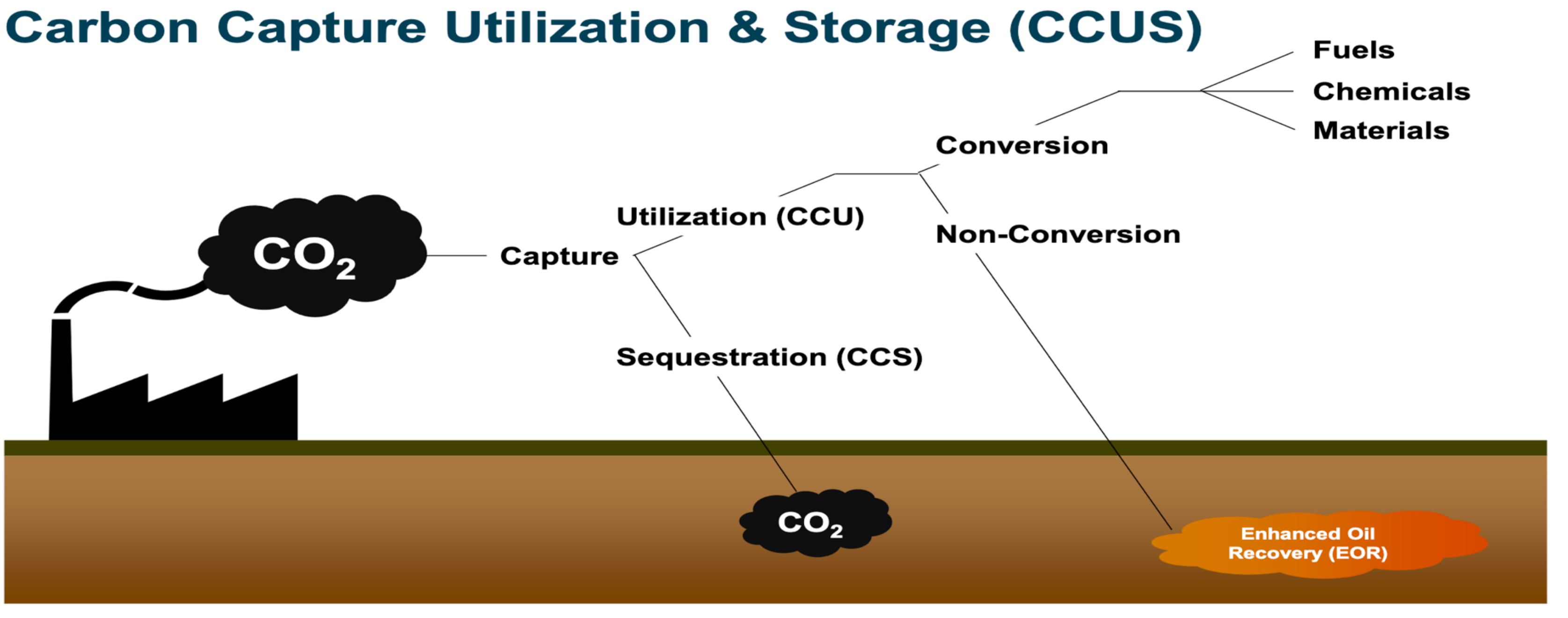
$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2$$

Comparison between technologies used to generate blue hydrogen

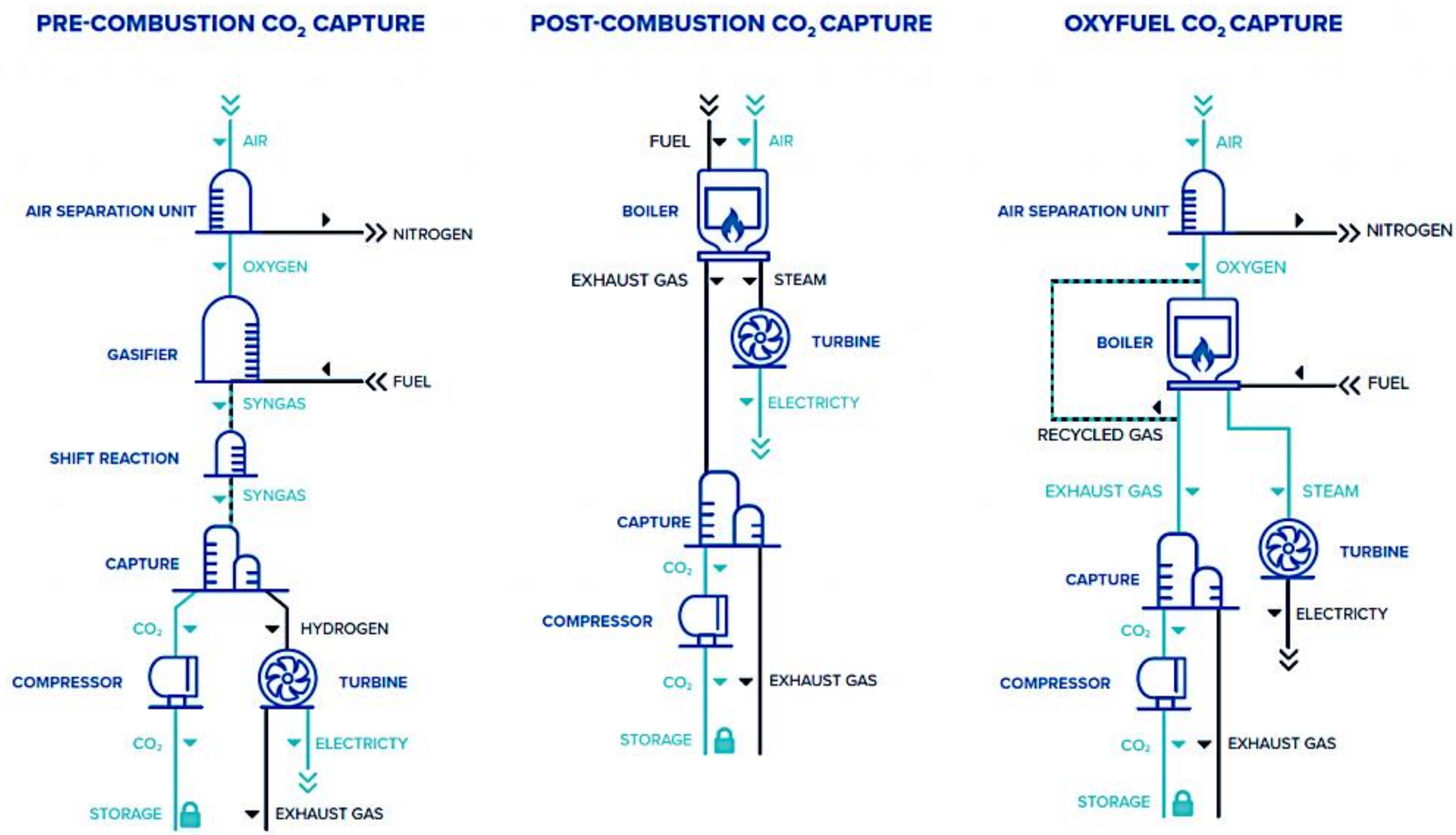
Attribute	Autothermal Reforming	Steam Reforming
Process	Simultaneous combination of partial oxidation and steam reforming	Reaction of hydrocarbons with steam
Reaction Temperature	Higher temperature range (700-1100°C)	Lower temperature range (500-700°C)
Reaction Exothermicity	Exothermic	Endothermic
Heat Source	External heat source (e.g., combustion of fuel)	External heat source (e.g., combustion of fuel)
Reaction Products	Synthesis gas (H2 + CO)	Synthesis gas (H2 + CO)
Reaction Efficiency	Higher efficiency due to simultaneous reactions	Lower efficiency due to separate reactions
Process Complexity	More complex due to simultaneous reactions	Less complex due to separate reactions
Start-up Time	Longer start-up time	Shorter start-up time

Carbon Capture and Storage

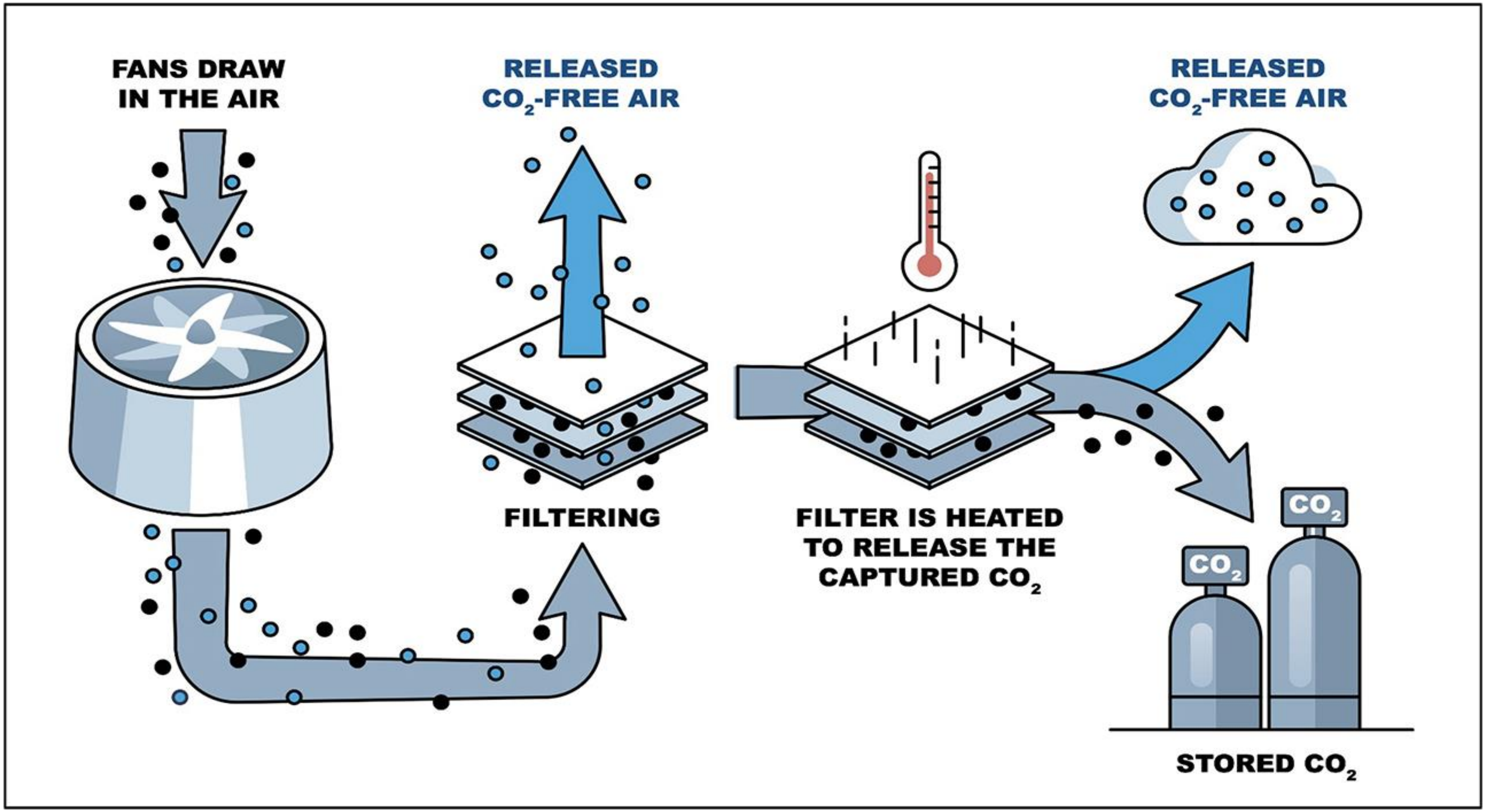
CCUS is the process of capturing carbon dioxide (CO_2) before it is released into the atmosphere and storing it in geological structures. CO_2 can be captured from emitters such as power stations or energy-intensive industries (i.e. cement, chemicals or steel plants), as well as on some hydrogen production facilities that reform natural gas. CO_2 can also be captured directly from the air.



Carbon capture methods



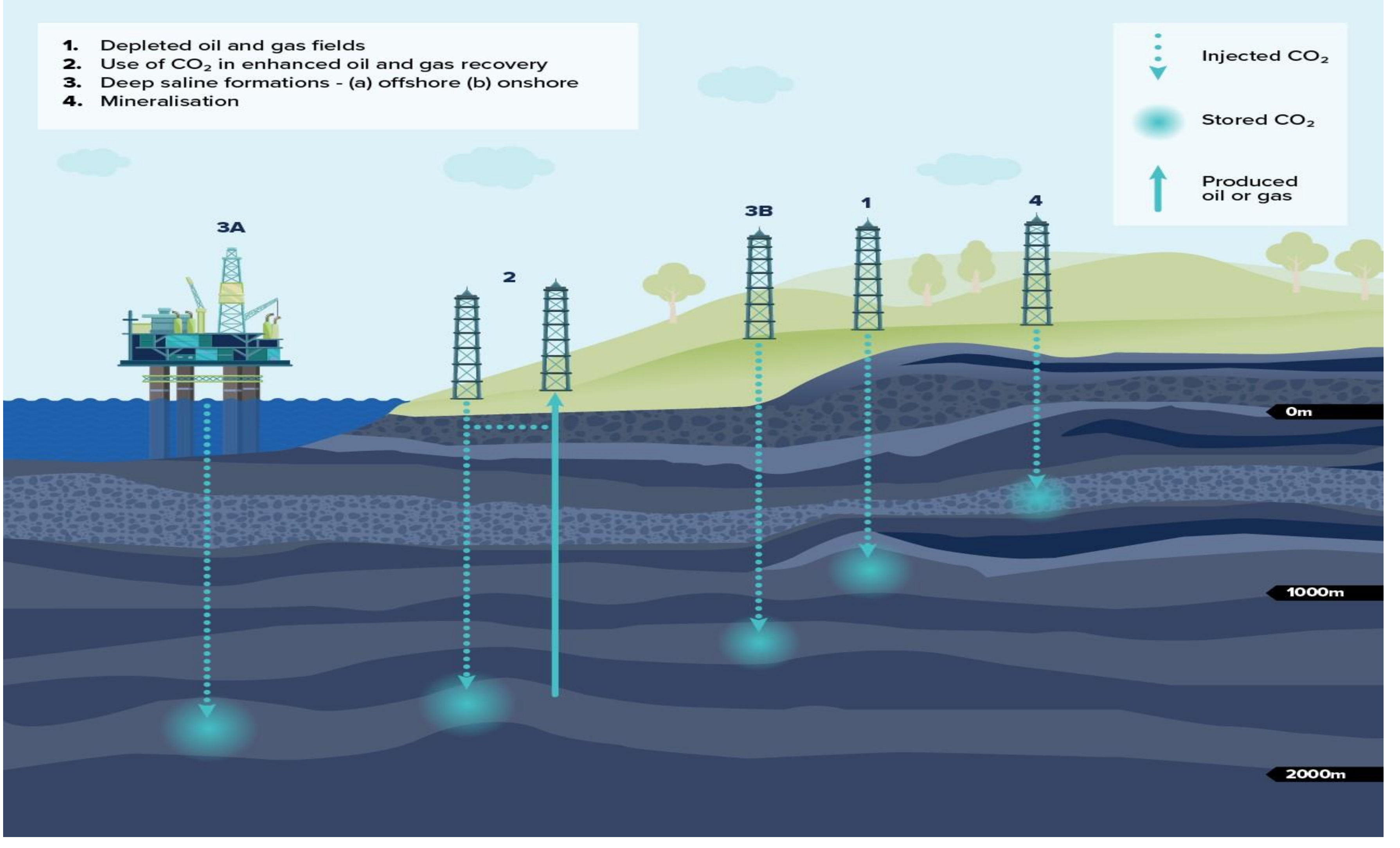
Direct air capture



A comparison between the CCS technologies

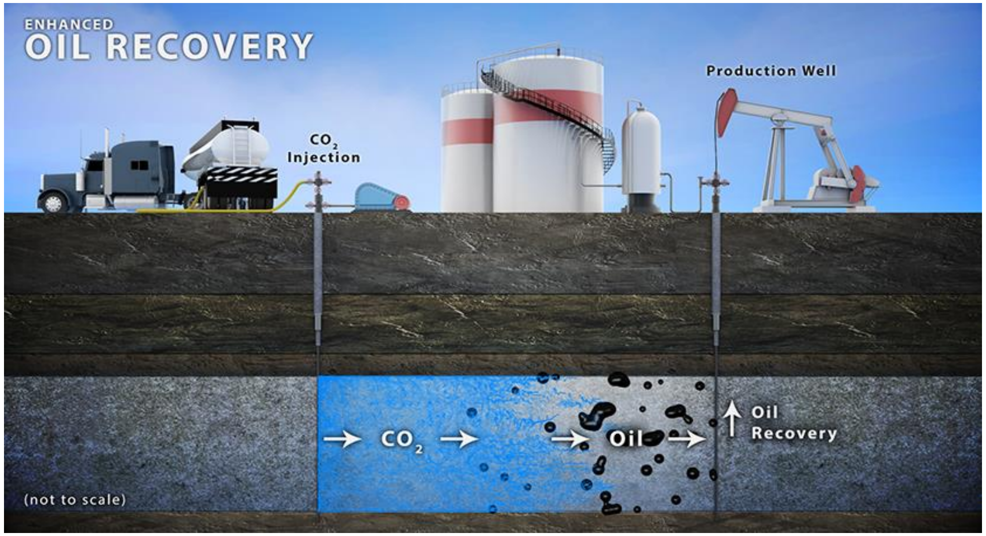
CO_2 capture method	Efficiency	Operating conditions	Cost	Advantages	Challenges
Pre-combustion	Up to 90%	High pressure and temperature	High due to gasification process	Highly efficient for CO_2 removal at large scale	Require new infrastructure, high capital investment
Post combustion	80%-90%	Ambient to low temperature and pressure	Medium due to solvent costs	Can be retrofitted to existing power plants	Energy-intensive solvent regeneration, solvent degradation
Oxy-fuel	90%-95%	High temperature	High (oxygen generation is costly	Produces highly concentrated CO2 stream for easier capture	High cost of oxygen separation, equipment corrosion

Carbon storage

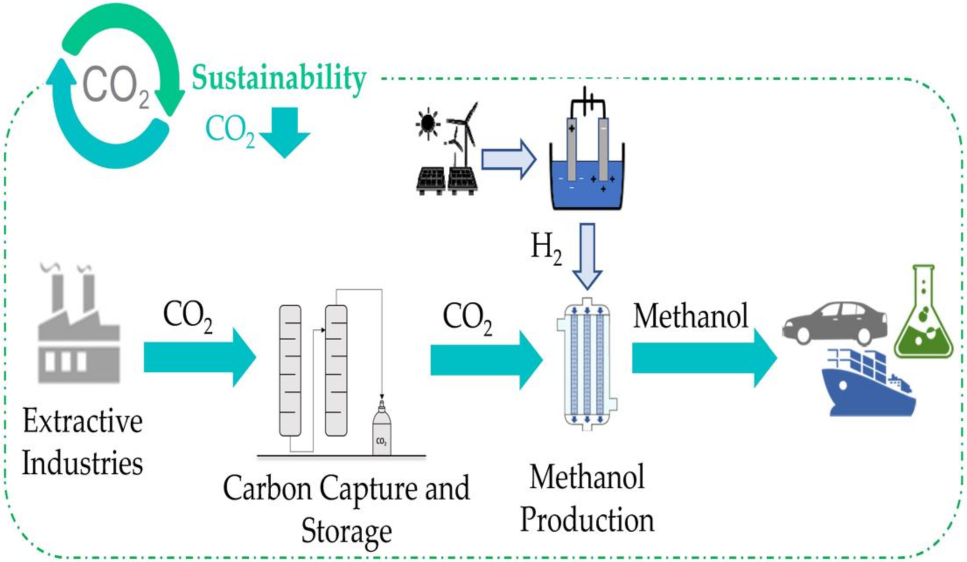


Uses of Captured Carbon

Enhanced Oil Recovery (EOR): Captured CO_2 can be injected into depleted oil fields to help increase oil extraction



Chemical Production: CO_2 can be used as a feedstock to produce various chemicals, including methanol, urea, and other hydrocarbons.



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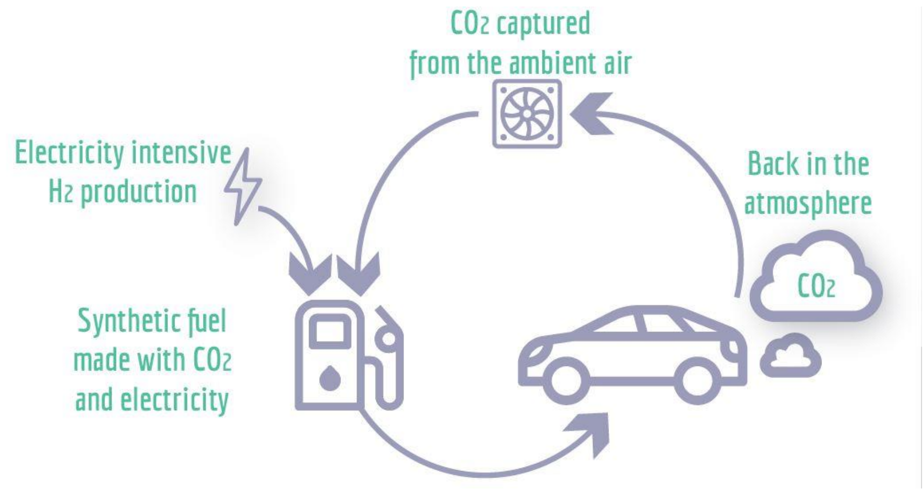
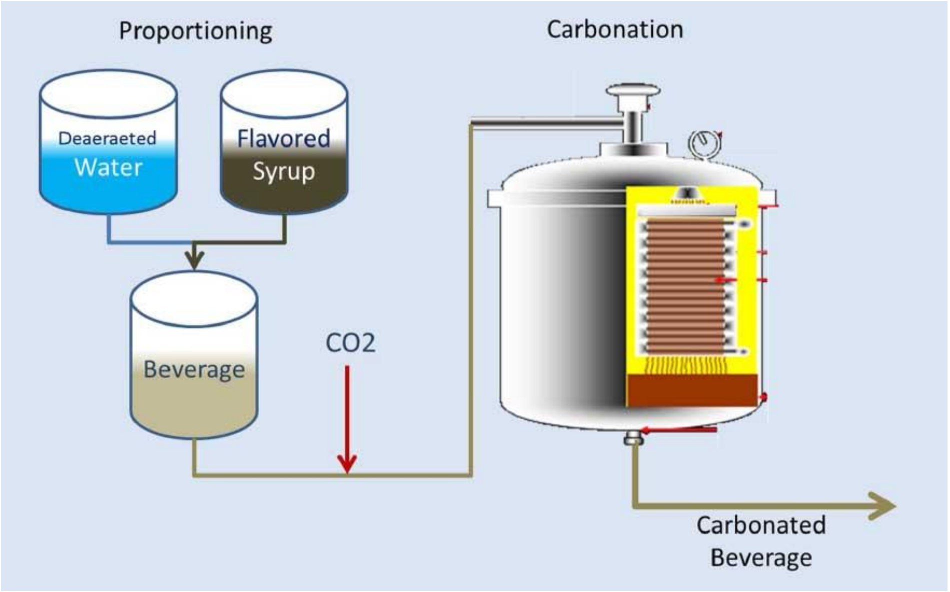
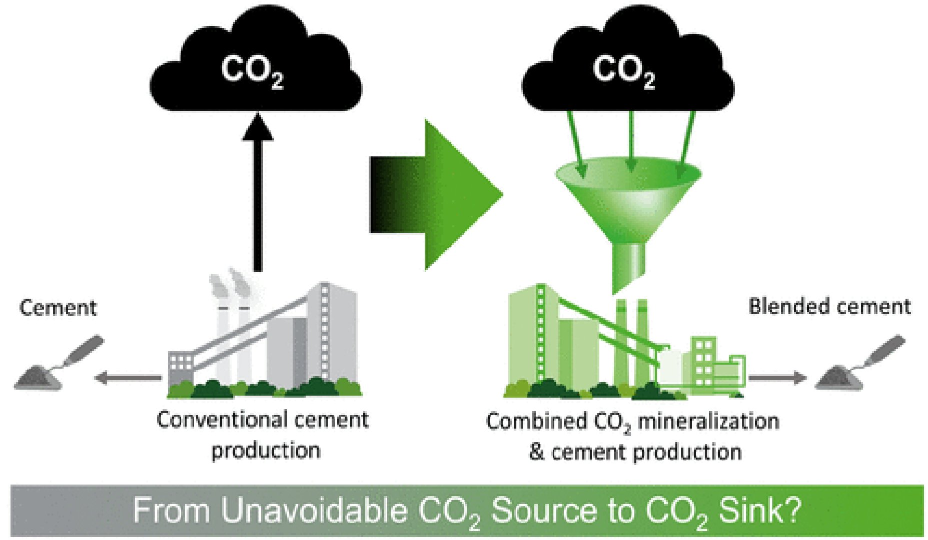
Sustainable Fuels: CO_2 can be combined with hydrogen (produced from water electrolysis or reforming) to create synthetic fuels, such as synthetic natural gas or liquid fuels.



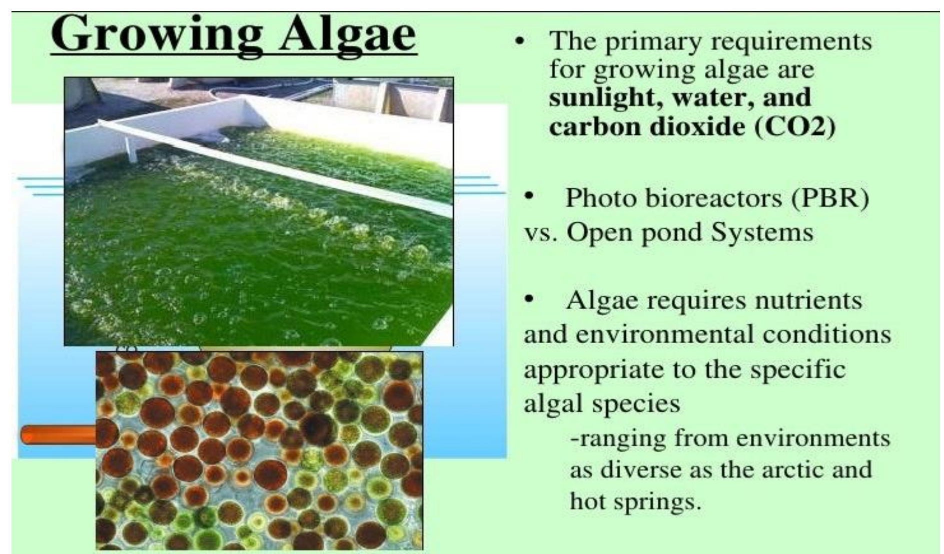
Carbonated Beverages: Captured CO_2 can be purified and used in the beverage industry for carbonating soft drinks and other beverages.



Building Materials: CO_2 can be utilized in the production of building materials, such as concrete and aggregates.



Algae Cultivation: Captured CO_2 can be used in bioreactors to grow algae, which can then be harvested for biofuels, animal feed, or food additives.



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Economic analysis of Blue Hydrogen

Overall Cost of Blue Hydrogen Production

ranges between $1.50 and $3.00 per kilogram

Production Costs of Blue Hydrogen vis Steam methane reforming

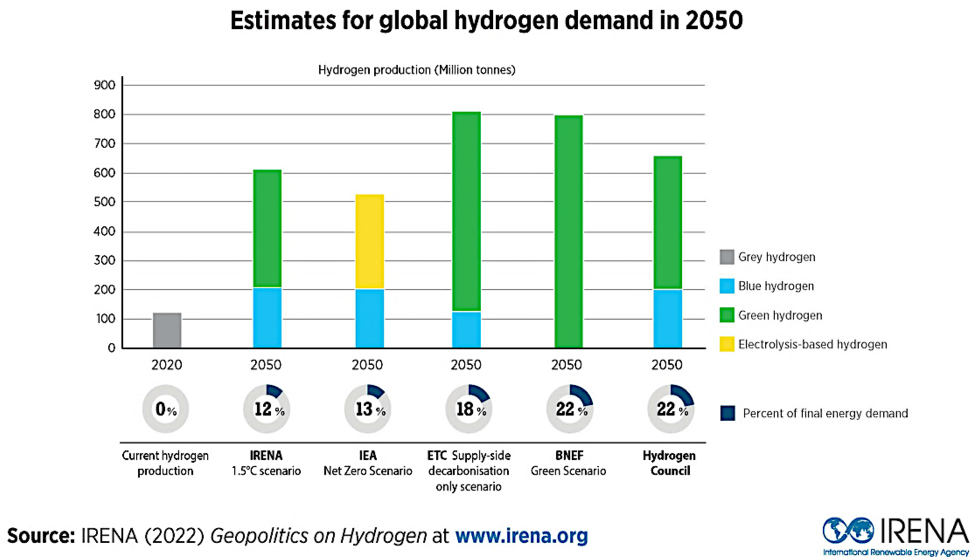
- **Feedstock Costs:** cost of natural gas has ranged from $3 to $6 per MMBtu
- **Operational and Maintenance Costs :** between $30 to $50 per megawatt-hour (MWh)
- **Capital Costs :** range from $600 to $900 per kilowatt (kW) of installed capacity

Costs of Carbon Capture and Storage

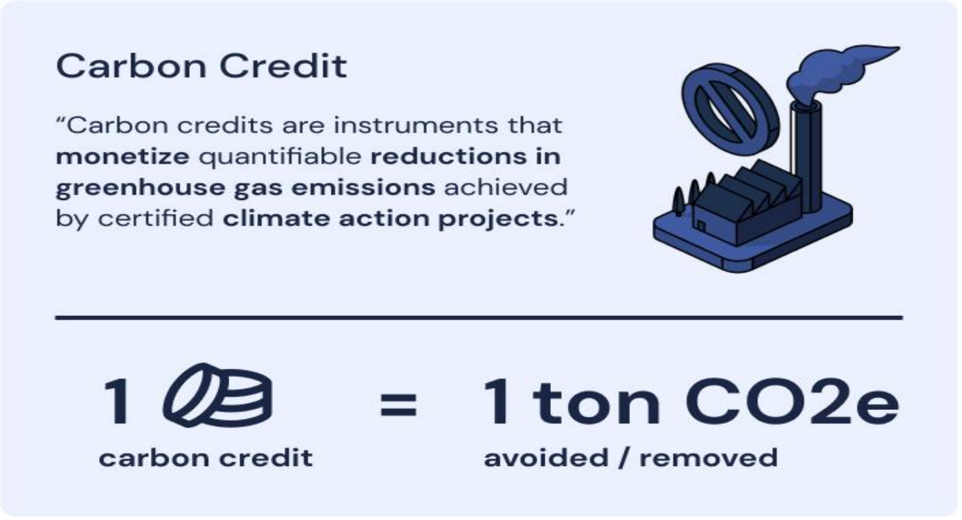
- **range from $30 to $70 per ton based on technology, the concentration of CO_2, and the scale of the operation**

Market dynamic for hydrogen

Demand and Supply: The demand for hydrogen, particularly in sectors like transportation, industrial processes, and energy storage, is expected to grow.



Government Policies and Incentives: Various governments are implementing supportive policies and incentives to promote the development of blue hydrogen



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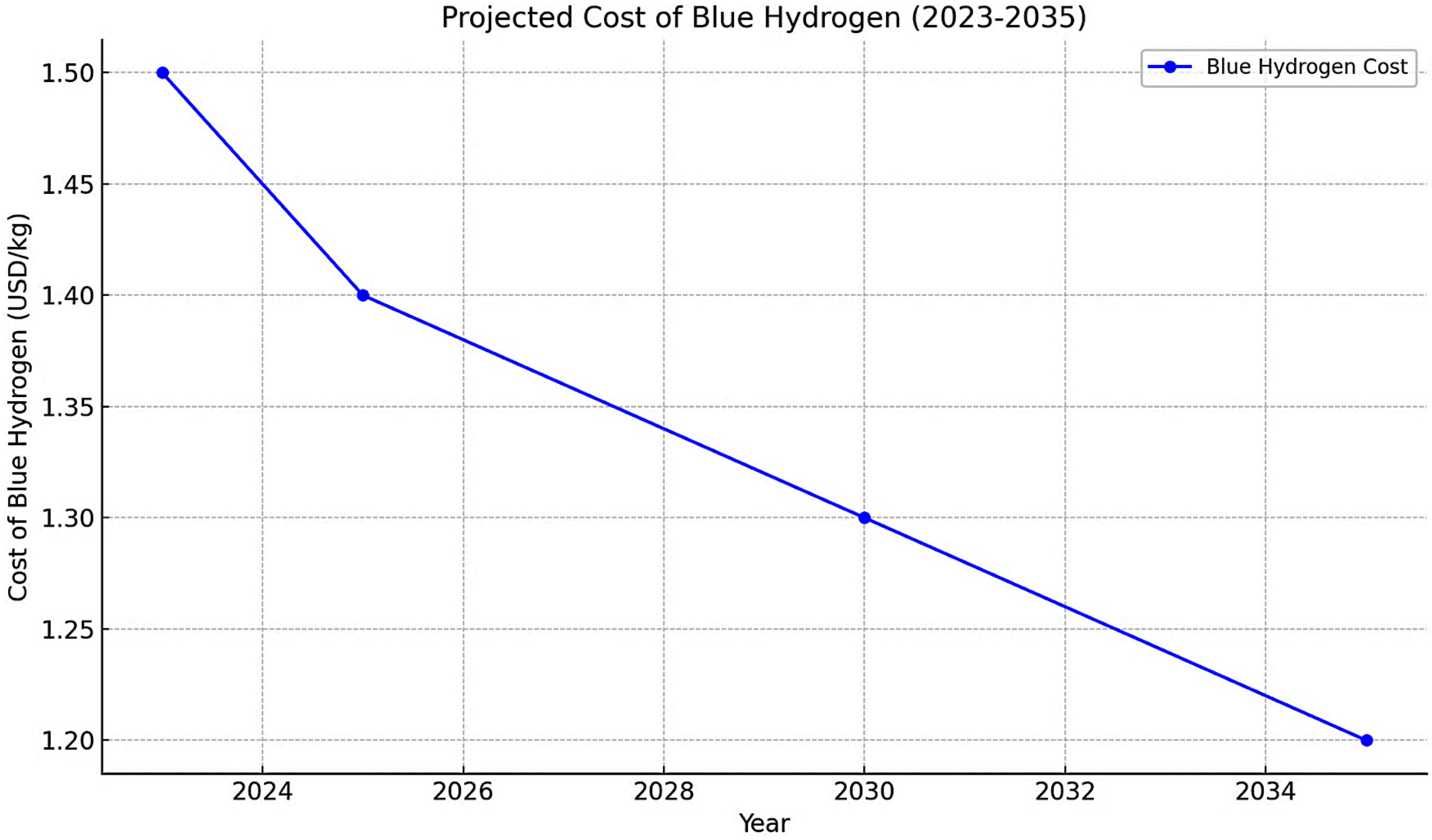
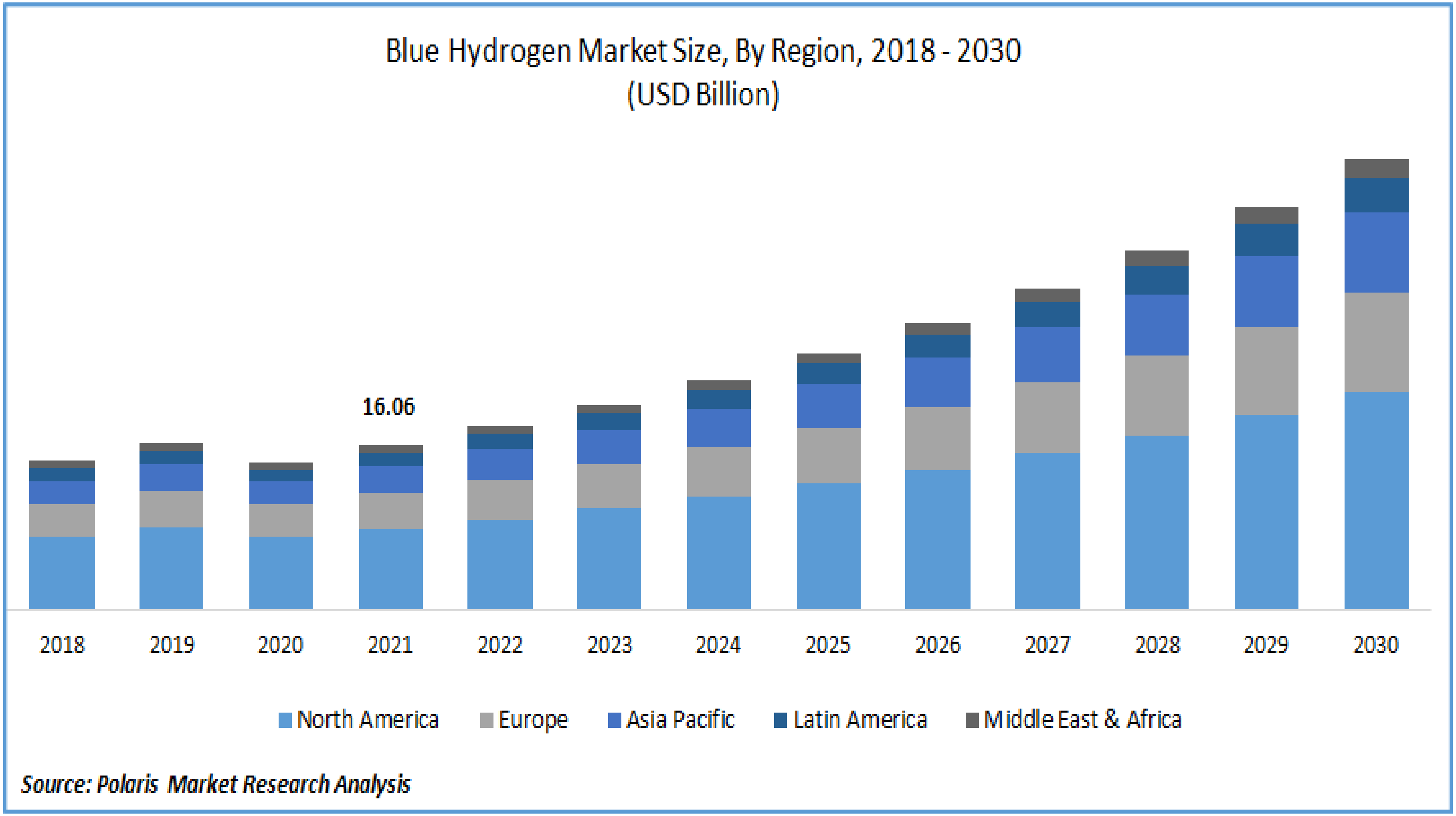
Future Price Predictions: As technological advancements and economies of scale are achieved; the cost of blue hydrogen is expected to decrease.



Reference: Bloomberg NEF Hydrogen Cost updated

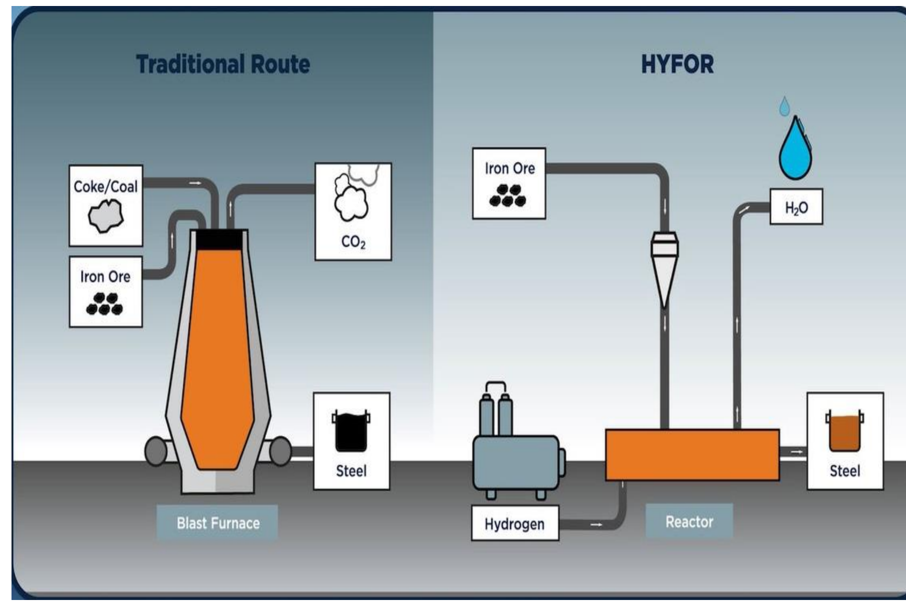
Blue hydrogen Market



BLUE HYDROGEN AS A TRANSIOTNAL TECHNOLOGY

1 - Short-Term Emissions Reduction

Blue Hydrogen offers an immediate solution for industries to cut emissions while transitioning to green hydrogen.



Blue hydrogen can help phase out higher-emission energy sources like coal and oil, especially in heavy industries like steelmaking, refining, and chemical production

2- Infrastructure Development

- **Utilize existing natural gas pipelines to scale hydrogen production in the short term :**

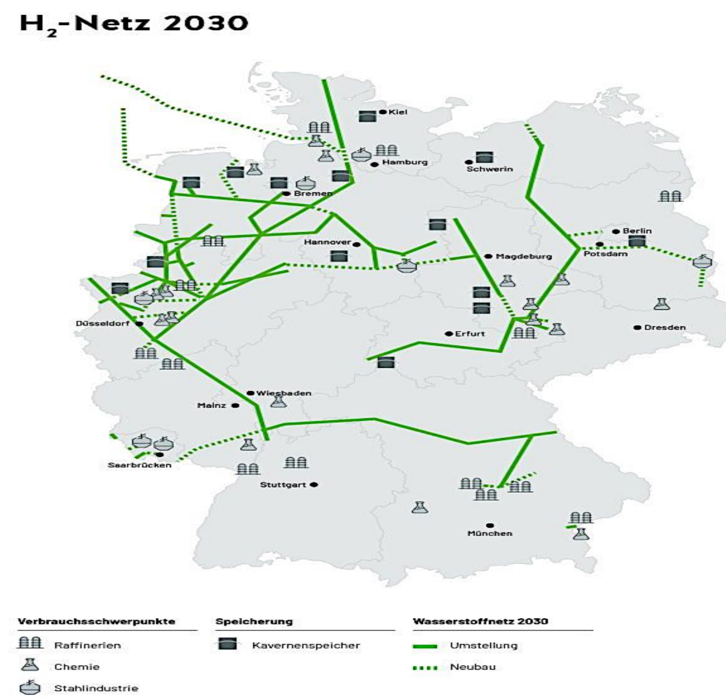
- The computability of material should be assessed, and older steel pipes should be replaced with more resistant materials.
- Seals should be well upgraded, and pipelines maintained and tested to prevent any hydrogen leak.
- Reinforcement of pipelines should be done to ensure that pipelines can safely handle higher pressures.

- **Hydrogen Embrittlement**: Hydrogen molecules are small and can penetrate the metal of pipelines, potentially causing hydrogen embrittlement, where the metal becomes brittle and prone to cracking. To mitigate this, high-strength materials such as certain grades of steel (e.g., X70 or X52) or composite materials are often recommended.
- **Low Diffusion**: Pipelines need to minimize hydrogen diffusion. Special coatings or materials with low permeability to hydrogen are essential to reduce leakage and maintain pipeline integrity.
- **Corrosion Resistance:** Hydrogen can interact with certain pipeline materials, causing corrosion over time. To prevent this, pipelines used for hydrogen transport often include protective coatings or are made from corrosion-resistant alloys.
- **Flexibility and Durability**: Hydrogen pipelines need to be designed to handle dynamic stresses such as temperature fluctuations, ground movements, or vibrations without significant damage. Flexibility in the pipeline material helps in preventing fractures or leaks.

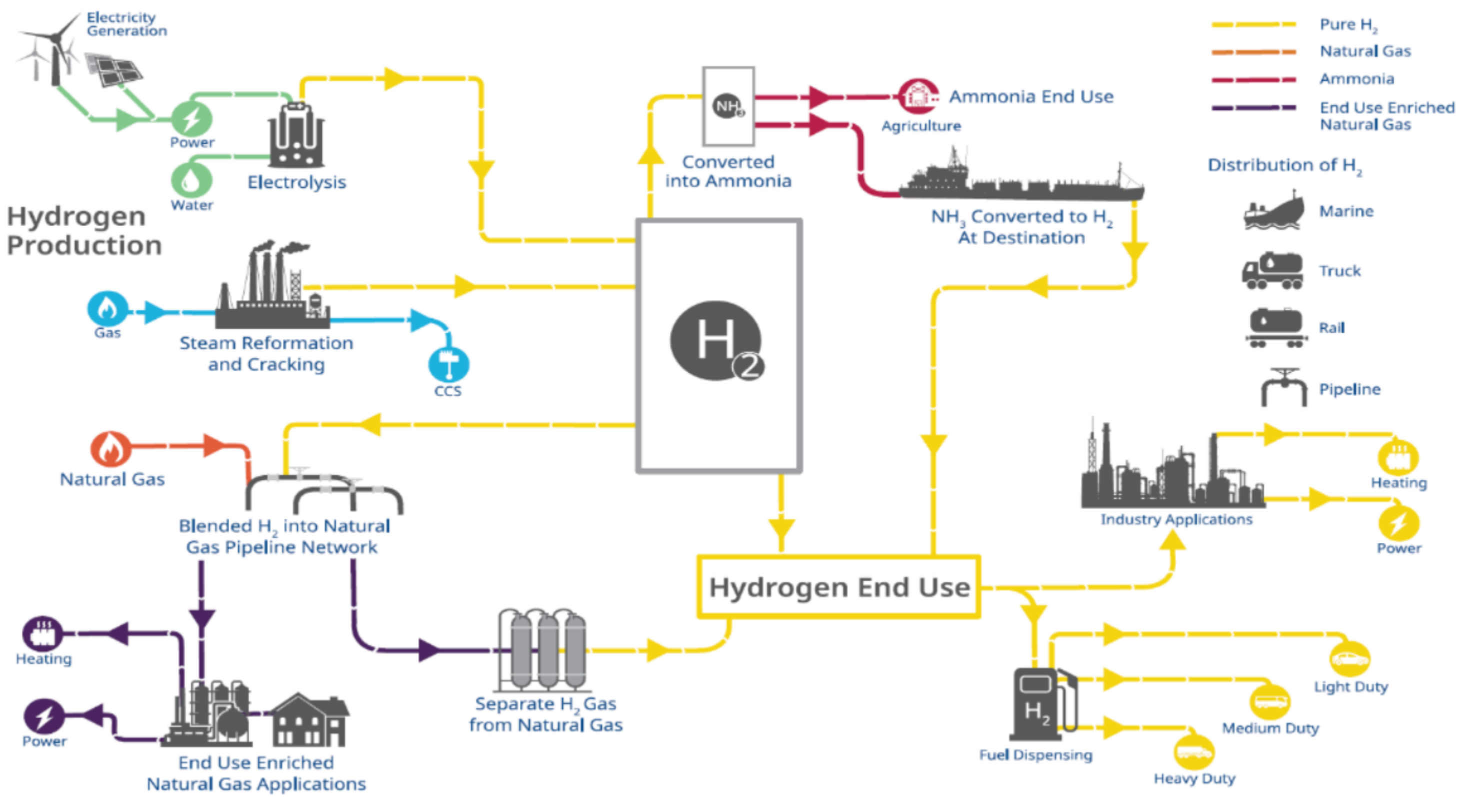
Germany and Netherlands are pioneers in adapting existing natural gas networks to accommodate their existing natural network as a part of their broader energy transition

<u>In Netherlands</u>: About 85% of the network will consist of reused natural gas pipelines, which is 75% cheaper than building new infrastructure.

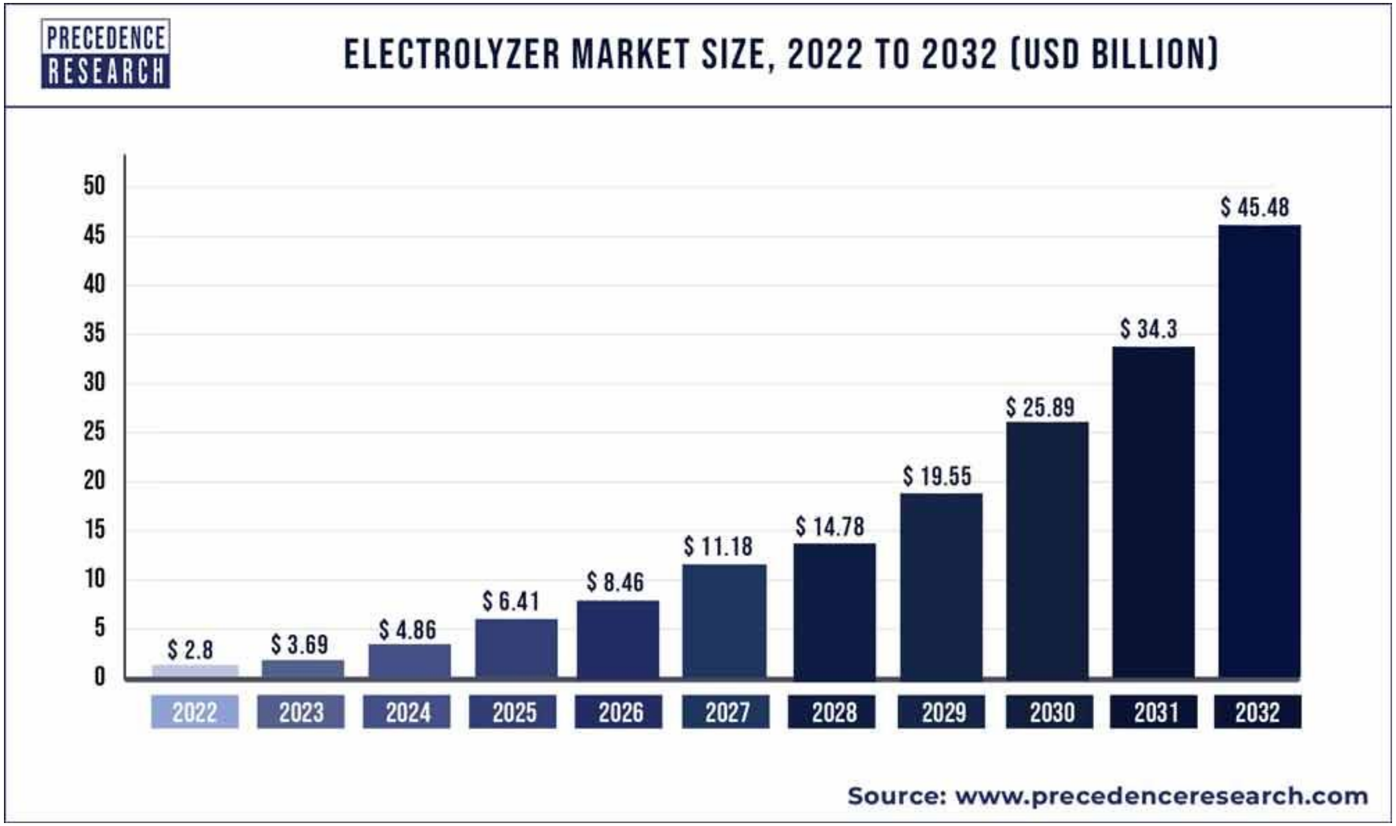
OGE and Nowega have started the conversion of a 46 km natural gas pipeline to hydrogen in Lower Saxony, **<u>Germany.</u>**



- **Establishing hydrogen production, distribution, and storage networks for blue hydrogen, regions and industries can create the foundational infrastructure required to support future green hydrogen scaling**

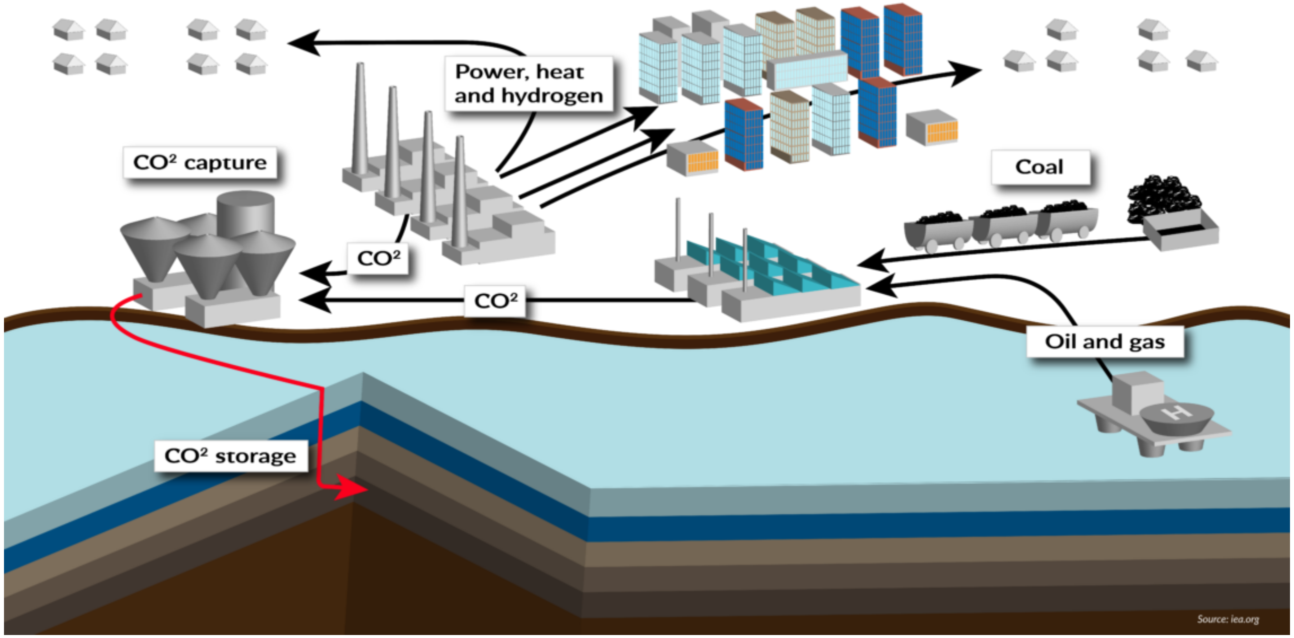


- **The initial hydrogen market driven by blue hydrogen can provide the momentum for increased investment in electrolyzer technologies, which are critical for scaling green hydrogen production.**



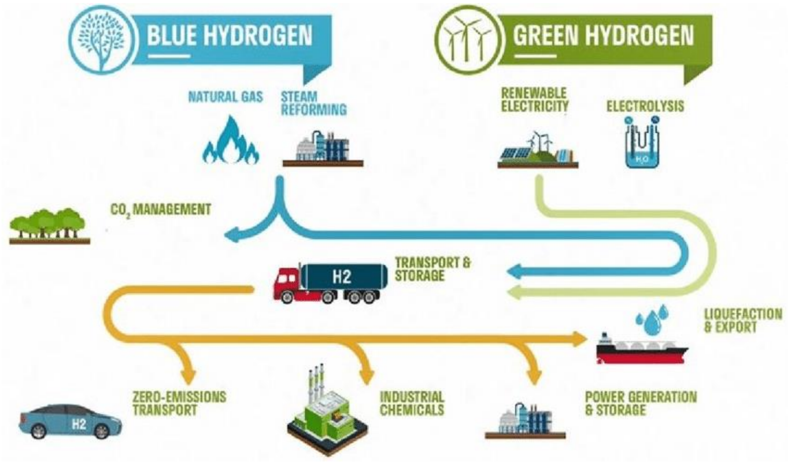
3- Technological Advancement

- **Developing blue hydrogen encourages investment in carbon capture and storage (CCS) technology, benefiting other industries and sectors reliant on carbon capture for decarbonization.**



Increase investment in electrolyzer technologies that could be driven the initial hydrogen market driven by blue hydrogen

Advances in electrolyser technologies can complement existing blue hydrogen facilities, providing modular solutions for producers to enhance their operations and reduce carbon footprint.

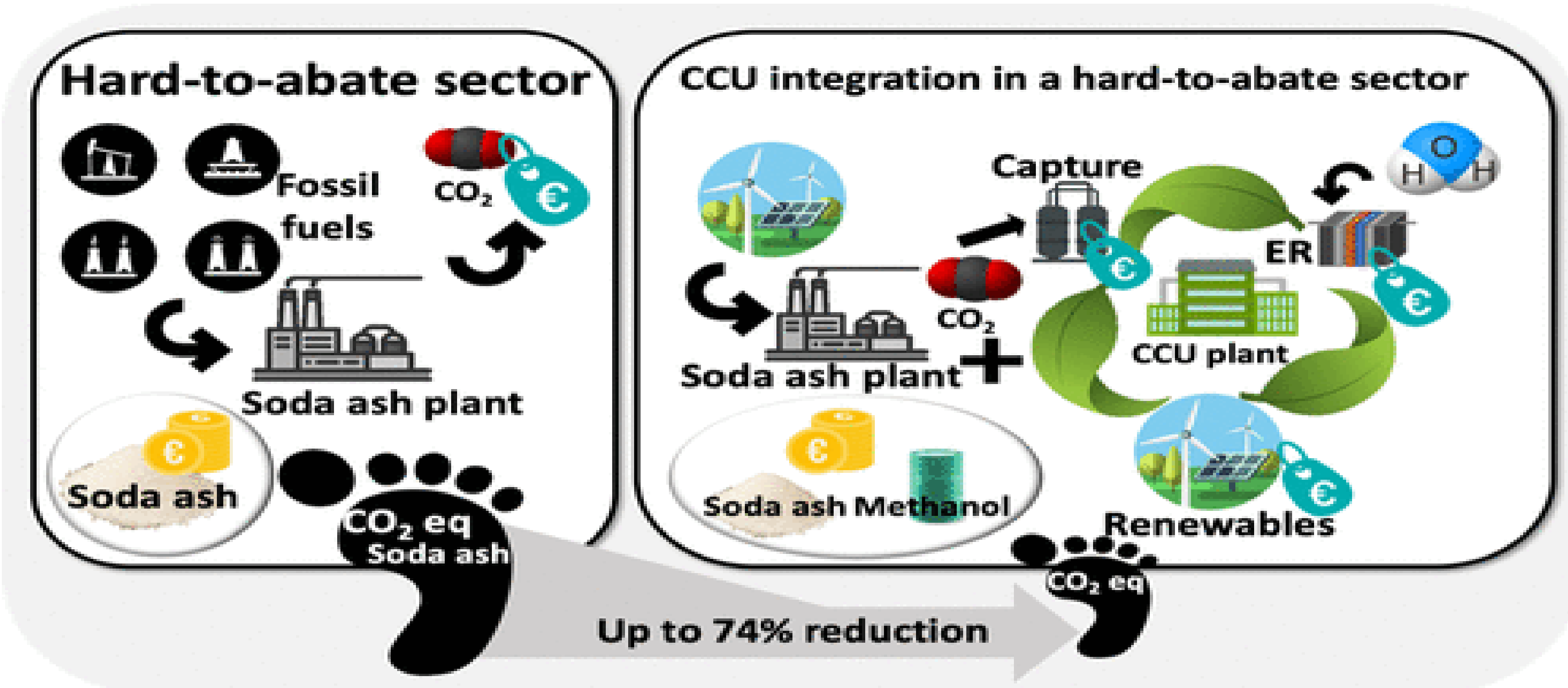


4- Economic Viability and Investment

- **Blue hydrogen production can help generate market interest in hydrogen as an energy carrier, attracting investments that can later be redirected toward green hydrogen**

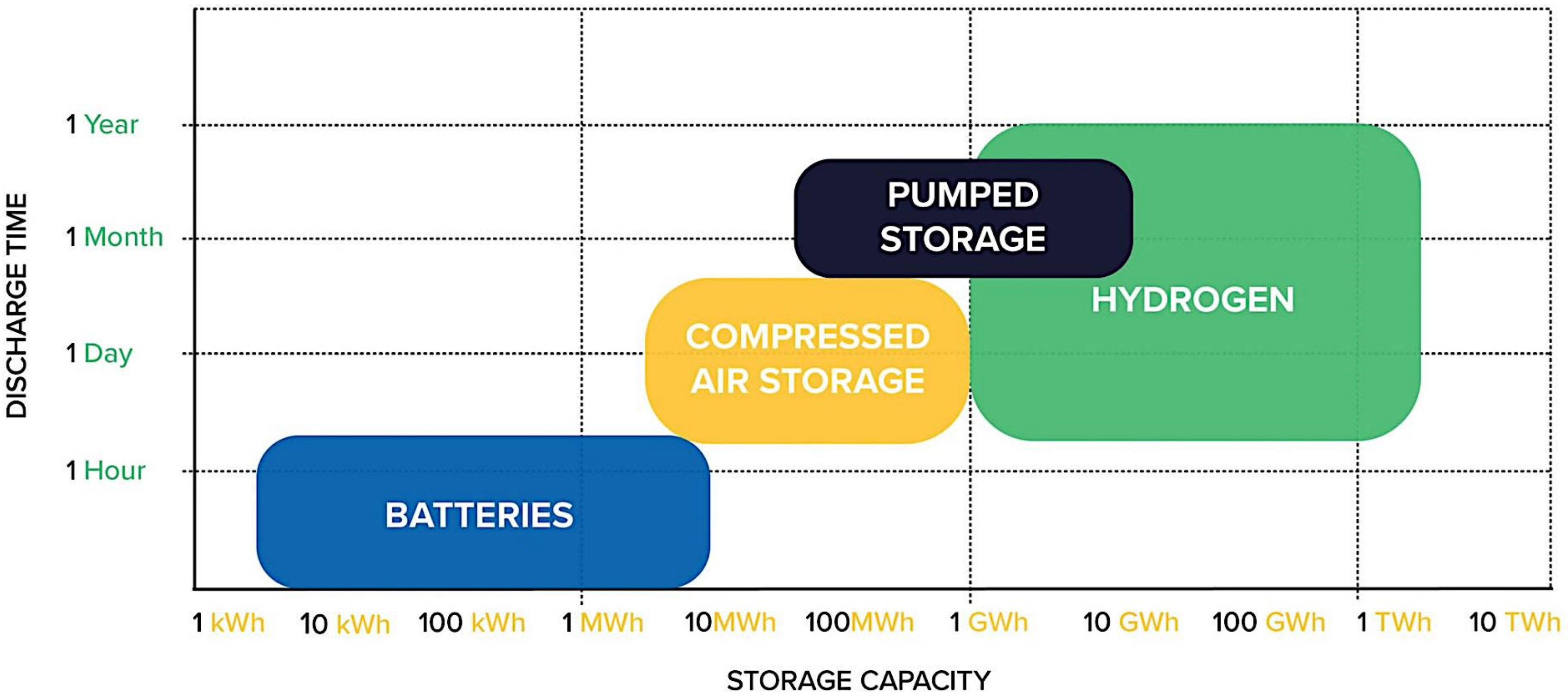
- **Blue hydrogen can generate employment in hydrogen production, carbon capture, and infrastructure development**

5- Industry and Energy Transition



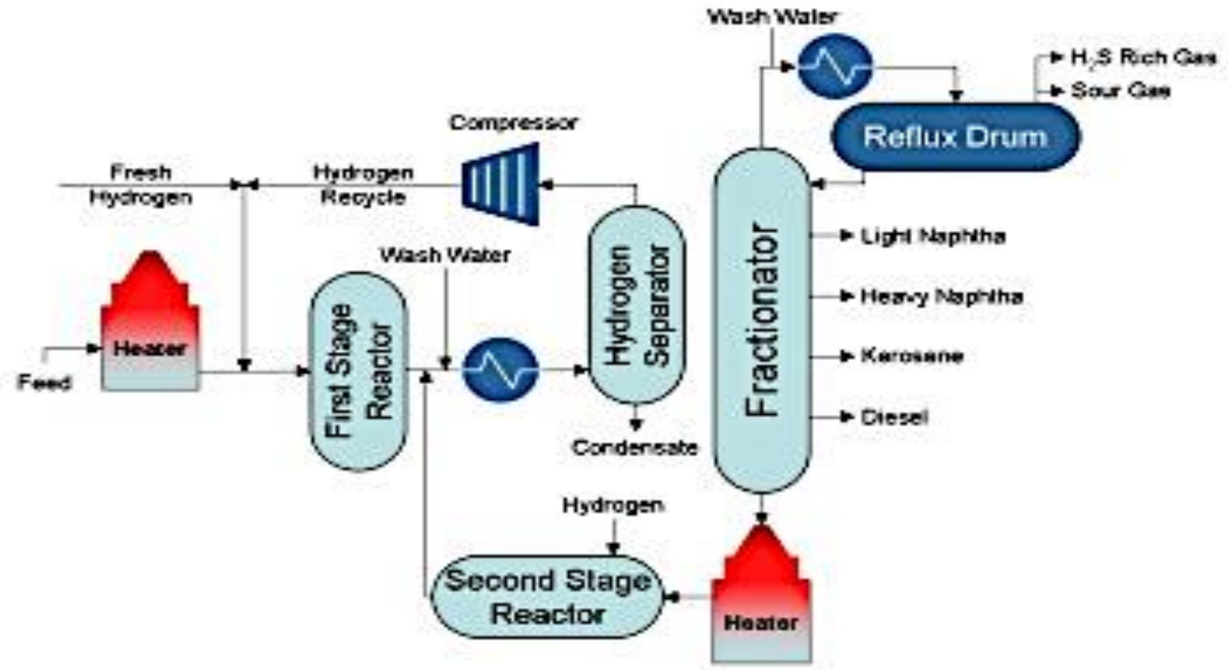
Blue hydrogen can be deployed in sectors like chemicals, refining, and heavy transportation, which are difficult to electrify.

Hydrogen as energy storage



Blue hydrogen can act as long-term energy storage medium, particularly in industries that require large amounts of energy and cannot immediately transition to intermittent renewable sources

Hydrogen is suitable for high temperature processes

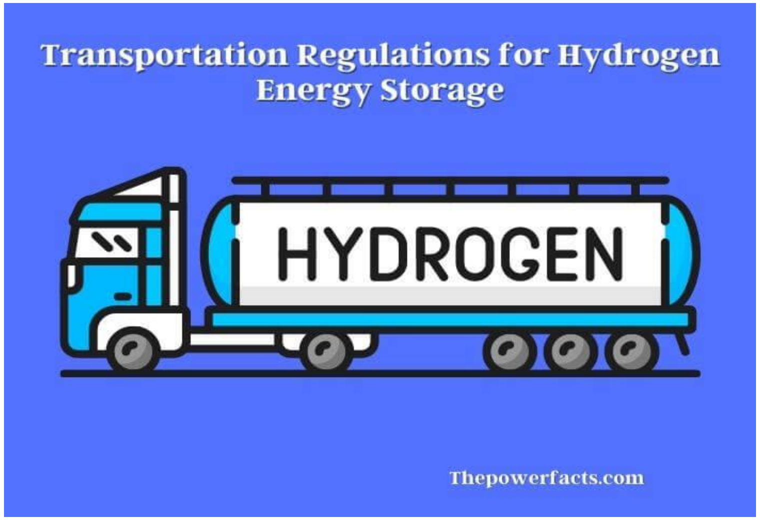


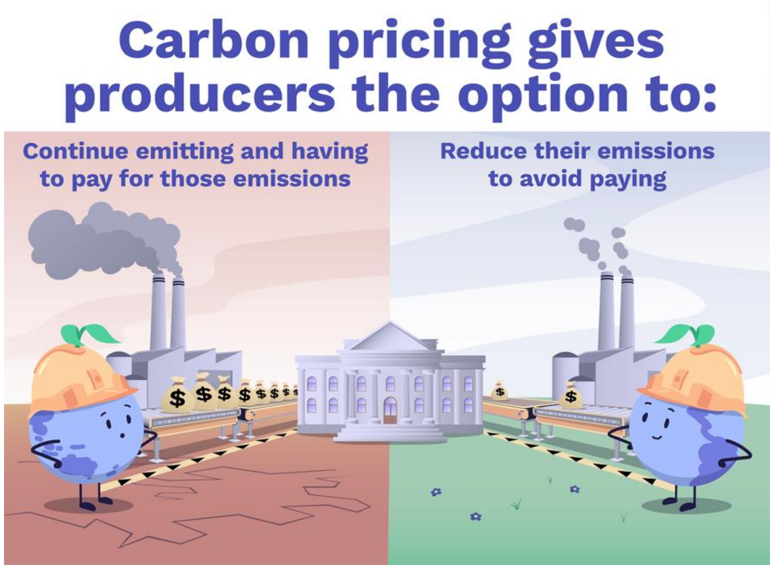
Hydrocraker process in refinery

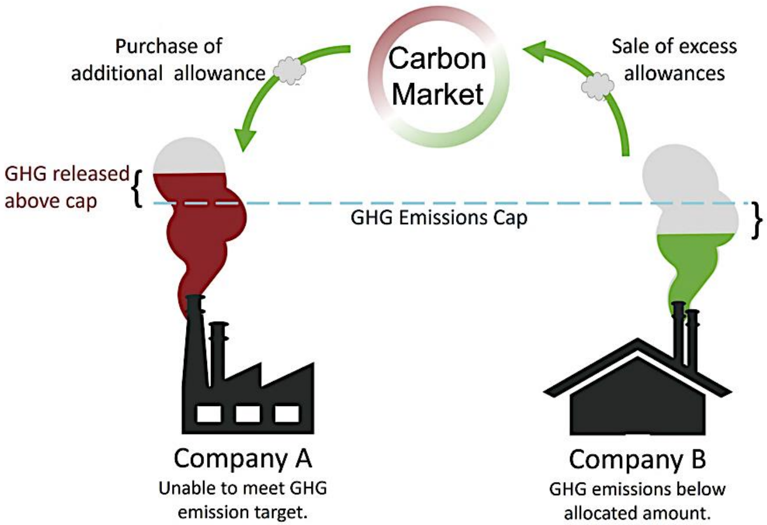
Blue hydrogen can be used in high temperature processes that require heat, like steams reforming and hydrocracking, replacing the natural gas currently used and reducing the overall carbon footprint operations.

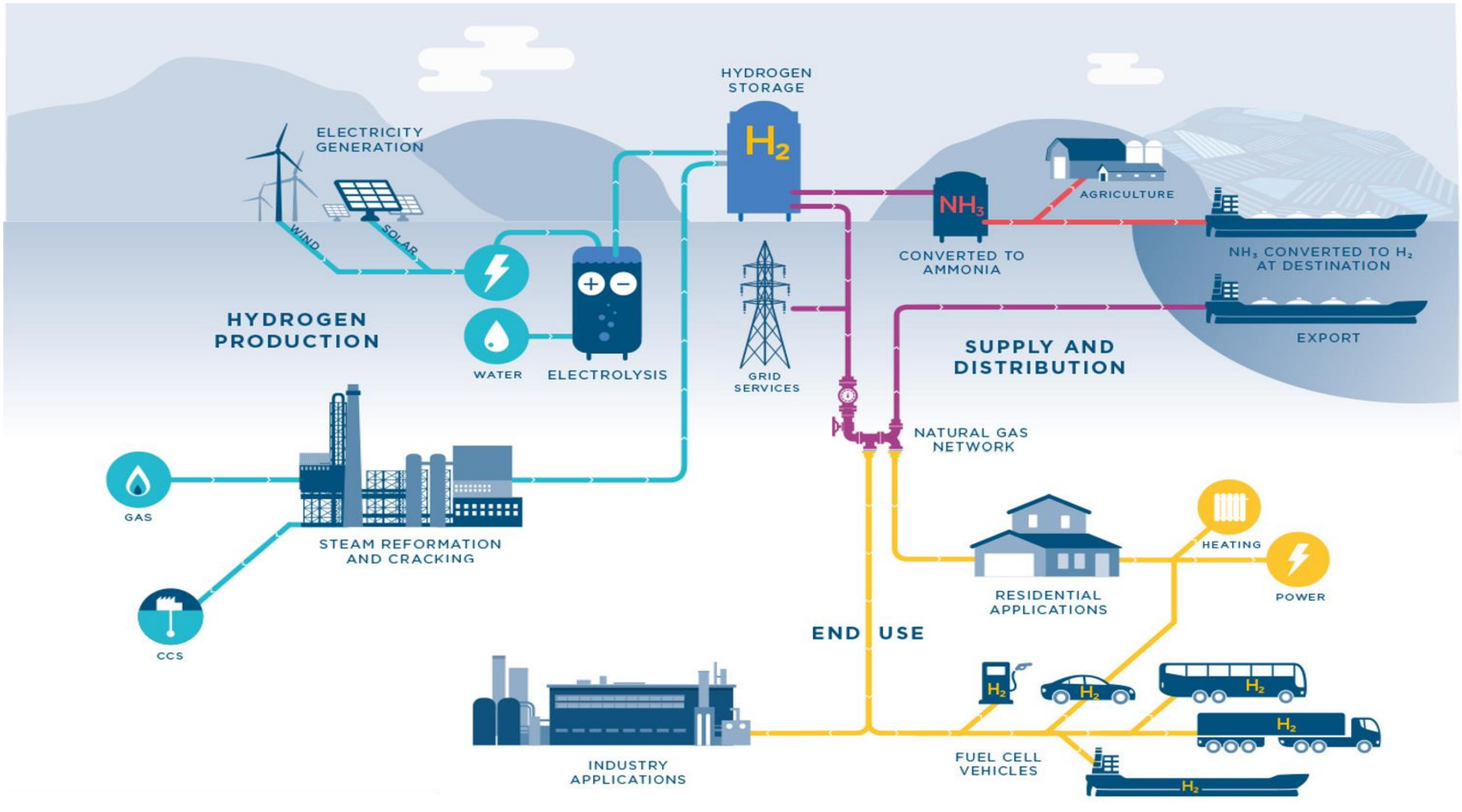
6- Policy and Regulatory Alignment

- **Policies can serve as a steppingstone to promote green hydrogen in the future as carbon prices rise and renewables become cheaper.**









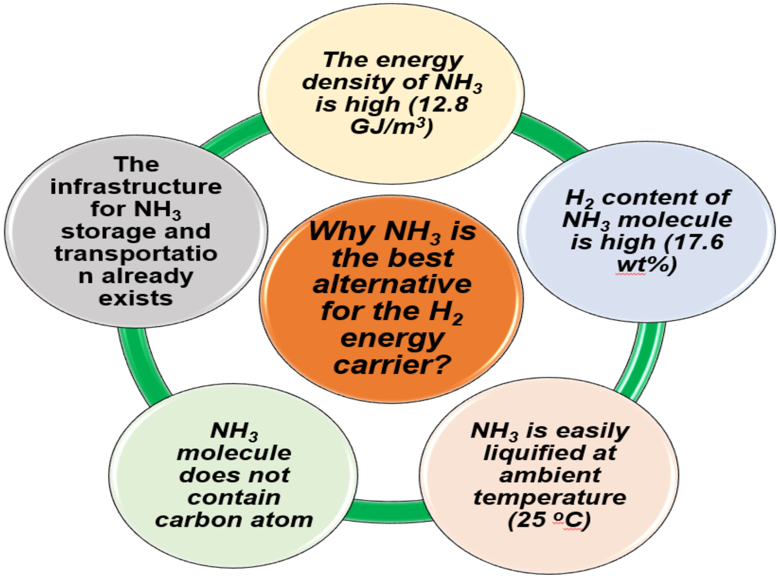
Fossil fuel companies can pivot to hydrogen production via blue hydrogen, allowing them to adapt to the energy transition. This reduces resistance from industries dependent on fossil fuels and allows smoother progress toward a renewable hydrogen economy.

7- Scaling the Hydrogen Economy

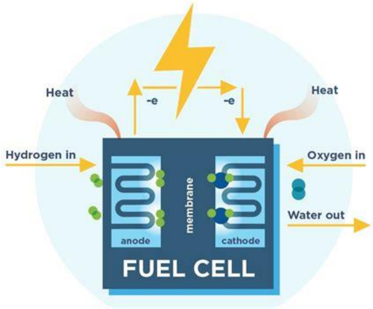
- **Stimulate hydrogen demand across various sectors, transport, industry, and power establishing the supply chains, markets, and applications necessary for future green hydrogen uptake**.

- **knowledge gained from producing and managing blue hydrogen can accelerate the development of green hydrogen technologies, facilitating smoother technological and industrial transitions**.

Ammonia as hydrogen carrier: Ammonia is produced using hydrogen and can serve as a carrier for hydrogen in global energy markets



Fuel cells: The increased availability of blue hydrogen can stimulate the development and deployment of fuel cell technologies, particularly in transport and power generation



Cases highlighting the growing adoption of blue hydrogen

- HyNet Northwest (United Kingdom)

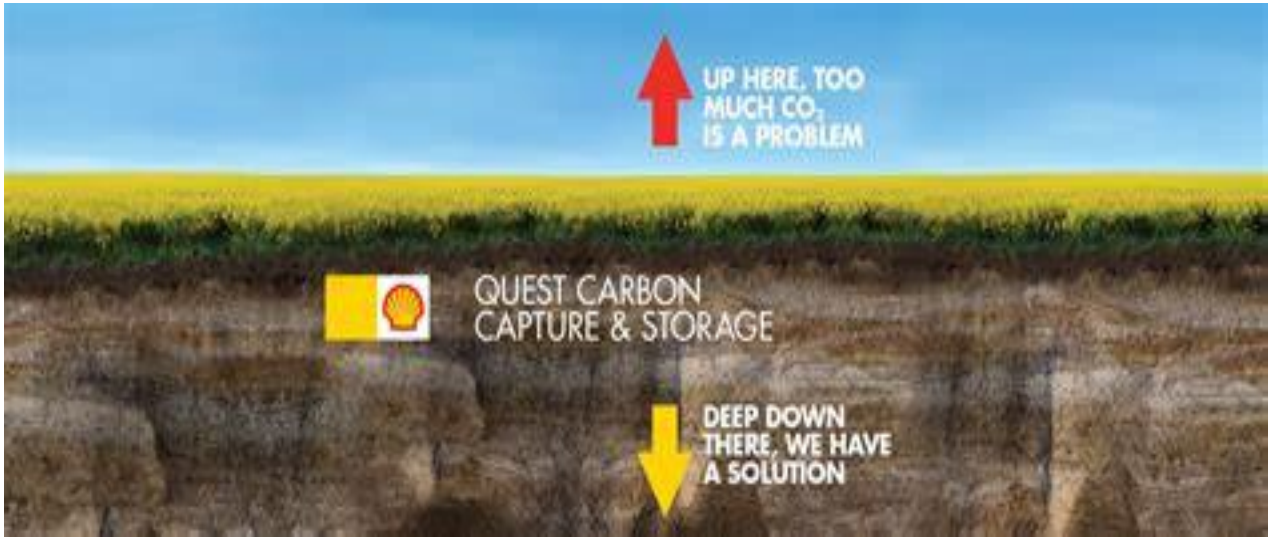
- It combines blue hydrogen production with CCS, utilizing natural gas reforming processes.
- The project leverages the region's existing industrial infrastructure, minimizing new capital expenditures while creating thousands of jobs.
- Hynet plans to reduce the region's carbon emissions by 10 million tons annually by 2030.
- The captured CO_2 is stored offshore in depleted gas fields in Liverpool **Bay**

- Air Products' Port Arthur Hydrogen Plant (United States)

- It operates one of the largest blue hydrogen plants in Texas, utilizing steam methane reforming (SMR) with CCS.
- By capturing and storing over 1 million tons of CO_2 annually, the project not only provides hydrogen for industrial uses but also benefits from tax credits for carbon capture under the 45Q federal incentive.
- The project reduces the carbon intensity of hydrogen production, supplying low-carbon hydrogen for refining processes, and setting the groundwork for hydrogen use in other sectors like transportation.

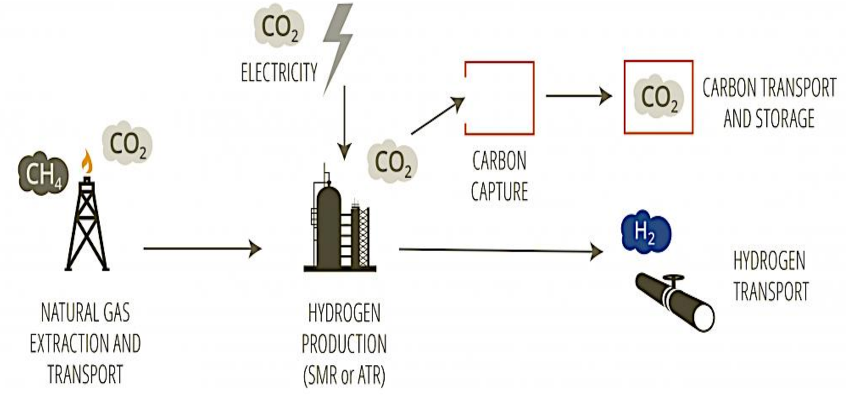
Shell's Quest CCS Facility (Canada)

- The project captures and stores around 80% of CO_2 emissions from hydrogen production at the Scotford Upgrader, where hydrogen is used to refine oil sands.
- The facility has captured and stored over 6 million tons of CO_2 since it began operations (2015), enabling Shell to offset emissions from hydrogen used in the refining process and reducing carbon taxes

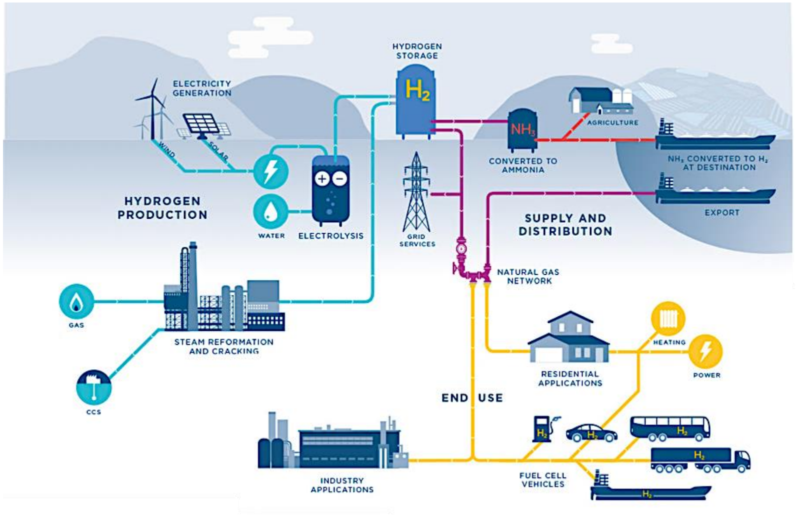


Challenges facing blue hydrogen

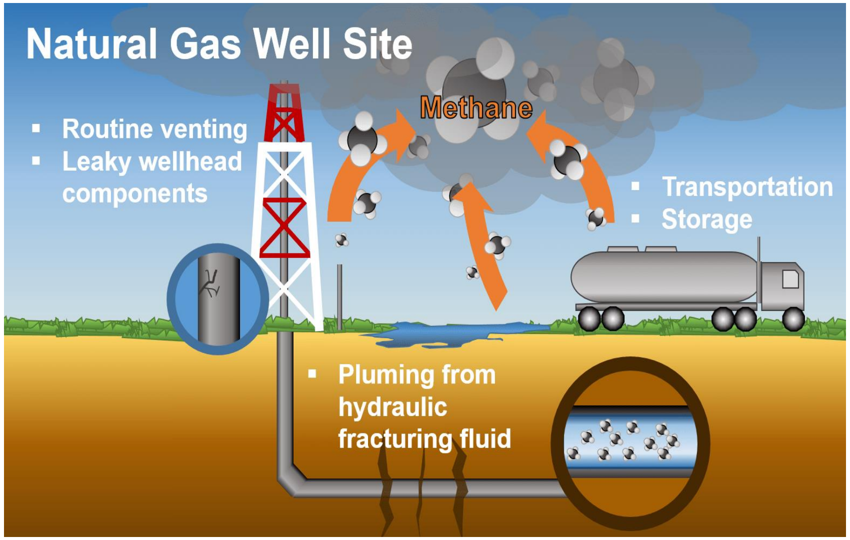
High cost of production: which remains largely dependent on natural gas prices and the economic viability of carbon capture and storage (CCS) technologies



Infrastructure: the infrastructure required for the transport, storage, and distribution of blue hydrogen is still underdeveloped, posing logistical challenges



Environmental concerns: associated with methane leakage during the natural gas extraction process, which could negate the carbon savings attributed to blue hydrogen**.**



Regulatory and policy: vary significantly between countries, which can complicate international investments and the development of a global hydrogen market.

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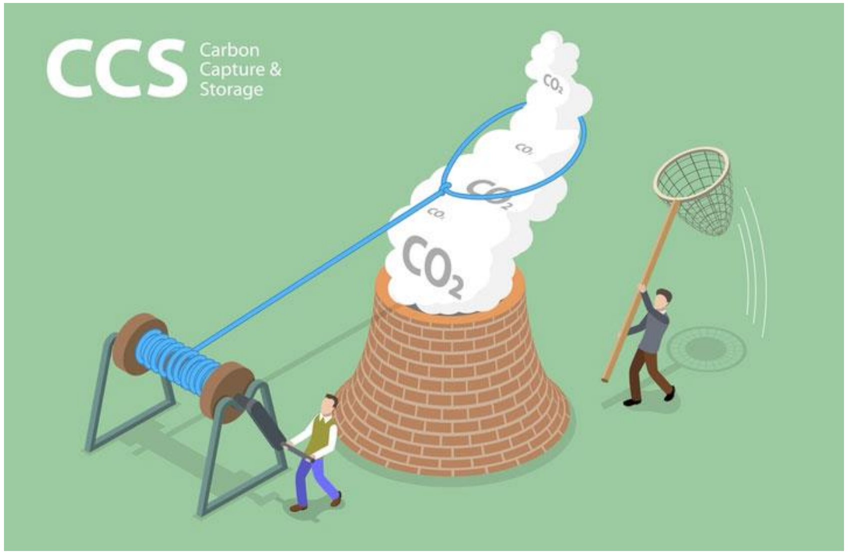
Long-Term Role of CCS Beyond Blue Hydrogen

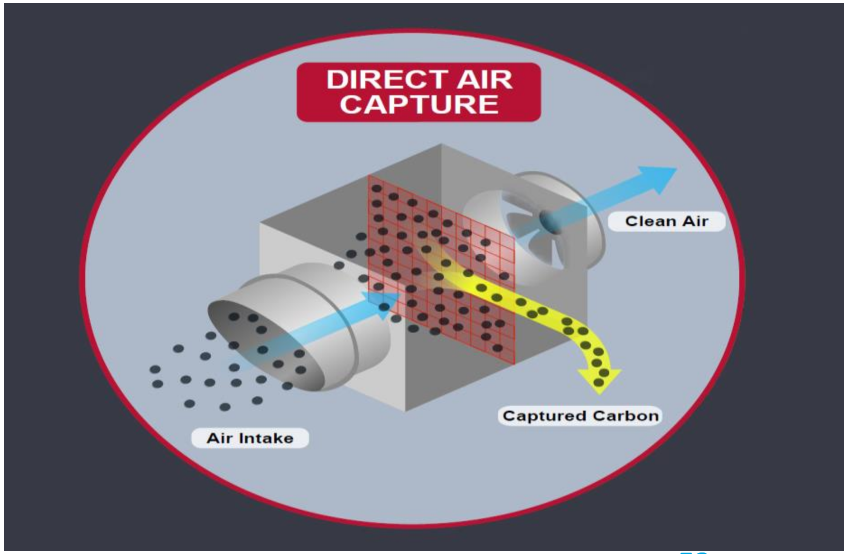
Even as green hydrogen becomes more viable, CCS will continue to play an important role in other sectors of the economy.

Industrial Decarbonization: Industries like cement, steel, and chemical production will continue to require CCS, as complete electrification or decarbonization through hydrogen may not be feasible in the short term.

Long-Term Storage Solutions: Developing CCS infrastructure now will help lay the groundwork for long-term CO_2 storage solutions that will be necessary to achieve net-zero emissions.

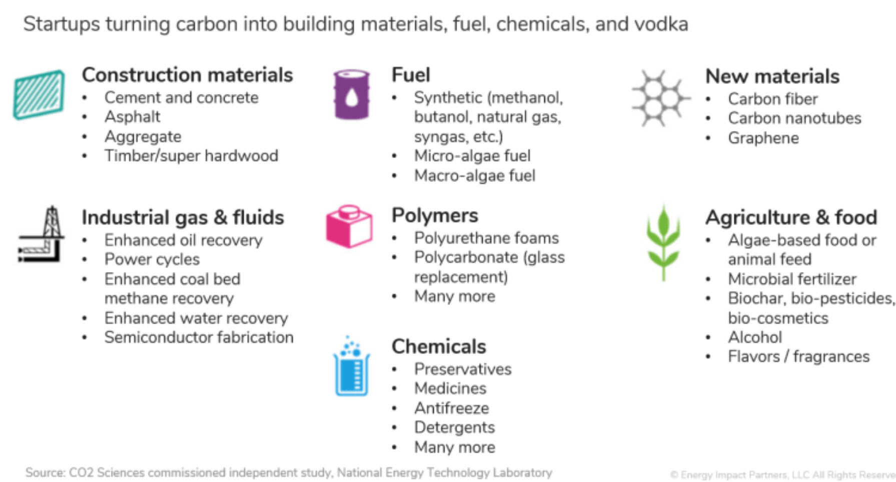


Direct Air Capture (DAC): CCS technology will also be crucial for negative emissions technologies, such as direct air capture, which can remove CO_2 from the atmosphere. DAC could complement green hydrogen by addressing sectors where emissions are hard to avoid.



Expanding CCS Beyond Industrial and Energy Sectors : CCS could be used to decarbonize agriculture sector, by capturing emissions from large scale livestock operation of applying CCS technologies to biomass processing

CO_2 utilization: many emerging technologies for using captured CO_2 such as enhanced oil recovery, carbon to value.



Conclusions

- **Blue hydrogen offers a practical, short-term solution to reduce emissions while laying the groundwork for a future dominated by green hydrogen.**
- **CCS allows for the continued use of hydrogen in high-demand industries, while also providing the flexibility needed to transition to a fully renewable hydrogen economy.**
- **CCS will remain a vital tool for reducing emissions in both hydrogen production and other industrial applications, supporting the broader goal of achieving a sustainable, zero-carbon future.**
- **Governments, industries, and innovators must work together to ensure that both CCS technologies and renewable energy systems are deployed at scale to accelerate the shift toward sustainable energy**

Thank you for your attention

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Discussion

As we look toward a fully decarbonized future, do you think that blue hydrogen and CCS have a viable long-term role in the energy transition, or are they simply a stopgap measure until green hydrogen becomes more feasible?

What do you see as the most critical technical or economic barriers that need to be addressed for blue hydrogen and CCS to significantly contribute to the global hydrogen economy without delaying the shift to green hydrogen?