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CLASS NK WEBINAR SERIES

Hydrogen Basic Information

June 2024

HYDROGEN: AN INTRODUCTION

Contents

HYDROGEN: AN INTRODUCTION

Hydrogen today

There are many hydrogen production methods

Steam Methane Reforming (SMR) (Grey)

Natural gas is mixed with steam and a catalyst under high temperature and pressure to produce hydrogen and CO_2. The CO_2 produced is not captured and released into the atmosphere.

Electrolysis (green)

Electrolysis, powered by renewable electricity, splits water molecules into oxygen and hydrogen.

Electrolysis with Solar (yellow)

Electrolysis, powered specifically by solar electricity splits water molecules into oxygen and hydrogen.

Electrolysis with Nuclear Energy (pink)

Electrolysis, specifically using electricity from nuclear reactors, splits water molecules into oxygen and hydrogen

Methane reforming with CCUS (blue)

Hydrogen produced via the SMR process however the carbon dioxide (CO_2) produced is captured and stored underground (Carbon Capture utilisation and storage (CCUS)).

Coal Gasification (brown/black)

Oxygen and steam contact coal in a high temperature oxygen deficient atmosphere to produced gas carbon monoxide (CO), CO_2, and hydrogen. This is the most environmentally damaging.

Methane Pyrolysis (turquoise)

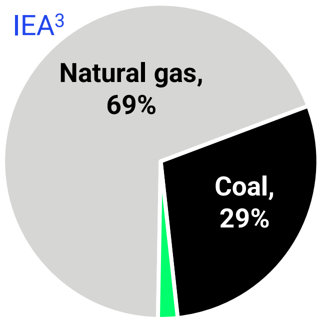
Methane pyrolysis, a high temperature process powered renewable electricity, splits methane to produce hydrogen and solid carbon which can be stored or used.

Geological hydrogen from fracking (white)

Hydrogen naturally occurring in underground deposits in accessed and extracted via fracking. This is at very early stages of development.

How is hydrogen used today?

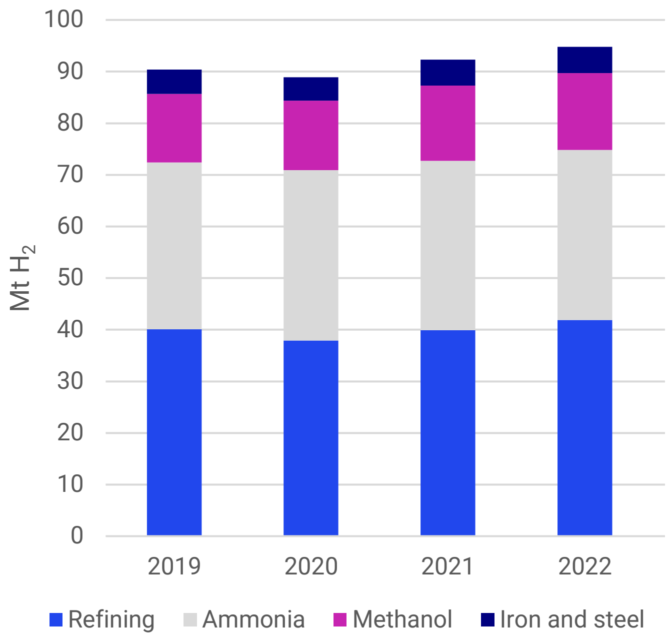
- Nearly **100 million tonnes (Mt)** of produced annually[1]
- Almost all used as a **chemical feedstock**
- **Produced at massive scale** centrally and continuously
- Overwhelmingly uses fossil fuels to be produced, with **significant carbon emissions - 12kg CO2 / kg H_2**[2]
- Fossil fuel based production processes are **very mature, highly integrated and highly efficient**



Carbon emissions ~1100 $MtCO_2$ per year[2]

2.5% of Global Final Energy Consumption[4]

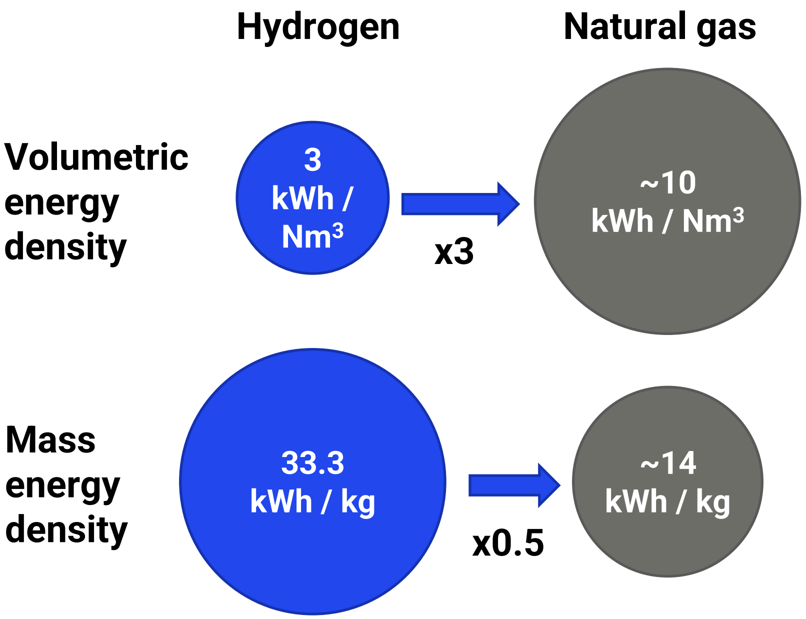
Global hydrogen demand by, 2019-2022[1]



[1] Hydrogen - IEA
[2] Hydrogen – IEA
[3] IEA Global Hydrogen Review 2023
[4] IEA Global Hydrogen Review 2022

Why does the current hydrogen value chain look like this?

- Production of hydrogen using fossil fuels is **extremely energy intense** and required **economies of scale** to produce an **economically viable feedstock.**
- Compared to natural gas, **volumetric energy density is low** making **transport and storage of hydrogen expensive.**
- Hydrogen is not traded as commodity, and **production is therefore sized to match end-use.**
- Local prices of natural gas dictate cost of products, and **therefore hydrogen production and use is concentrated in areas where natural gas is cheapest**



All energy densities in LHV

Why is hydrogen seen as a tool in the energy transition?

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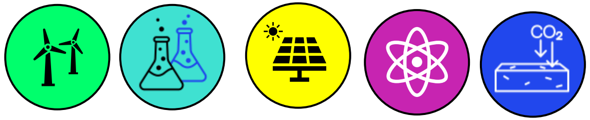
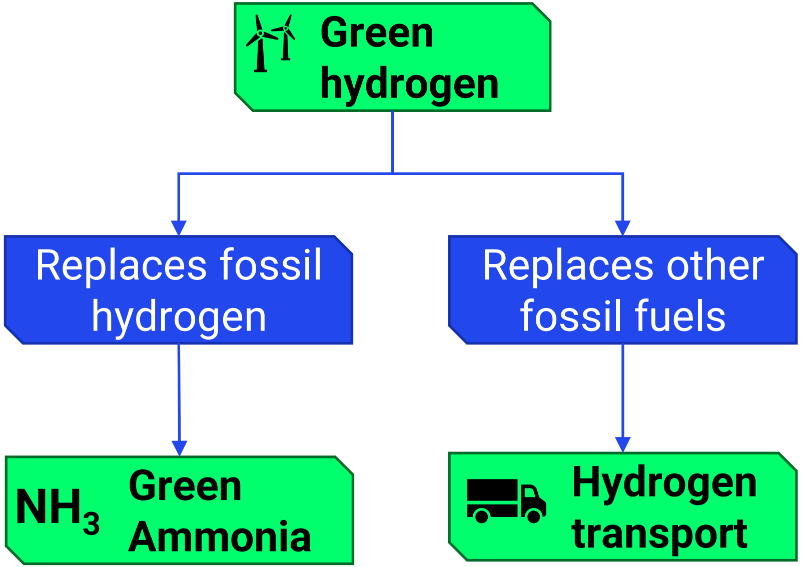
- While current hydrogen production is very carbon intense, there are ways to **produce hydrogen with very low or no carbon emissions** (clean hydrogen).



- These methods **can replace grey or black hydrogen** in areas like refining and fertiliser production to help decarbonise them.
- This also enables hydrogen to function as a **low or zero carbon energy vector** – providing an alternative to renewable electricity for decarbonising many sectors.
- Additionally green hydrogen and electrolysers can be a key component in **sector coupling** between gas and electricity.



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HYDROGEN: AN INTRODUCTION

Production, distribution, storage and end-use

Grey, blue, and green hydrogen are the most important

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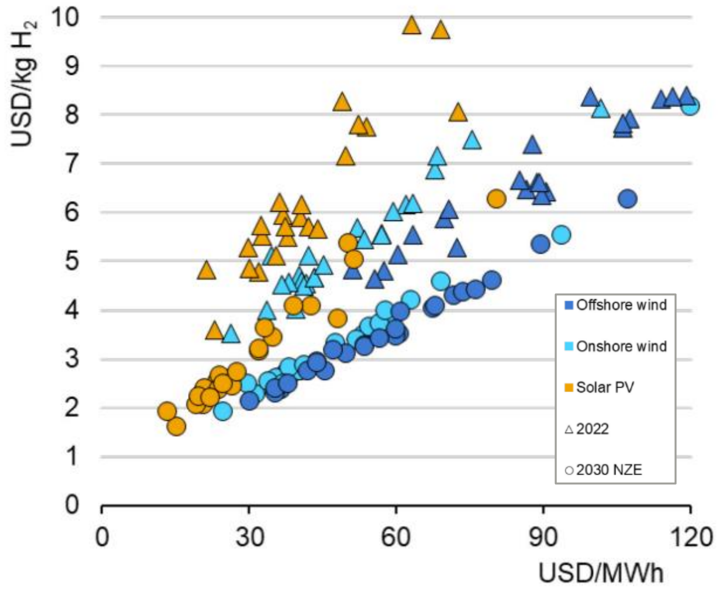
	Grey hydrogen	Blue hydrogen	Green hydrogen
How is it made?	Methane + Steam Heat + pressure ↓ Hydrogen + CO_2	Methane + Steam Heat + pressure ↓ Hydrogen + CO_2 CCUS	Water Renewable Electricity ↓ Hydrogen + Oxygen
Carbon emissions	~**12 kg**[2] CO_{2eq} / kg H_2	> **1 kg** CO_{2eq} / kg H_2	**0* kg** CO_{2eq} / kg H_2
Approximate cost per kg	~**$3** / kg H_2 IEA[1] est. $1-6 / kg H_2	~**$3.5** / kg H_2 IEA[1] est. $2-7 / kg H_2	~**$7** / kg H_2 IEA[1] est. $3.5-12 / kg H_2
Other characteristics	Very mature process, very efficient, production sized for demand and operated continuously.	Uses knowledge from grey, CCUS can capture up to 95% CO_2, production sized for demand and operated continuously.	Must use renewable electricity. Requires energy storage to balance supply and demand as renewables are intermittent.

[1] IEA Global Hydrogen Review 2023
[2] Hydrogen – IEA

Introduction to green hydrogen economics

- The levelized cost of green hydrogen is typically high compared to blue and grey
- This cost is predominantly derived from the **capital cost of the electrolyser** and the **cost of electricity required** to run the electrolyser.
  - Electrolyser capital costs are expected to reduce as production capacity increases and supply chains are refined.
  - This will increase the proportion of overall cost of production derived from electricity costs.
- As a result, to make the **cheapest green hydrogen**, you must secure **low-cost renewable electricity.**
- The cheapest renewable electricity may not be available when or where you need it….

Levelised cost of hydrogen production based on different renewable electricity prices, 2022 / 2030 (IEA[1])



[1] IEA Global Hydrogen Review 2023

Why use hydrogen storage?

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Advantages of hydrogen storage

Hydrogen storage can balance out differences in supply and demand profiles for green hydrogen

Stored hydrogen can supply power to the grid at times of the year when demand is higher than supply

Hydrogen can be used for long-duration energy storage to help decarbonise grids

Disadvantages of hydrogen storage

Limited availability of large-scale storage sites

Low energy density of hydrogen = increased cost of storage (vs natural gas)

Storage of hydrogen increases delivered cost

Hydrogen carriers and liquid hydrogen can address the energy density issues of hydrogen gas – at a cost

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Ammonia	Methanol	Liquid organic hydrogen carriers (LOHCs)	Liquid Hydrogen
Dense hydrogen content (17.6wt%). More volume efficient to transport than hydrogen. Can transport larger amounts of energy over long distances compared to pure hydrogen. Carbon free when used as fuel, only produces nitrogen and water.	Dense hydrogen content (12.5wt%). Liquid at ambient temperature making it easier to store in lower pressure structures. Can be reformed on site into hydrogen, e.g., at fuelling stations for fuel cell cars.	Organic compounds capable of absorbing (hydrogenating) and releasing hydrogen (dehydrogenation) through chemical reactions with a catalyst. Can store hydrogen at a high density in a liquid state. However, these processes require high temperatures and pressures, requiring energy.	More energy dense than hydrogen gas, better for storage and distribution Lower volume is required for same energy output so less and smaller storage required. However, requires very low storage temperatures to be maintained.

Hydrogen carriers are practical and efficient mediums for hydrogen storage and distribution, enabling broader adoption of hydrogen as a clean energy. They are also compatible with existing fuel infrastructure.

Storing hydrogen – from project level to national asset

Gaseous storage tanks

Compressed hydrogen gas is stored on site in small volumes to be used as buffer storage and inter-day storage.

Being used today, will play key role in the energy transition in the 2020s.

The amount of hydrogen stored ranges from high kWh – low MWh.[1]

Geological storage

Compressed hydrogen gas is stored in geological formations such as lined rock caverns, salt caverns, and depleted gas fields to provide seasonal, long duration storage.

Hydrogen stored in these geological formations can range from GWh – TWh.[1]

Salt caverns are in use for hydrogen storage today.

Solid state storage

Hydrogen is stored in a solid-state structure. This method of storage is more energy dense and may be used at hydrogen refuelling stations.

1MWh solid-state hydrogen storage system is currently being tested in Scottish Isles.[2]

Ammonia and other carriers

The energy density of hydrogen is improved by converting it to ammonia which can be shipped over long distances.

[1] Technical and Economic Feasibility Analysis of Underground Hydrogen Storage: A Case Study in Intermountain-West Region USA (2022)
[2] Shylo: Solid hydrogen at low pressures (2024)

Volume and distance dictates hydrogen distribution

Tube trailers

Semi-trailers carrying high pressure hydrogen gas tanks (tubes).

Being used today, will play key role in the energy transition in the 2020s.

Suitable for local distribution from production sites to industrial users.

Pipelines

For cross country distances, hydrogen gas will need to be distributed at varying pressures in transmission and distribution sized pipelines.

Some new pipelines will need built but natural gas pipelines can be repurposed.

Liquid hydrogen tankers

Liquid hydrogen (LH2) can be transported in highly-insulated, cryogenic tanker trucks.

Can be used to supply in high value applications where pipelines cannot be built.

Suitable for cross country distances distribution.

Ships

Required for larger energy demands and intercontinental transport.

Hydrogen is typically converted into ammonia, methanol or liquid hydrogen.

Still in development.

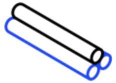
Each distribution option has benefits and challenges

Tube trailers

There are already market options for tube trailers with capacity of ~500kg[1].

Technical improvements are required to improve performance and reduce leakage.

Commercial improvements are required to optimise tube trailer logistics.



Pipelines

Pipeline is often the most cost-effective method to transport large volumes over long distances.

Hydrogen embrittlement of steel pipelines is likely.

This can lead to cracking of the material and increased leaks.

Liquid hydrogen tankers

Better economies of scale than compressed gas tube trailers, as liquid hydrogen is can be distributed in larger masses of ~3,500kg of liquid hydrogen[2].

But liquification is expensive and energy intensive and liquid hydrogen can "boil off".

Ships

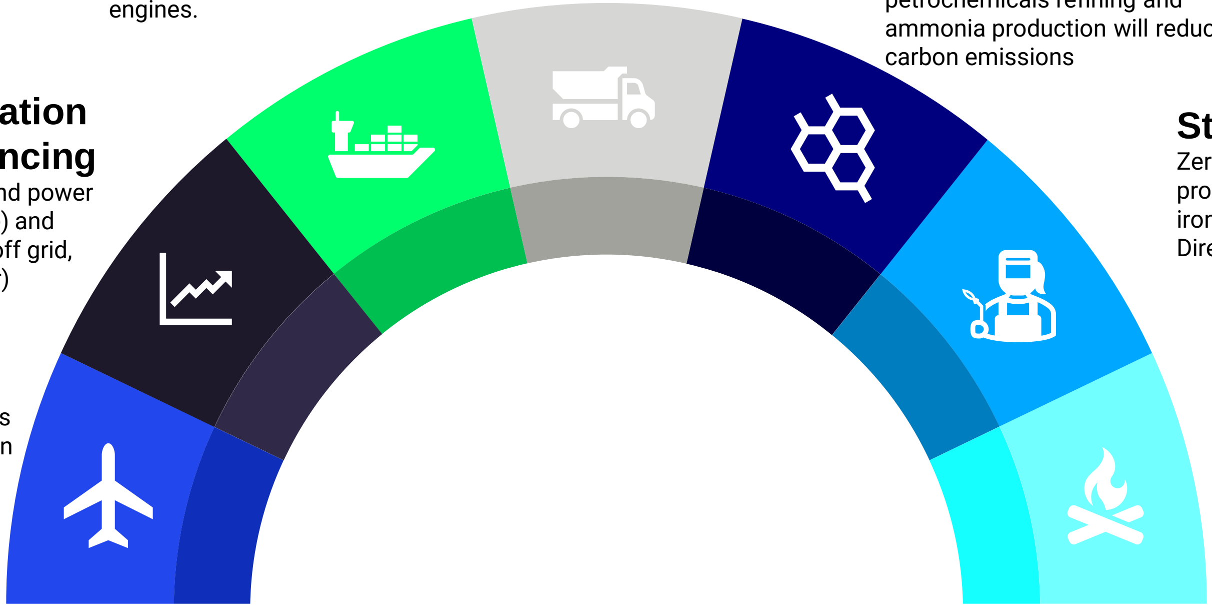
Allows intercontinental trade of hydrogen, resulting in market growth.

Current liquid hydrogen tankers can carry 75 tonnes of Liquid hydrogen.[3]

Currently limited market.

[1] Hydrogen Europe (2021)
[2] Hydrogen Europe – Tech (2021)
[3] JSEA (2023)

Hydrogen is versatile and can be used in many sectors:



Power generation and grid balancing
Centralized, on-demand power (including storage) and distributed power (off grid, backup power)

Shipping
Ammonia or methanol can be used to replace heavy fuel oil for ship engines.

Heavy Transport
Enables long-range heavy goods to become competitive in cost compared to running on diesel

Chemical Production
Displacing grey hydrogen used in petrochemicals refining and ammonia production will reduce carbon emissions

Steel Production
Zero carbon emission steel production can produce pig iron with hydrogen through Direct Reduced Iron process.

Aviation
In place of kerosene, it Is possible to use hydrogen and reused CO2 based synfuel.

Heating
Substituting the use of natural gas for hydrogen can help to decarbonise high temperature process heating

How can hydrogen energy be exploited?

There are three major ways in which hydrogen can be used to provide clean energy:

	Feedstock	Combustion	Fuel cell
How is it used?	$H_2 + N_2$ → (Heat + pressure) → Ammonia (NH_3)	Hydrogen + Oxygen → (Burners / Turbines) → Heat + Water	Hydrogen + Oxygen → (PEMFC / SOFC) → Electricity + Water
Applications	Direct reduction of iron (steel); Chemicals; Methanol; Synthetic fuels	High temperature process heat; Electricity generation (turbines); Boilers; Engines	Transport; Combined heat and power (CHP)
Characteristics	• Replaces grey hydrogen. • Low / zero carbon reductant.	• Replaces natural gas • Provides high temp heat. • Low (>99%) purity needed • Minor changes to current technology (turbines, engines, boilers)	• Replaces engines • Provides electricity and low-grade heat • High (<99%) purity needed • “New” technology development

Low carbon hydrogen should be prioritised for sectors where it can deliver maximum decarbonisation impact

Existing hydrogen production

Switching from carbon-intensive hydrogen feedstock currently used in industrial processes (oil refining and chemical production) to clean hydrogen is critical to minimise the environmental impact of residual fossil fuel usage for these applications.

Industrial processes

Fossil fuel combustion for heat is responsible for a large proportion of industrial emissions. Heat is often used to melt or vaporise substances or to enable chemical reactions (e.g. steel production). Hydrogen has comparative advantages for industrial heat above other clean options as it is likely to face fewer barriers in terms of securing a network connection (a barrier for electrification) or sourcing fuel (a barrier for biomass).

Unlocking grid flexibility

Decarbonisation of the energy system will be almost impossible without production of electricity from stored hydrogen at times when energy demand is not matched by renewables supply. The long-term, inter-seasonal storage capacity of hydrogen enables it to be produced at times of lowest cost to the wider energy system and re-electrified when needed. Provision of flexibility to the energy system should therefore be explored further as a future role for hydrogen.

Hard-to-abate sectors

Some sectors, such as long-haul aviation and shipping, are almost impossible to electrify due to fundamental physical limitations of battery technology. Hydrogen and hydrogen-derived fuels can play a role here, but there is a huge need for innovation and cost reduction to make it scalable. De-risking investment in hydrogen will be essential to enable hydrogen innovation in these hard-to-abate sectors.

Low carbon hydrogen should not be used in sectors where mature electrification technologies exist

Home heating

The overwhelming majority of evidence indicates that hydrogen boilers would be less efficient and more expensive to run than electrified heat, such as heat pumps. Retrofitting hydrogen heating infrastructure is highly complex and cost-intensive, even in the UK where there is an existing gas network for residential heating. While there may be a limited number of applications for hydrogen-based heating as part of a regional cluster approach (e.g. where the primary hydrogen use is for industry), hydrogen should not be pursued as the primary route to decarbonisation of home heating.

Personal transport

EVs are a mature, efficient, low carbon solution to petrol and diesel vehicles. EVs are an efficient use of renewable energy supplies due to their direct charging mechanism (only around 20% of energy is lost from production through to powering the vehicle) and have the potential to support grid resilience through demand-responsive charging. Hydrogen fuel-cell vehicles are significantly less efficient for the overall energy system, as around 60% of energy is lost from production to powering the vehicle. Market developments have established EVs as the most efficient, readily available solution, with ever-expanding infrastructure to support wide-scale use. Use of hydrogen fuel-cell vehicles in return-to-home fleet transport may be an efficient approach to decarbonisation of heavy transport and applications requiring rapid refueling, but their cost effectiveness is yet to be conclusively evidenced.

Thanks for listening

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