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Hydrogen and the energy transition.

ALI, D.

2023

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Hydrogen and the Energy Transition

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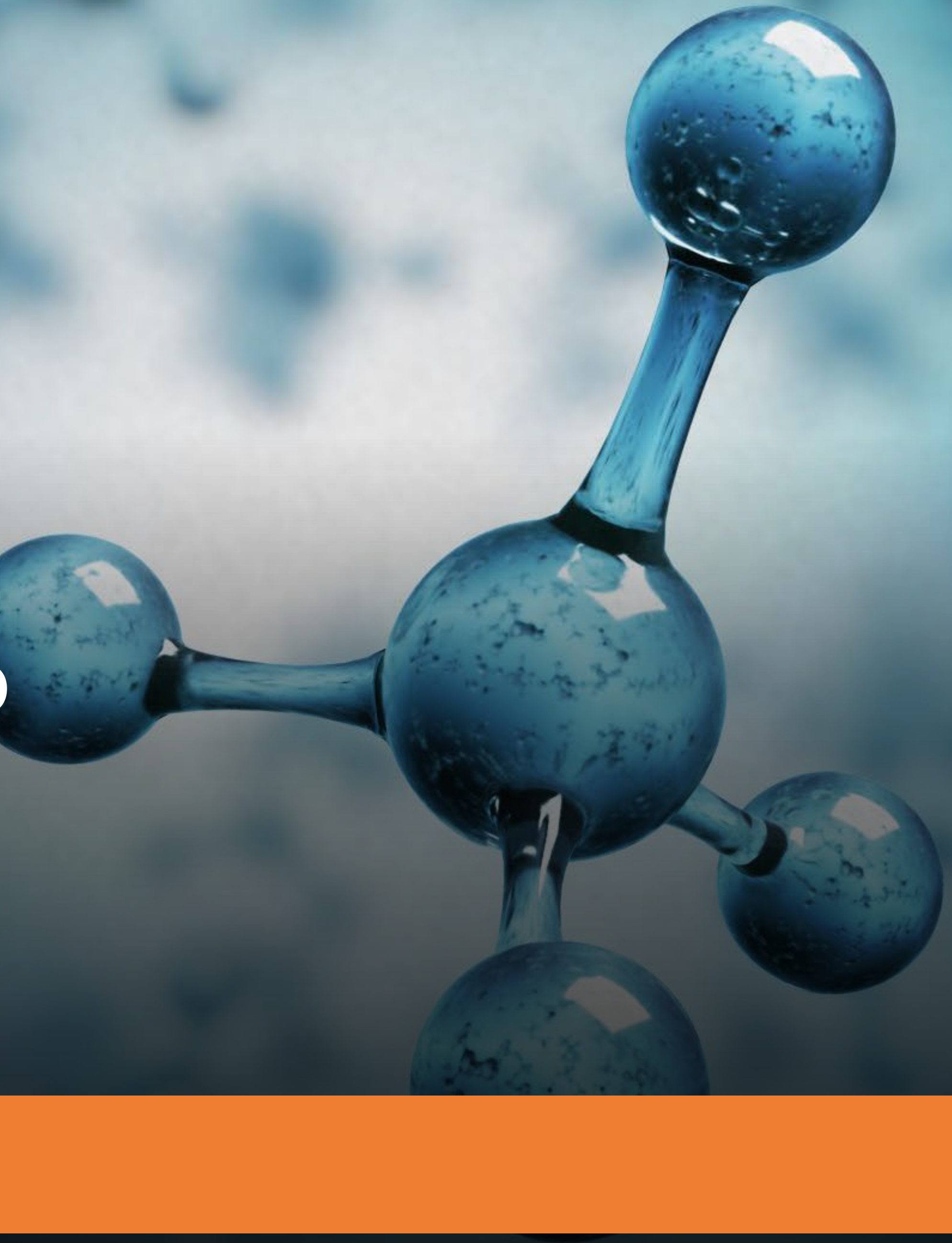
Outline

- Why Hydrogen ?
- Global Hydrogen Status, Future Markets, and Targets
- Hydrogen Properties
- Hydrogen Production and Color Code Nomenclature
- Hydrogen as an Energy Carrier
- Hydrogen Potential in Supporting the Net Zero Energy Transition – UK Exemplar Projects
- Hydrogen Energy Storage System (Electrolyser, Storage and Fuel Cell)
- Renewable-Hydrogen Energy Systems – Case Studies
- Conclusion

Why Hydrogen?



Emissions Brief (IEA CO2 Emissions Analysis 2022)

- Emissions from natural gas decreased by 1.6% or 118 Mt in 2022 due to Ukraine war.
- Emissions from coal grew 243 Mt to a new all-time high of almost 15.5 Gt. This 1.6% increase was faster than the 0.4% annual average growth over the past decade.
- Emissions from oil grew by 2.5% (or 268 Mt) to 11.2 Gt in 2022. Around half of the year-on-year increase came from aviation as air travel continued its recovery from pandemic lows.
- Total transport emissions increased by 2.1% (or 137 Mt), also driven by growth in advanced economies. Nonetheless, emissions would have been higher without the accelerating deployment of low-carbon vehicles.
- The largest absolute sectoral increase in emissions in 2022 was from electricity and heat generation. Electricity and heat sector emissions increased by 1.8% (or 261 Mt), reaching an all-time high of 14.6 Gt. Gas-to-coal switching in many regions was the main driver of this growth.

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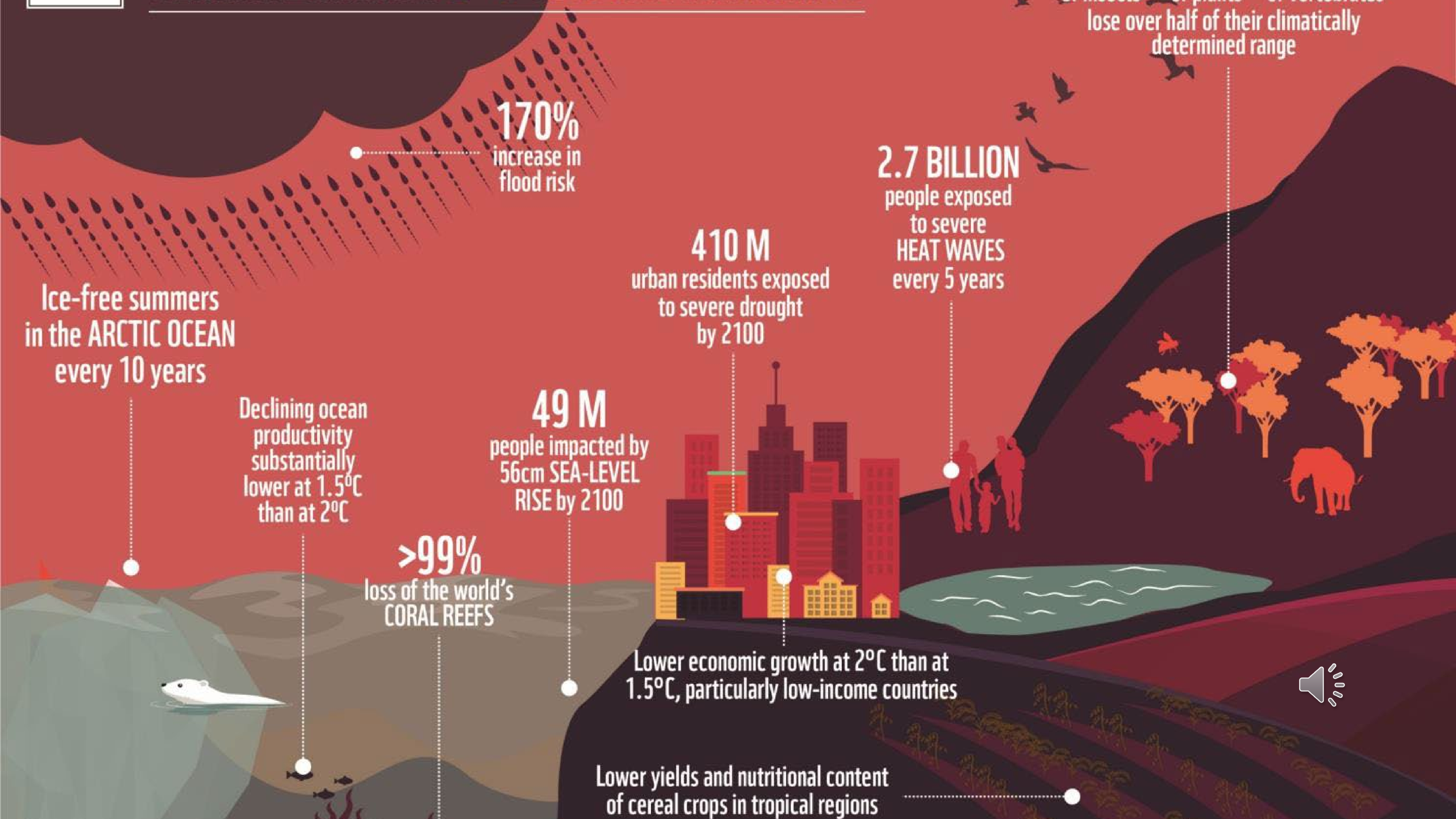
Environmental Concerns

- Air Pollution (causing health issues)
- Water Contamination (affecting humans, animals & plants using it)
- Land Degradation or destruction from human activities. (this lessens the quality and/or productivity of the land for agriculture, forestation, construction, etc.)

  Note that the air, water and soil pollution raise public health issues and require many years to recover.
- Climate Change (destructive impacts include, but are not limited to, melting of polar ice, change in seasons, new illnesses, and change in the general climate situation).
- Global Warming (this results from the fossil fuel GHG emissions)
- Effect on Marine Life (affecting shellfish and microscopic fish)
- Ozone layer Depletion (loss of earth protection from the sun unsafe beams)


lose over half of their climatically
determined range
170%
increase in
flood risk
2.7 BILLION
people exposed
to severe
HEAT WAVES
every 5 years
410 M
urban residents exposed
to severe drought
by 2100
Ice-free summers
in the ARCTIC OCEAN
every 10 years
Declining ocean
productivity
substantially
lower at 1.5°C
than at 2°C
49 M
people impacted by
56cm SEA-LEVEL
RISE by 2100
>99%
loss of the world's
CORAL REEFS
Lower economic growth at 2°C than at
1.5°C, particularly low-income countries
Lower yields and nutritional content
of cereal crops in tropical regions

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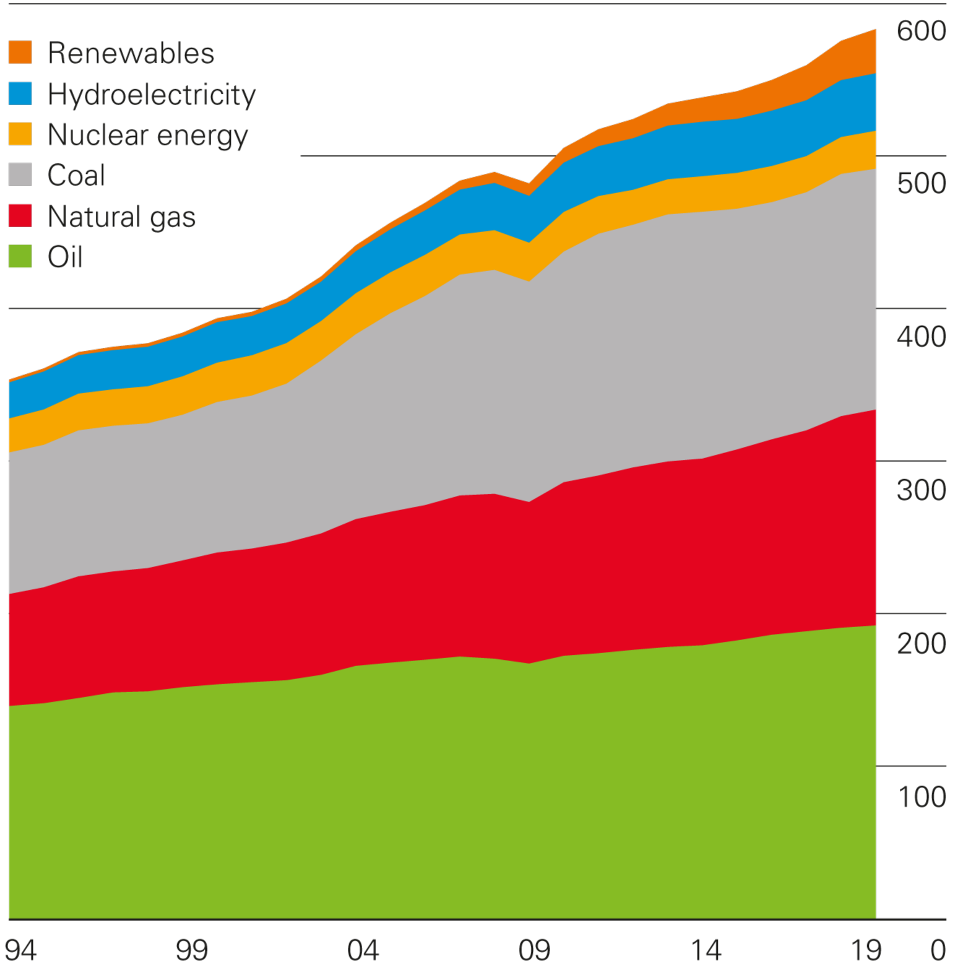
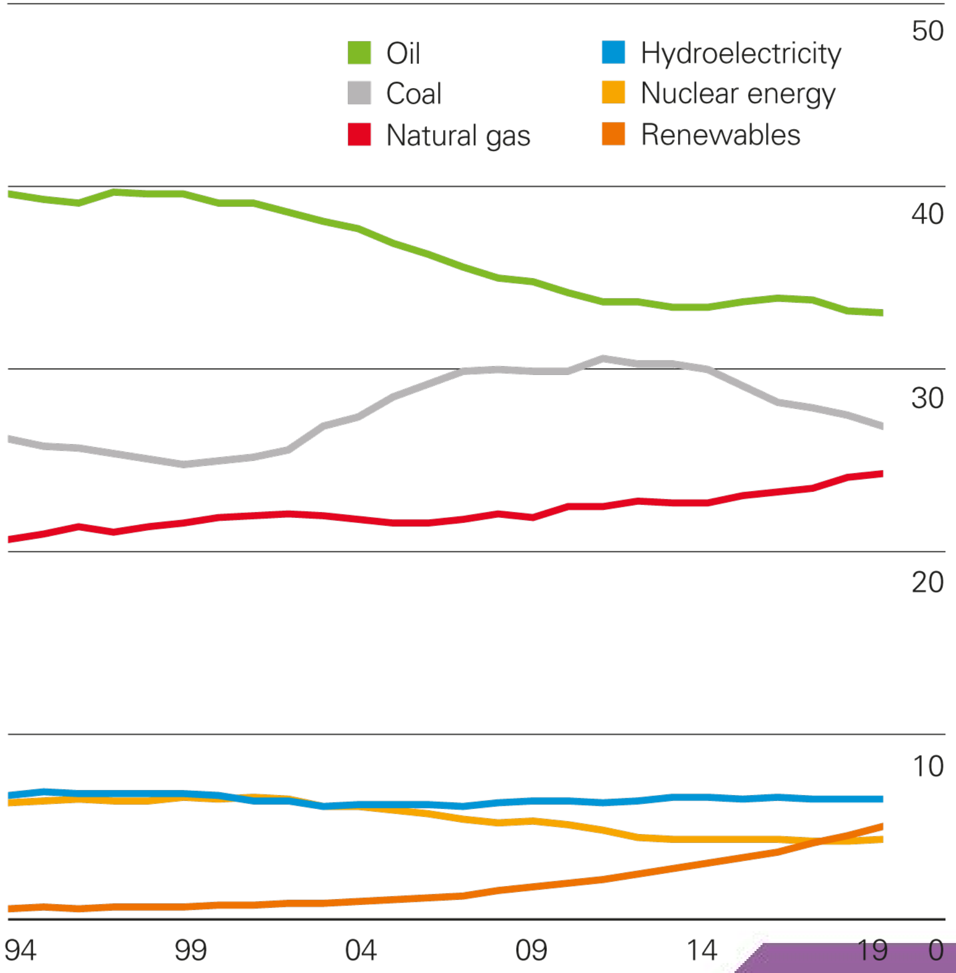
Global Energy Consumption

Exajoules (1 exajoule = 10^{18} joules)





BP Statistical Review of World Energy 2020

Exploiting the Renewables Potential

Exploiting the full renewable potential depends on several factors including the usage of adequate energy storage systems that can absorb the excess of renewable energy and address their intermittency.

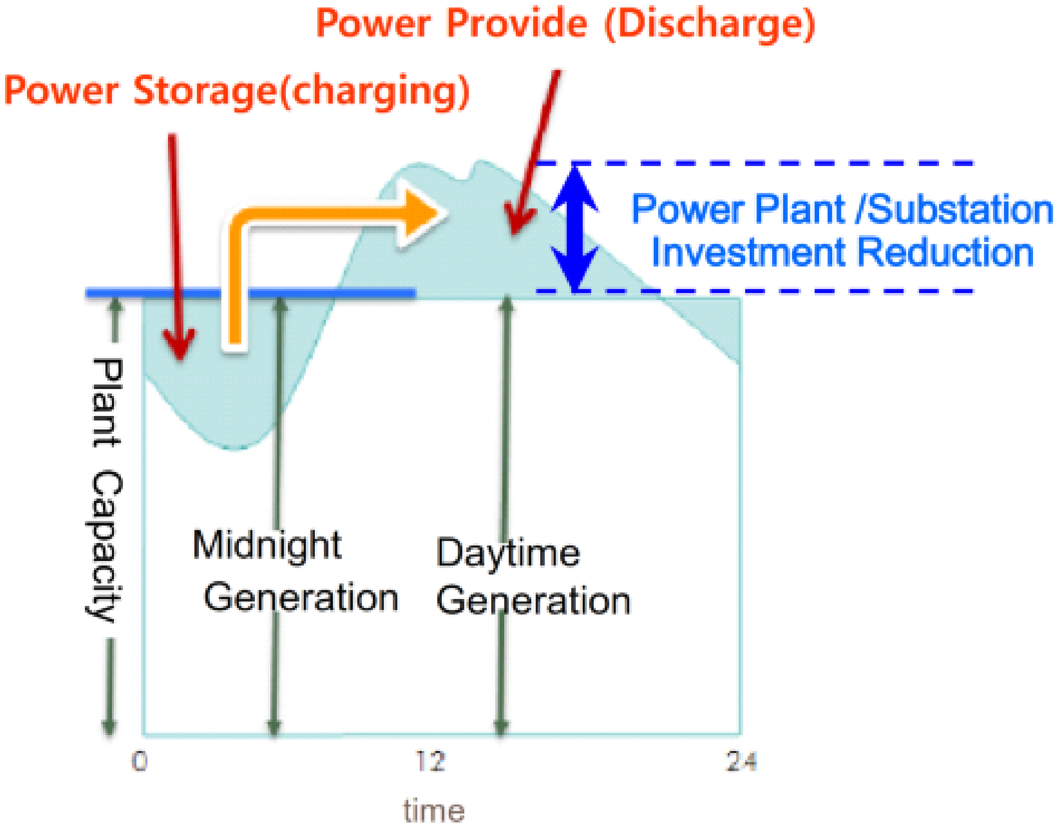
Challenges facing the Electrical Power System

1. **Challenges linked with the Electrical Demand Variations**

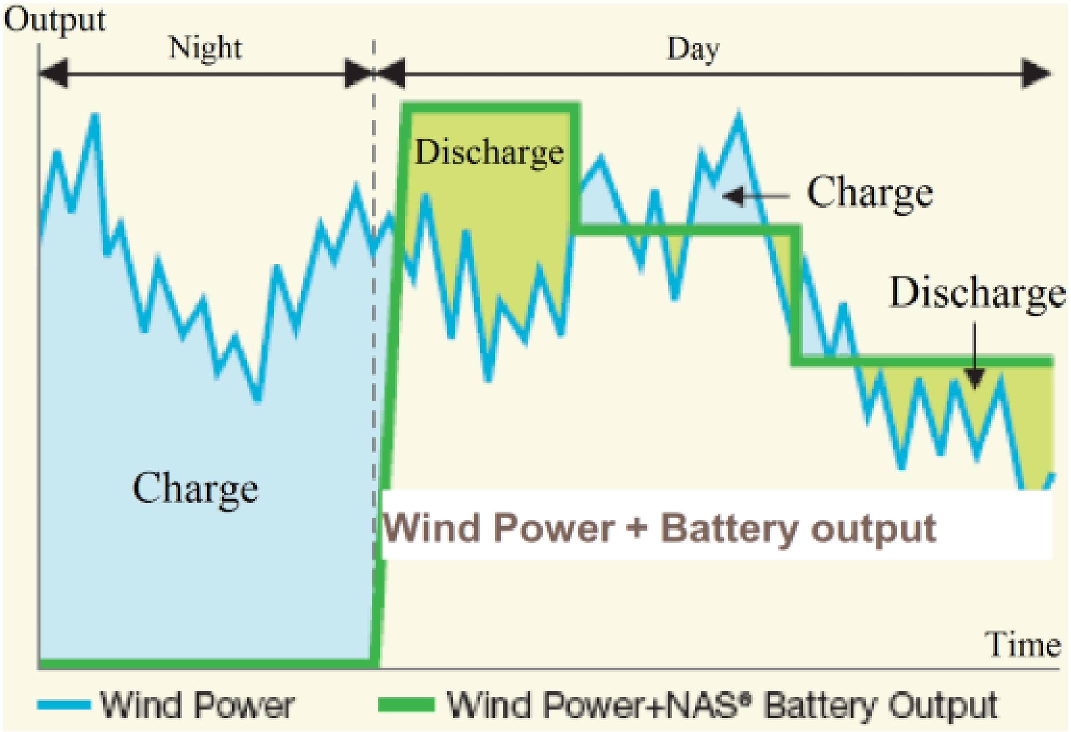
   The electrical power system faces annual demand variations; seasonal demand variations; weekly demand variations and daily demand variations

2. **Challenges linked with the use of Renewable Energy Sources (RES)**

   The renewables availability and generation intermittency make their integration with the national power system problematic

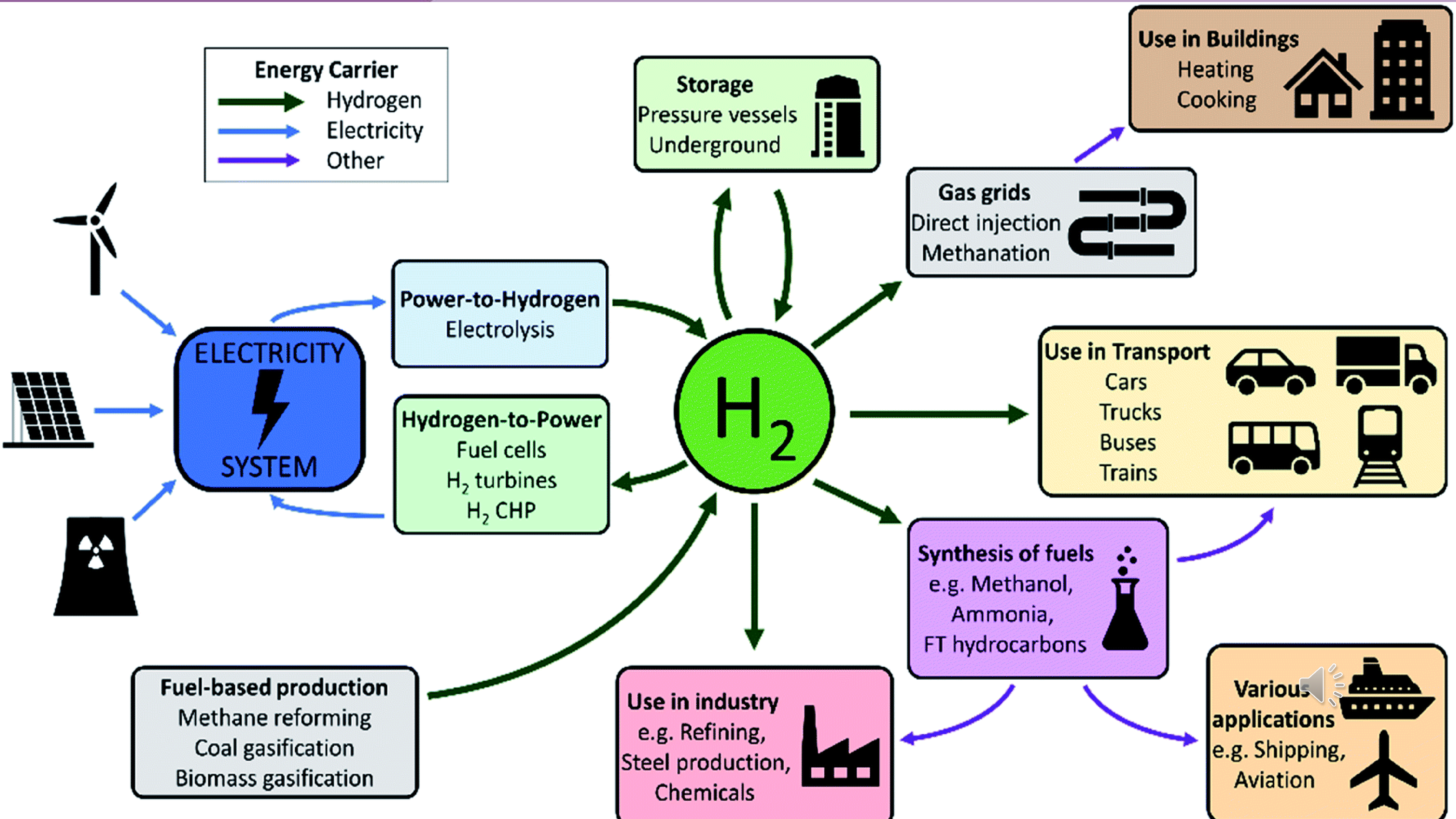


Implementing Energy Storage with Conventional Plants for addressing demand variations (Load Levelling and Peak Shaving)



Implementing Energy Storage with Renewables to address their intermittency and facilitate their High Penetration into grid


Hydrogen
Now
Hope
More Jobs
Energy storage
Marine hydrogen
Transformative technology
More renewables
Grid balancing
Green transport
Community jobs
Community benefiting
Deforestation reduction
Exciting jobs
Unlock grids
H2 Exports
Remote communities
Increase renewable
Emissions reduction
Brain gain
Women job creation
H2 vehicles
Green fuel
Equality
Carbon capture
Gender equality
Energy security
Green agriculture
Green power generation
Energy independent "nation"
Green NH3
Green CNG
H2 ICE
H2 cooker
H2 BBQ
H2 heater
Green H2
Fuel cell
Freedom
Transition
Methanation
Money stay in communities
Wealthier communities
Women entrepreneurship



Energy Carrier
Hydrogen
Electricity
Other
Storage
Pressure vessels
Underground
Use in Buildings
Heating
Cooking
Gas grids
Direct injection
Methanation
Power-to-Hydrogen
Electrolysis
ELECTRICITY SYSTEM
Hydrogen-to-Power
Fuel cells
H_2 turbines
H_2 CHP
H_2
Use in Transport
Cars
Trucks
Buses
Trains
Synthesis of fuels
e.g. Methanol,
Ammonia,
FT hydrocarbons
Fuel-based production
Methane reforming
Coal gasification
Biomass gasification
Use in industry
e.g. Refining,
Steel production,
Chemicals
Various applications
e.g. Shipping,
Aviation

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Why H2 is on the UK Net Zero Agenda?

Hydrogen is a **carbon-free energy carrier** that can be produced from fossil energy resources (with CCS) or from renewable energy resources

Hydrogen allows cost-efficient bulk energy transport over long distances, thus can **decouple the energy production and usage in location and time**

Hydrogen can Decarbonise;

- **Electricity Network:** in 2 ways, H2 as a form of energy storage enables balancing the largescale integration of renewable generation into the network, and H2 as a clean source of power generation can complement the intermittent renewables generation
- **Gas Grid:** by injecting clean H2 in the UK national gas network
- **Industry:** by using clean H2 in industrial high temperature heating, and as a feedstock for processes like the production of ammonia (hence fertilizers) & methanol (for the manufacture of many polymers)
- **Transport:** by using clean H2 as fuel for the road, railway, water and air transport
- **Buildings:** by transforming clean H2 at the point of use into power and heat for buildings

Why H2 is on Scotland Net Zero Agenda?

- Hydrogen is used extensively across all sectors.
- Hydrogen plays a supporting role in decarbonising sectors that are hard to abate by other means.
- Hydrogen can be produced near to where it's used
- A balanced mix of blue and green H2 offers one of the main ways to Scotland's energy system decarbonisation.
- Scotland has vast renewable resources, particularly offshore wind, that can be used to produce green hydrogen.
- H2 economy will develop lots of new jobs opportunities.

Hydrogen Status, Future Markets, and Targets

Global H2 Status

H2 is receiving international and cross-sectional interest with the need for climate change action & governments' commitment to Paris Agreement.

- Over 200 H2 projects worldwide with 17 of these in giga-scale production and Europe leads globally.
- Cost of electrolysis has decreased by 60% since 2010. From USD10-15/kg to USD 4-6/kg, and It will continue to fall.
- Driven by the scale of production and technological advancements, the entire system CAPEX has decreased 60% and the efficiency improved.

Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf (hydrogencouncil.com)

Future H2 Markets

- **Market 1 – Ammonia**
  - $48 billions of ammonia sales in 2016 and will reach over $76 billion in 2025
  - Green ammonia by using green H2
- **Market 2 – Methanol**
  - Methanol generates $55 billion/year and creates 90,000 jobs globally.
  - Green methanol by using green H2
- **Market 3 – H2 Trains**
  - The market for H2 trains for the next 30 years is €44 billion for the CAPEX alone
  - H2 trains use fuel cells
- **Market 4 – H2 Boats**
  - Using H2 fuel cell boats
  - Using H2 internal combustion engines
  - New H2 production systems to supply fuel for boats

Ammonia Potential

- Today, ammonia production causes some 500 million tons of CO2 emissions – 1% of the world's greenhouse gas emissions.
- Ammonia, mainly used to produce fertilizers, plastics, dyes and pharmaceuticals, is a market that will stay and even grow and thus it becomes very important to decarbonize its production.
- Ammonia market will even get bigger with other potential applications which includes using it as fuel for the shipping and power sectors and as a hydrogen carrier especially in international trade.
- Green ammonia production is where the process of making ammonia is 100% carbon-free. One way of making green ammonia is by using green hydrogen produced from renewably-powered water electrolysis and nitrogen separated from the air.
- Green ammonia can be a global energy commodity and thus unlocking its potential is crucial.

Global H2 Targets

On a Pathway to NetZero (NZ)	Electrolysers Installed for Renewable H_2 (GW)	Renewable H_2 Production (metric ton per day - Mt)	Target Sector
<u>EU Strategy</u> 2020 - 2024 2025-2030 2030 – to NZ	≥ 6 ≥ 40 Large scale	1 10 Large scale	Decarbonize existing production in industry New end-use applications Reach hard-to-abate industries
<u>UK Strategy</u> 2020 – 2024 2030 – to NZ	5 Large scale	1 Large scale	Drive decarbonisation across the economy H_2 infrastructure and technologies with high potential for expansion. Established regulatory and market framework

Hydrogen Properties

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Introduction

- Hydrogen is the most common element on Earth, but it remains combined with other elements found as part of water, biomass and fossil hydrocarbons. Hydrogen is currently produced from a variety of primary sources such as natural gas, naphtha, heavy oil, water and coal

- H2 can be used as feedstock, fuel or energy carrier. It has an energy density of approximately 120 MJ/kg, almost three times more than diesel or gasoline, while Natural gas has 53.6 MJ/kg. In electrical terms, the energy density of hydrogen is 33.6 kWh/kg versus 12–14 kWh/kg for diesel.

- H2 is a source of clean energy that can replace natural gas with no carbon emissions when burnt and can generate clean electricity through a fuel cell with water & heat by-products and no carbon emissions; thus, has high potential for decarbonising our economy.

- Hydrogen can be used as an energy carrier, stored and delivered where needed.

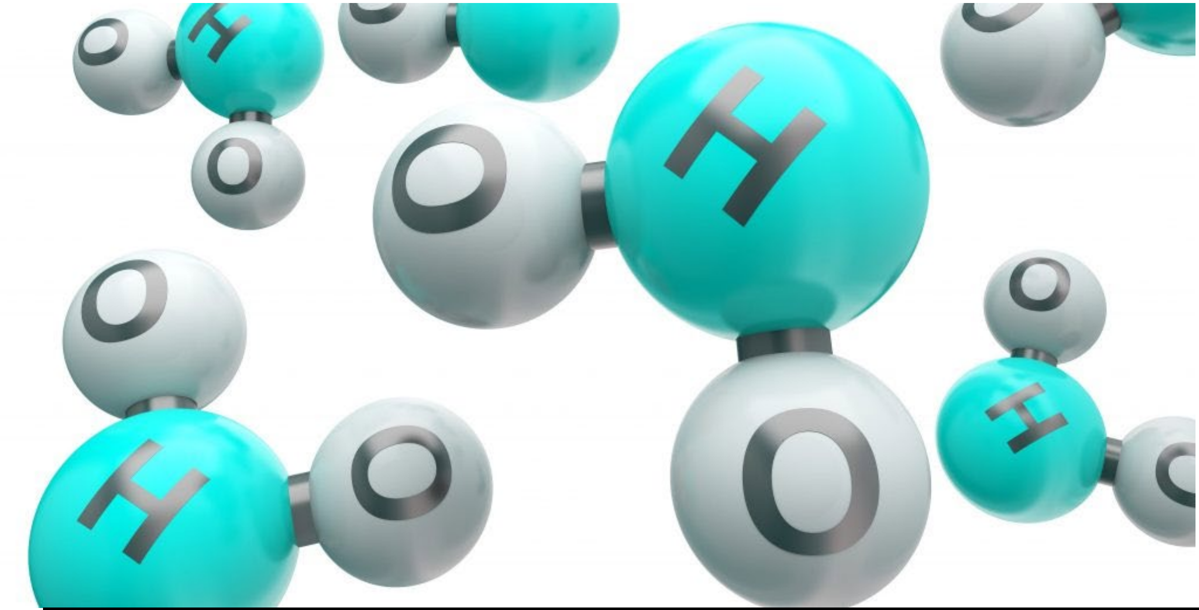
- Green H2, as a form of energy storage with renewables, allows a clean fuel for transport or for making clean power and heat while addressing renewables' intermittency; thus allowing:
  - more renewables integration into the grid while eradicating energy wasting & constraint payments (ex. in April 2014, approximately £890,000 compensations were paid over few hours to six wind farms) as well as costs for updating the electricity network capacity.

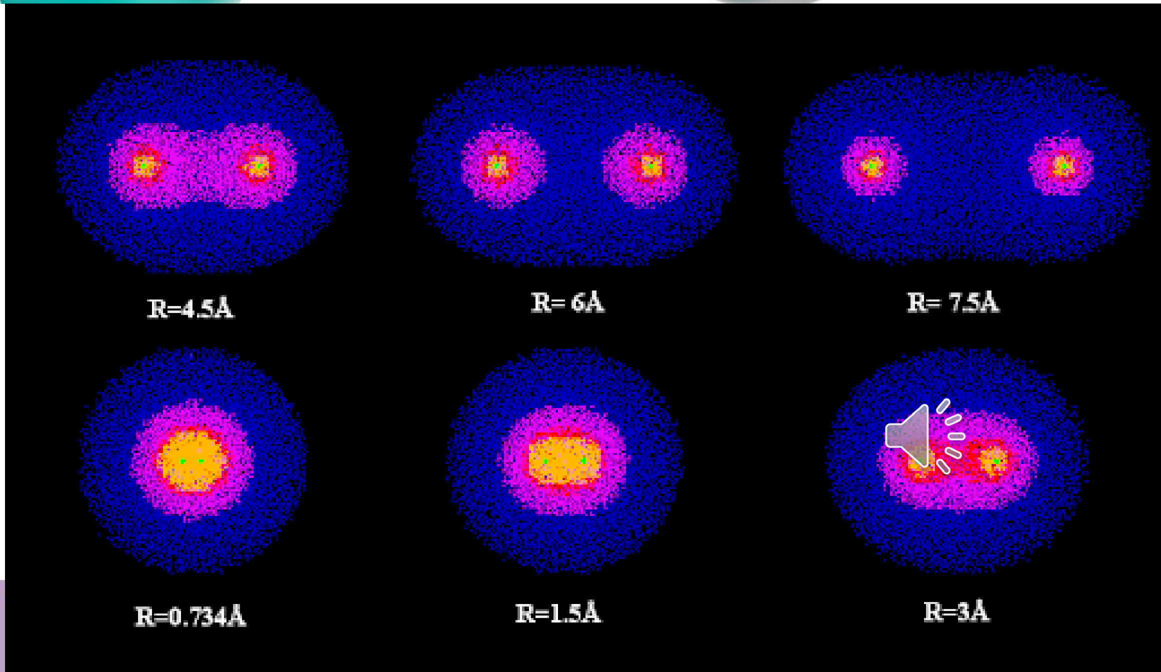
Hydrogen Properties

Hydrogen
- Melting point −259.14 °C (−434.45 °F; 14.01 K)
- Boiling point −252.87 °C (−423.17 °F; 20.28 K)

Hydrogen Density
- 0.08988 g/L (a gas at STP)
- Methane is 0.657 g/L
- 0.07 g/cm^3 (as a liquid)
- 0.0763 g/cm^3 (as a solid)

Hydrogen Energy Density
- Hydrogen - 120MJ/kg
- Natural gas – 53.6 MJ/kg
- Methane 3.25 x hydrogen energy “content”





Hydrogen physics

- 1 kg ↔ 11,1 Nm³ ↔ 33,3 kWh (LHV) and 39,4 kWh (HHV)
- High mass energy density (1 kg H_2 = 3,77 l gasoline)
- Low volumetric density (1 Nm³ H_2 = 0,34 l gasoline)

Hydrogen production from water electrolysis (~5 kWh/Nm³ H_2)

- **Power:** 1 MW electrolyser ↔ 200 Nm³/h H_2 ↔ ± 18 kg/h H_2
- **Energy:** +/- 55 kWh of electricity → 1 kg H_2 ↔ 11.1 Nm³ ↔ ± 10 liters demineralized water

Power production from a hydrogen PEM fuel cell from hydrogen (+/- 50% efficiency)

- **Energy:** 1 kg H_2 → 16 kWh

Cars and buses

FCEV	H_2 tank	H_2 consumption	Driving range	Annual driving distance	Annual H_2 consumption
Car (passenger)	5 kg	1 kg/100 km	500 km	15.000 km	150 kg
Bus (12 m)	35 kg	8 kg/100 km	350 km	60.000 km	5 tons

Hydrogen Production and Colour Code Nomenclature

H2 Production

- H2 gas is currently produced from a variety of primary fossil energy sources such as natural gas, naphtha, heavy oil, coal and water. H2 can be environmentally friendly only if the energy used in its production is clean' renewables.
- Most of the world H2 production comes from steam reforming (SR) of natural gas. Other comes from higher hydrocarbons reforming, coal gasification, and from water electrolysis. CO_2-neutral H2 can be produced by the conversion of biomass via gasification, pyrolysis of bio-oils, SR of biomass-derived higher alkanes and alcohols, and APR of oxygenated hydrocarbons
- Steam reforming of methane and light hydrocarbons involves three reactions, namely, the splitting of hydrocarbons with steam, the water–gas shift, and the formation of methane.
- Gasification of coal and heavy hydrocarbons involves the reaction at high temperatures (1200–1400 K) and moderate pressure (5–10 bar) of the carbon source with a source of hydrogen, usually steam and/or oxygen.
- Water electrolysis is one of the easiest methods for hydrogen production although it is relatively expensive technology. If relatively small quantities of hydrogen are required, on-site electrolysis of water may result more economical than other methods. This technique is very clean and produces more than 99.989% purity of hydrogen gas. In addition, electrolysis can be linked to renewable electricity-producing technologies and hence could become even more important in the future.

White H2 refers to the naturally occurring H2 (rarely) found in underground deposits. Thus, different processes are used to generate H2 artificially.

Grey H2 accounts for most of the production today and emits about 9.3 kg of CO2/kg of H2 production.

Black/Grey Hydrogen

- Black H2 produced from coal gasification; Grey H2: produced via steam reforming of natural gas or methane
- 100% carbon emissions

Blue Hydrogen

- Blue H2 produced from steam reforming of methane or natural gas while utilizing CCS to negate emissions with 85-95% efficiency

Green Hydrogen

- Green H2 produced using renewable energy in electrolysis
- Zero-carbon emissions, ideally suitable for green energy transition

Pink Hydrogen

- Pink H2 produced using nuclear energy in electrolysis
- Zero-carbon emissions. Not commercialized yet

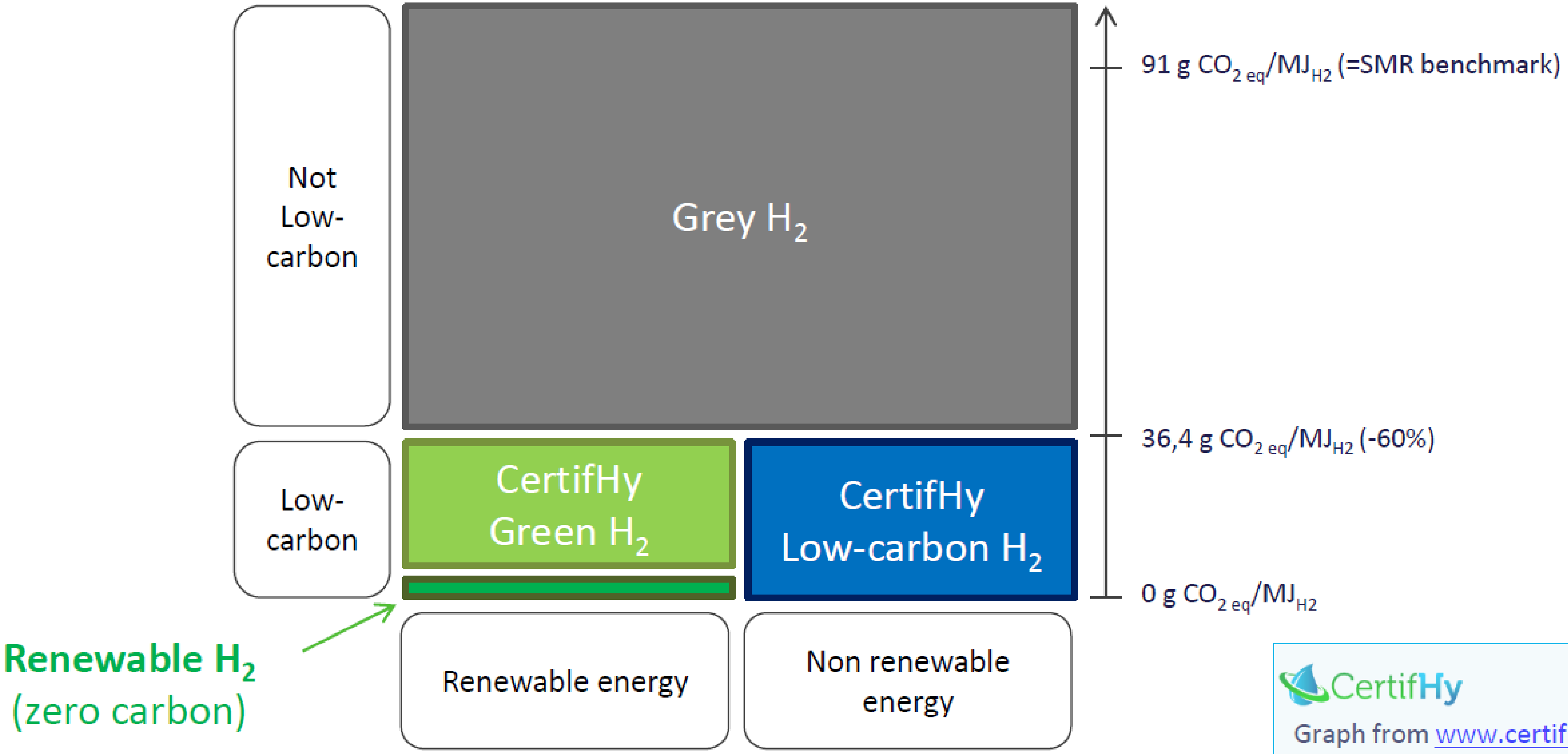
Hydrogen Production Pathways and Colour Code

H_2 Color Code

- **Natural H_2** Natural extraction (Drilling +/- CCS)
- **Grey** $CH_4 + O_2 = 2H_2 + CO_2$ (SMR, ATR)
- **Blue** $CH_4 + O_2 = 2H_2 + CO_2$ (SMR/ATR + CCS)
- **Green** $2H_2O = 2H_2 + O_2$ (Electrolysis)

- > 98% of H_2 currently produced from fossil, chiefly by SMR (Grey)
- Approx. 2% of global H_2 currently produced by renewables (Blue & Green)

Clean H2 Definition and Certification



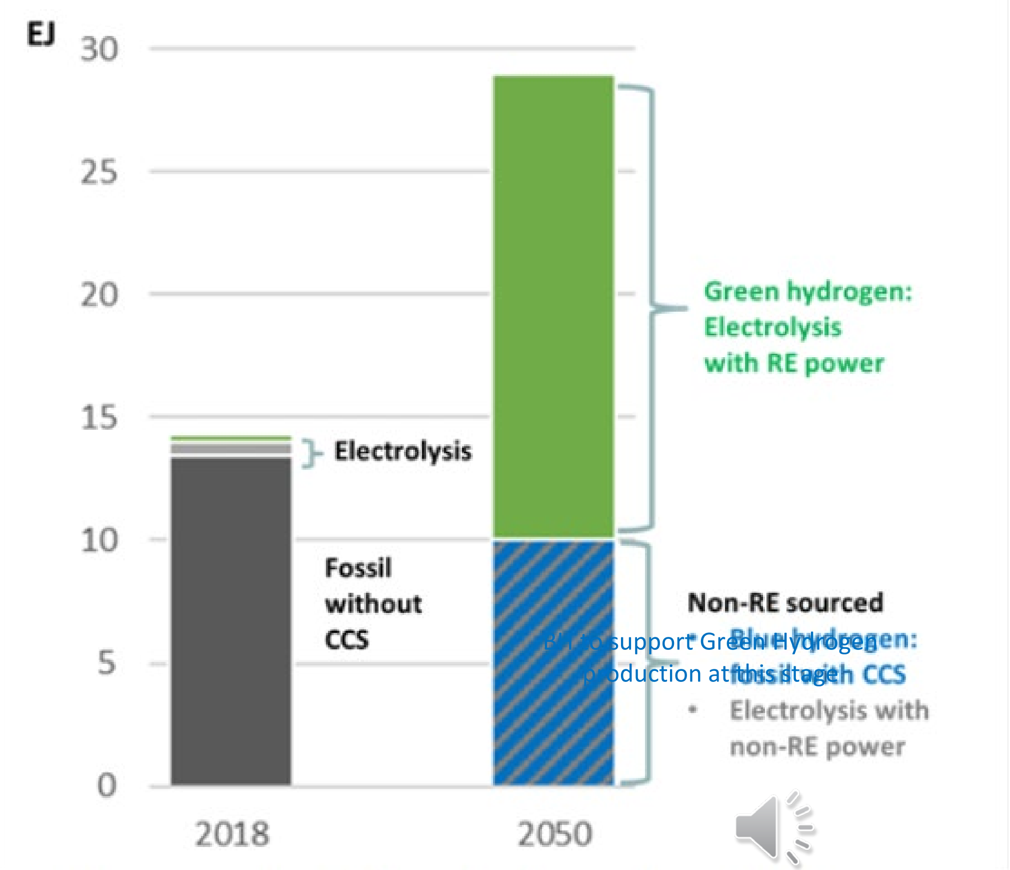
Source: ETIP Wind – Wind2H2| Brussels (BE) | 21.02.2019

CertifHy
Graph from www.certifhy.eu
modified by Hydrogenics

From Where the UK can get the Needed H2?

UK has:

- Significant offshore wind resources to produce Green H2 from Renewables by electrolysis
- Industrial Carbon Capture, Utilization and Storage (CCUS) for producing Blue H2 from methane reforming



to support Green Hydrogen production at this stage

Figure – Role of clean hydrogen in IRENA Remap scenario. Source: IRENA

Blue Hydrogen
Convert natural gas at scale
(Available now)

Green Hydrogen
Renewable energy at scale
Electrolysis at scale
(Timeframe 5-20 years)

Hydrogen to end use
By pipeline (NTS & local grid)

- Cars
- Trucks
- Trains
- Heating
- Electricity
- Industrial

Hydrogen as an Energy Carrier

Hydrogen can be used as an energy carrier, stored and delivered where needed

Introduction

- Most of the produced H_2 is used in making ammonia which is a major component of fertilizers, whereas the second largest amount of H_2 is used in refineries for chemical processes such as removing sulphur from gasoline and converting heavy hydrocarbons into gasoline or diesel fuel.
- H_2 is also used in many other industries like methanol, food, metallurgy, glass, and pharmaceutical.
- In addition to these H_2 end-uses, H_2 is also considered an ideal energy carrier for future environmentally sustainable energy systems.
- With H_2 considered as an alternative energy carrier, intensified exploration of H_2 from a wide range of sustainable primary sources such as biomass, wind, solar and nuclear is taking place.
- A key precondition for realizing a hydrogen economy is the development of a hydrogen infrastructure which includes hydrogen production, storage and delivery to users.
- Another key precondition is the government support to research that verify the feasibility and competitiveness of the hydrogen economy.

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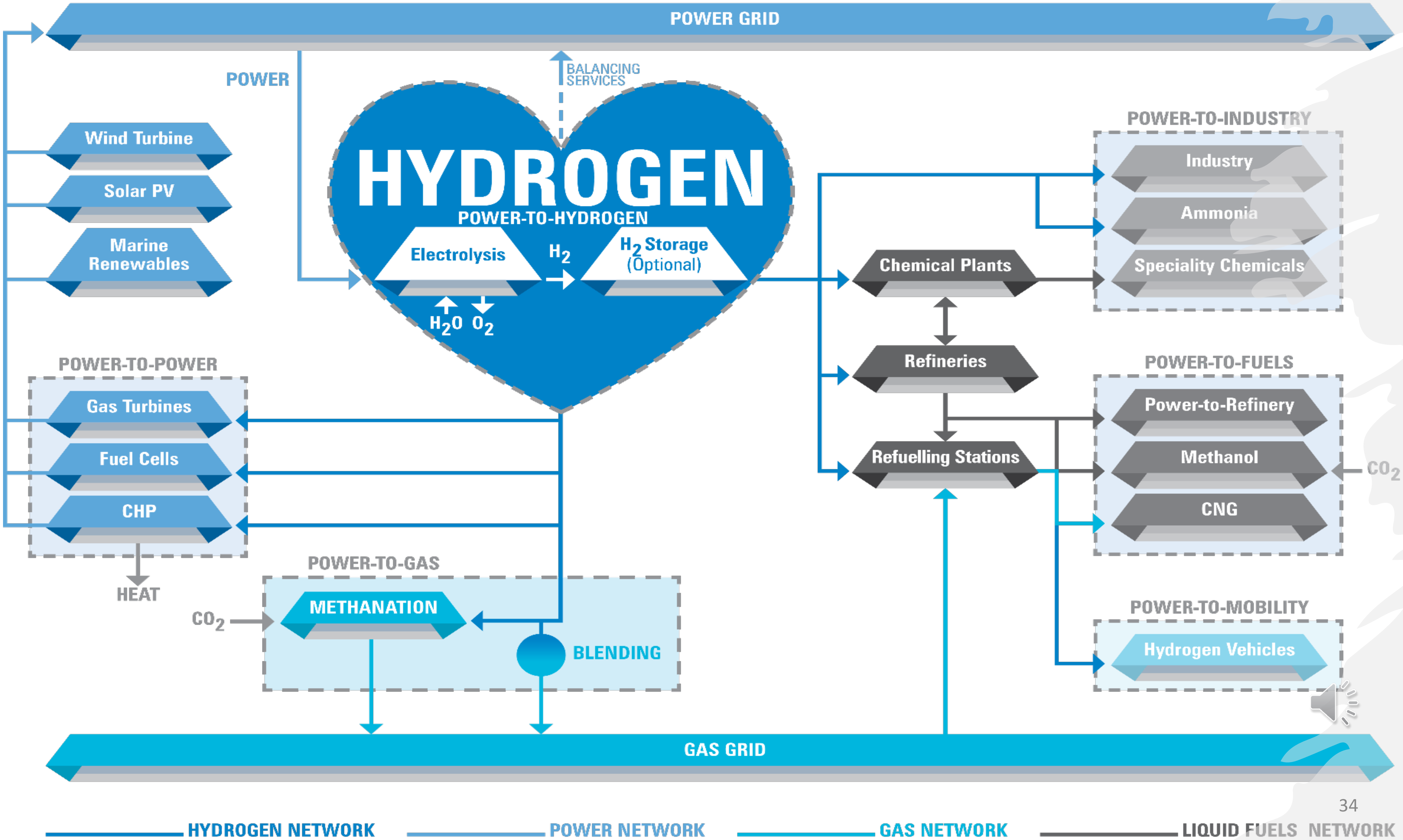
Hydrogen as an Energy Carrier

Clean energy carrier can be realized by utilizing zero-carbon Hydrogen produced from renewable energy resources (Green H2) or low carbon H2 produced from fossil energy resources with CCS (Blue H2)

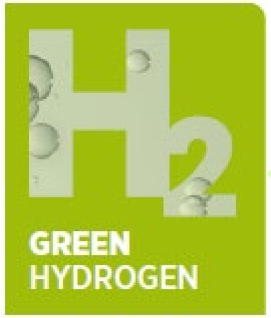
H2 as an energy carrier **decouple the energy production and usage in location and time and allows bulk energy transport over long distances.**

Utilizing the clean H2 as energy carrier can help decarbonise;

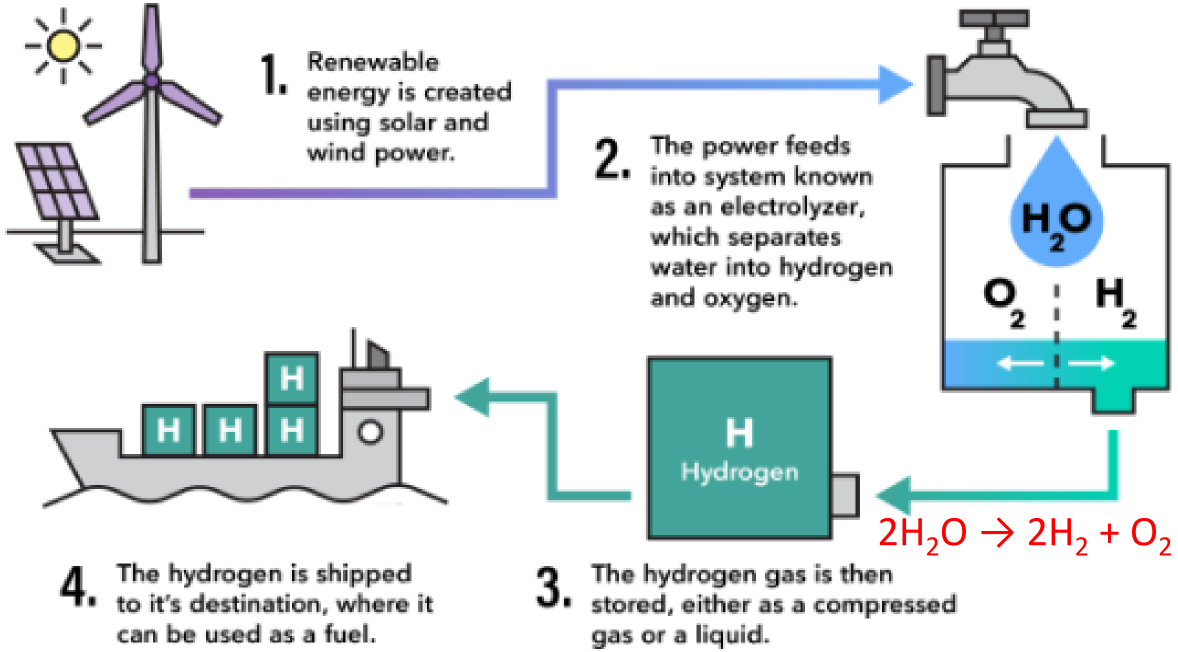
- **Electricity Network:** in 2 ways, when used as energy storage to balance the largescale integration of renewable generation into the network, and when used as a clean source of power generation to complement the intermittent renewables generation
- **Gas Grid:** when injected in the UK national gas network
- **Industry:** when used in industrial high temperature heating, and as a feedstock for processes like the production of ammonia (hence fertilizers) & methanol (for the manufacture of many polymers)
- **Transport:** when used as fuel for road, railway, water and air transport
- **Buildings:** when transformed at the point of use into power and heat for buildings

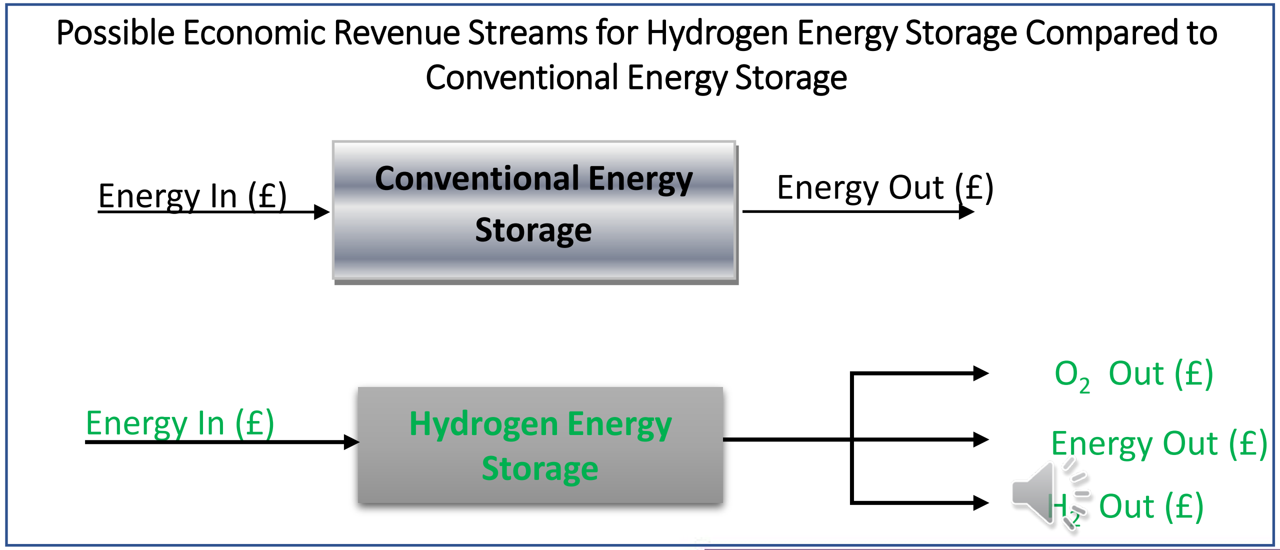

POWER GRID
POWER
BALANCING SERVICES
Wind Turbine
Solar PV
Marine Renewables
HYDROGEN
POWER-TO-HYDROGEN
Electrolysis
H2
H2 Storage (Optional)
H2O
O2
POWER-TO-INDUSTRY
Industry
Ammonia
Speciality Chemicals
Chemical Plants
Refineries
Refuelling Stations
POWER-TO-FUELS
Power-to-Refinery
Methanol
CNG
CO2
POWER-TO-MOBILITY
Hydrogen Vehicles
POWER-TO-POWER
Gas Turbines
Fuel Cells
CHP
HEAT
POWER-TO-GAS
CO2
METHANATION
BLENDING
GAS GRID
HYDROGEN NETWORK
POWER NETWORK
GAS NETWORK
LIQUID FUELS NETWORK

Green Hydrogen as Energy Carrier



Green H2 is produced using renewable energy in water electrolysis to split water molecules into H_2 and O_2 with Zero carbon-dioxide emissions. H2 is stored as energy carrier and transported to the point of use. O2 can also be utilized to improve the energy efficiency





Hydrogen Potential in Supporting the Net Zero Energy Transition (Some UK Demonstration Exemplar Projects)

Implementing green H2, as a form of energy storage with renewables, can support the Net Zero transition of many end-users while addressing the renewables' intermittency

The UK 2050 Net Zero Emissions Target

In June 2019, the parliament passed legislation requiring the government to reduce the UK's net emissions of greenhouse gases by 2050 by 100% relative to 1990 levels.

This target can be realised by:

1. **Decarbonising the electricity grid through more renewables' integration:**
   The UK offshore wind can make this option viable; however, energy storage support is needed for balancing the grid.

2. **Decarbonizing the CO_2-Intensive Sectors like:**
   - Industrial feedstock for production processes and industrial high heat requirements
   - Transportation
   - Residential and Commercial Power and Heat

H2 can make both options Viable

How Hydrogen makes these Options Viable?

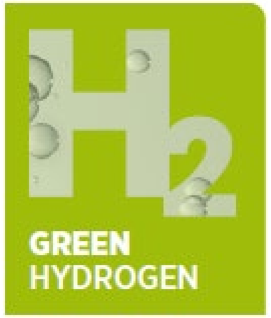
- Hydrogen energy storage (HES) can be implemented with renewables to store their surplus generation and produce it back during their deficit generation periods or when the electrical network is experiencing a period of high demand – thus helping balance the grid.

- The clean stored H2 can be used to decarbonise the aimed sectors:
  - ❖ H2 can be injected into the existing gas grids (decarbonise heat)
  - ❖ H2 can be used to generate electricity and heat by using a Fuel Cell (decarbonise residential & commercial CHP)
  - ❖ H2 can be used to power fuel cell or combustion engine' vehicles (decarbonise transport)
  - ❖ H2 can be used as feedstock in many industrial processes (decarbonise industry)

Green H2 Role in the Energy Transition

- Green hydrogen is becoming key component in bringing energy transition and ensuring a sustainable future.
- Green H2 and Green Ammonia are envisaged to be the future fuels to replace fossil fuels supporting the environmentally sustainable energy security of the nation.
- Producing green hydrogen using renewable energies, can be used by individual industries, buildings, electrical networks and transport applications as a climate-friendly alternative to fossil fuels.
- Green H2 can be stored for long periods of time to be converted back to electricity and water vapour using a fuel cell.
- The mass adoption of green hydrogen will significantly aid the global energy transition; however, the following issues need to be addressed:
  - Costly H2 production
  - High energy requirement in compressed hydrogen storage
  - Temperature and pressure requirements while storing hydrogen in solid form.
  - Design aspects, legal issues, social concerns.

Green H2 and the Path to Net-Zero Ambition

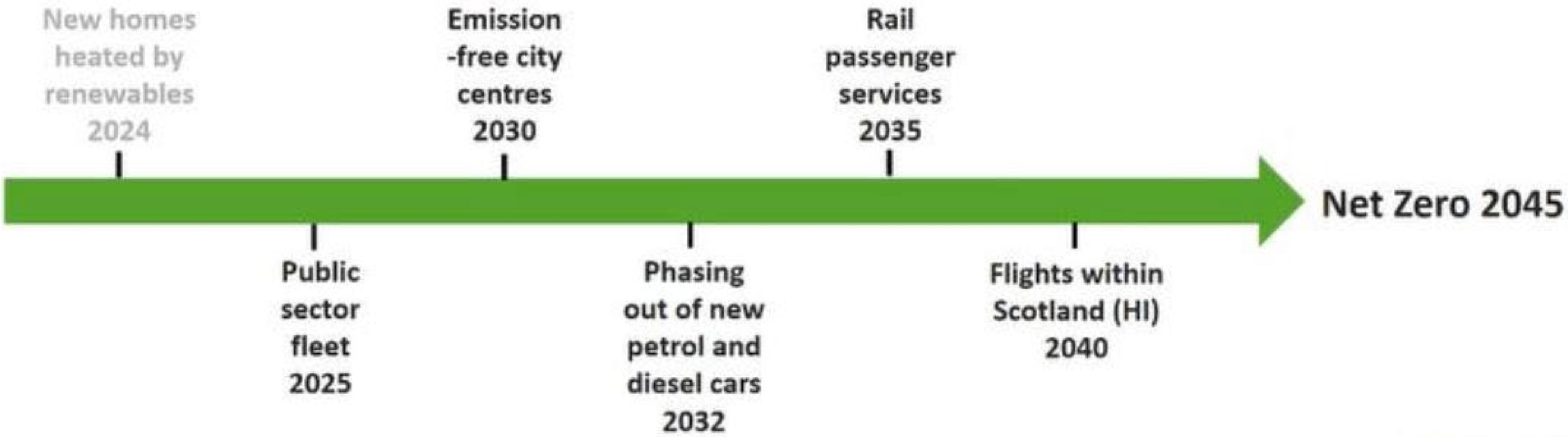


Green Career Pathways at COP26

- A total of 32 countries — including the US, China and India — plus the EU, have vowed to work together to accelerate the development and deployment of clean H_2 and ensure that "affordable renewable and low-carbon hydrogen is globally available by 2030".
- The fossil-fuel-led lobby group, the Hydrogen Council, said in a new report that up to 40% of the H_2 being produced by mid-century will come from natural gas with incomplete carbon capture and storage.
- Forrest's Fortescue Future Industries (FFI) is planning to build a 15GW green hydrogen project in Argentina, it was announced at COP26.
- A bid to develop a global Green Hydrogen Standard was launched at COP26 by the Switzerland-based non-profit Green Hydrogen Organisation (GH2), and the UN High-Level Climate Action Champions.
- Australia's Fortescue Future Industries (FFI) signed a memorandum of understanding for JCB and Ryze to buy 10% of its global green hydrogen production,

Scottish Government Timeline for Decarbonisation

- Scotland set an ambition to support the development of 5GW of renewable and low-carbon hydrogen production by 2030 and 25GW by 2045.
- Scotland's unique selling points to become producer of lowest cost hydrogen in Europe by 2045 are its energy natural resources, infrastructure and skilled energy workforce.
- Scotland supports demonstration, development and deployment of hydrogen for decarbonisation of critical industry functions and processes, transport and heat.



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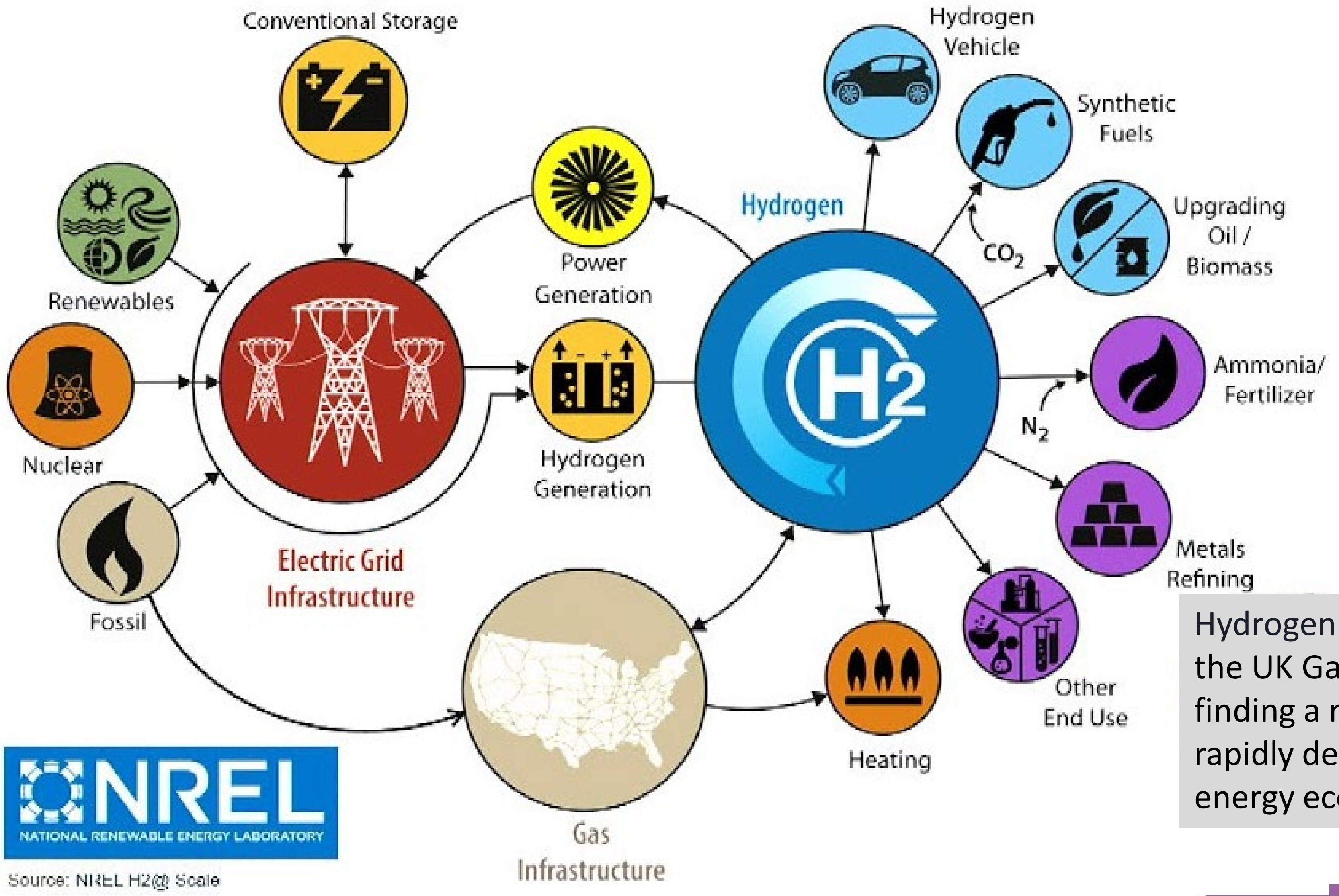
H2 Potential in Supporting the O&G Industry Net Zero Transition



Hydrogen can support the UK Gas Industry in finding a role within the rapidly decarbonizing energy economy

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H2 Potential in Supporting the Transport Sector Net Zero Transition

Transport accounted for (34%) of the UK CO2 emissions in 2019, thus implementing H2 fuel in transport can reduce or eliminate this emissions.

Aberdeen City Council continues to grow their hydrogen vehicle fleet

H2 trains allow hybrid configurations of batteries and fuel cells thus increasing performance & range

Hydrogen tank and Ballard fuel cell system on CRRC-Sifang light rail - https://blog.ballard.com/fuel-cell-trains

- Fuelling a H2 train is faster than charging a battery-based train.
- H2 trains demonstrated in Europe high-performance and adaptability as diesel-powered trains of similar range while eliminating emissions.
- Electric cars & trains are not essentially clean (electricity source).
- Railway Electrification has high CAPEX and visual impact.
- Deploying Renewable-H2 trains can support the electrical network when integrating large-scale renewables, and help creating new jobs.

Scotland Exemplar H2 Projects

Some of the Hydrogen projects delivered in Scotland includes:

1. Kirkwall airport CHP (Kirkwall Airport CHP : EMEC: European Marine Energy Centre**)**

- Aims to decarbonise airport terminal and supplement weak electrical supply
- Integrate assets in existing grid, deferring grid upgrade costs
- Provide market for green hydrogen

2. HydroGlen Project at Glensaugh Farming Community (HydroGlen: transforming Glensaugh farm into a renewable powerhouse | The James Hutton Institute**)**

Aims to demonstrate the transformation of the farm into net-zero carbon emissions through the integration of renewable energy sources in conjunction with hydrogen energy storage to meet the farm's electrical, heating, and transport demands.

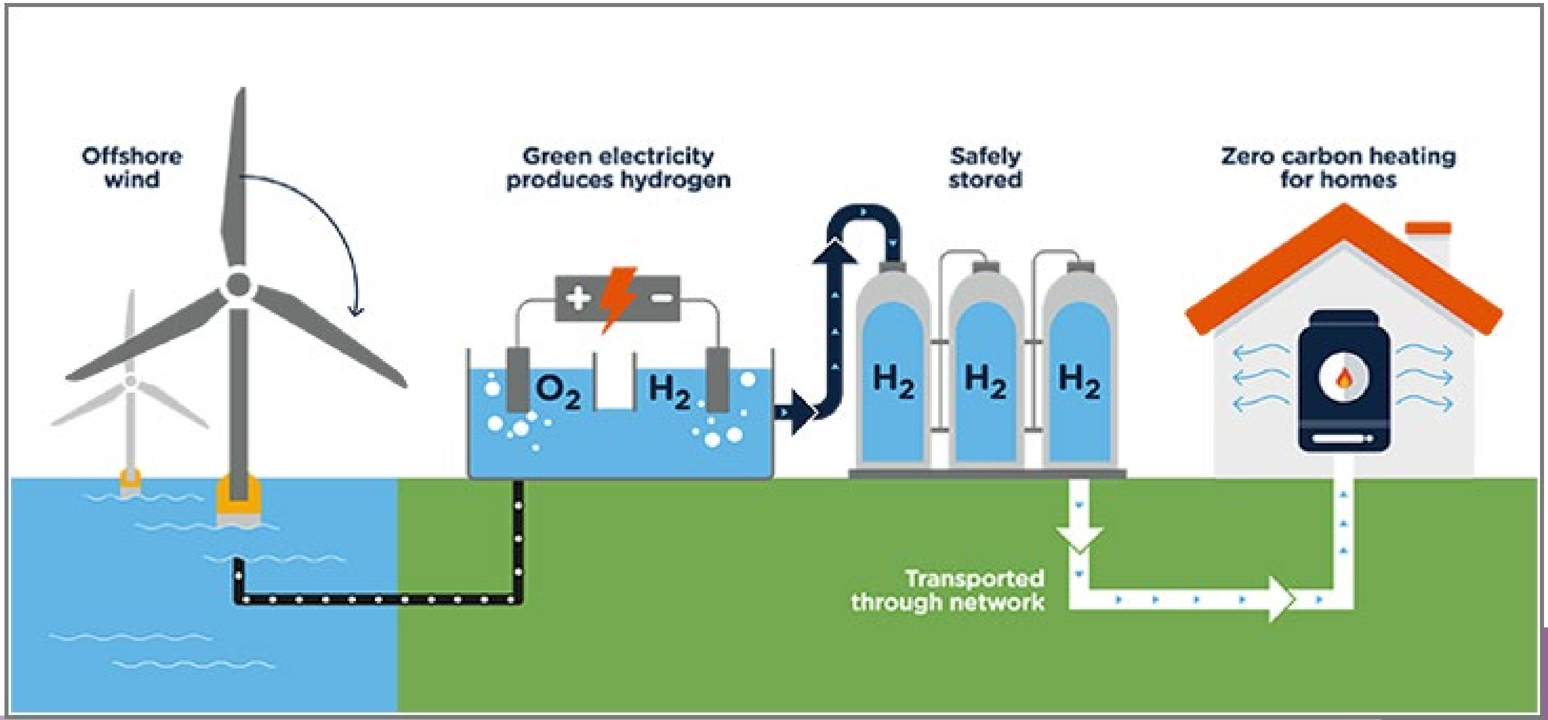
3. Project JIVE 2 (Dundee Hydrogen Bus Deployment Project – Hydrogen Accelerator (h2-accelerator.org**)**

- Hydrogen Refuelling Station (HRS) at the Michelin Scotland Innovation Parc powered by two 2 MW wind turbines.
- Hydrogen will be compressed to 350 bar onsite and used to refuel vehicles

Scotland Exemplar H2 Projects

4. H100 Fife Project-Key (H100 Fife | Future of Gas | SGN)

- Demonstration project for evidencing the role of hydrogen in decarbonising heat using the gas networks.
- Green H2 production from offshore wind, storage and distribution in a 100% H2 new network to customer homes



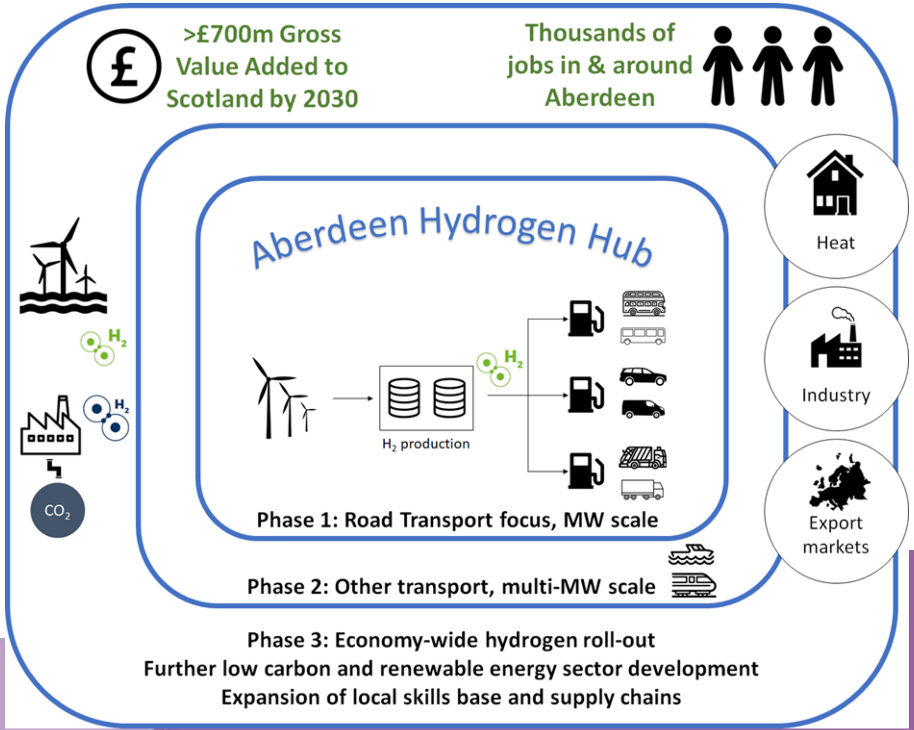
Scotland Exemplar H2 Projects

5. Zero Emission Train Project (Zero Emission Train Project – Hydrogen Accelerator (h2-accelerator.org))

- Support rail decarbonisation targets
- Provide the rail supply chain opportunity to develop skills
- Create economic opportunities for Scotland and high-quality jobs

6. Aberdeen H2 Hub (Homepage - Aberdeen (bpaberdeenhydrogenhub.com))

- **Phase 1** – Resilient, cost-effective supply of green hydrogen on a commercial basis to the market to support existing and proposed transport projects.
- **Phase 2** – Short to medium term expansion to connect to larger volume utilisation of hydrogen – trains, trucks and marine.
- **Phase 3** – Innovation, skills and transition hub to support expansion of the local supply chain and pursue Aberdeen ambition to be the centre of new energy production business, exporting H2 to the world.



England HyGreen and H2 Teesside Project (HyGreen Teesside | Where we operate | Home (bp.com & h2teesside | Where we operate | Home (bp.com))

- HyGreen Teesside aims to be one of the biggest green hydrogen production facilities in the UK.
- HyGreen Teesside, developed in multiple stages, targets 80MWe of green H2 capacity by 2025 and growth to 500 MW by 2030, delivering up to 5% of the UK government's H2 target of 10GW by 2030.
- H2Teesside is BP & ADNOC H2 project aiming 1GW of CCUS-enabled blue H2 production by 2030.
- The combined capacities of HyGreen Teesside and H2Teeside could deliver 30% of the UK Government's target of developing 5GW of H2 production by 2030.

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Other New Projects

- Rolls Royce and easyJet in collaboration with Loughborough University have recently announced an advancement with their project aiming to develop hydrogen combustion engine technology to power a range of aircrafts (Rolls Royce and easyJet aim to develop hydrogen combustion engine technology - Hydrogen Technology Expo Europe (hydrogen-worldexpo.com).
- The Board of Santa Cruz Metro California announced approving the purchase of 57 hydrogen-powered buses to replace some of its ageing diesel and CNG (compressed natural gas) buses after the battery-electric buses had problems navigating the steep hills outside the coastal city.
- VSB Buleon wind farm in Brittany France of 13.2MW capacity is now building Lhyfe Bretagen's green and renewable hydrogen production site to produce up to 2 tonnes of hydrogen per day. It will have an installed capacity of 5MW and will be operational in late 2023.
- H2 Green Steel has raised $1.6bn with help from an investor group which included Hy24, Altor, GIC, and Just Climate, also including Andra AP – fonden and Temasek, plus a pre-existing group of investors. This money will go into building a large-scale green steel plant and a giga-scale hydrogen electrolyser.

Hydrogen Energy Storage Systems (Electrolyser, H2 Storage and Fuel Cell)

Why Use H2 Energy Storage Systems?

- Hydrogen energy storage (HES) is a stable storage medium which can be scaled-up to enable storing energy over long time periods with no restrictions on its location.
- The energy storage mechanism, which is chemical in the form of hydrogen (gas or liquid), does not suffer high rate of self-discharge or degradation in performance.

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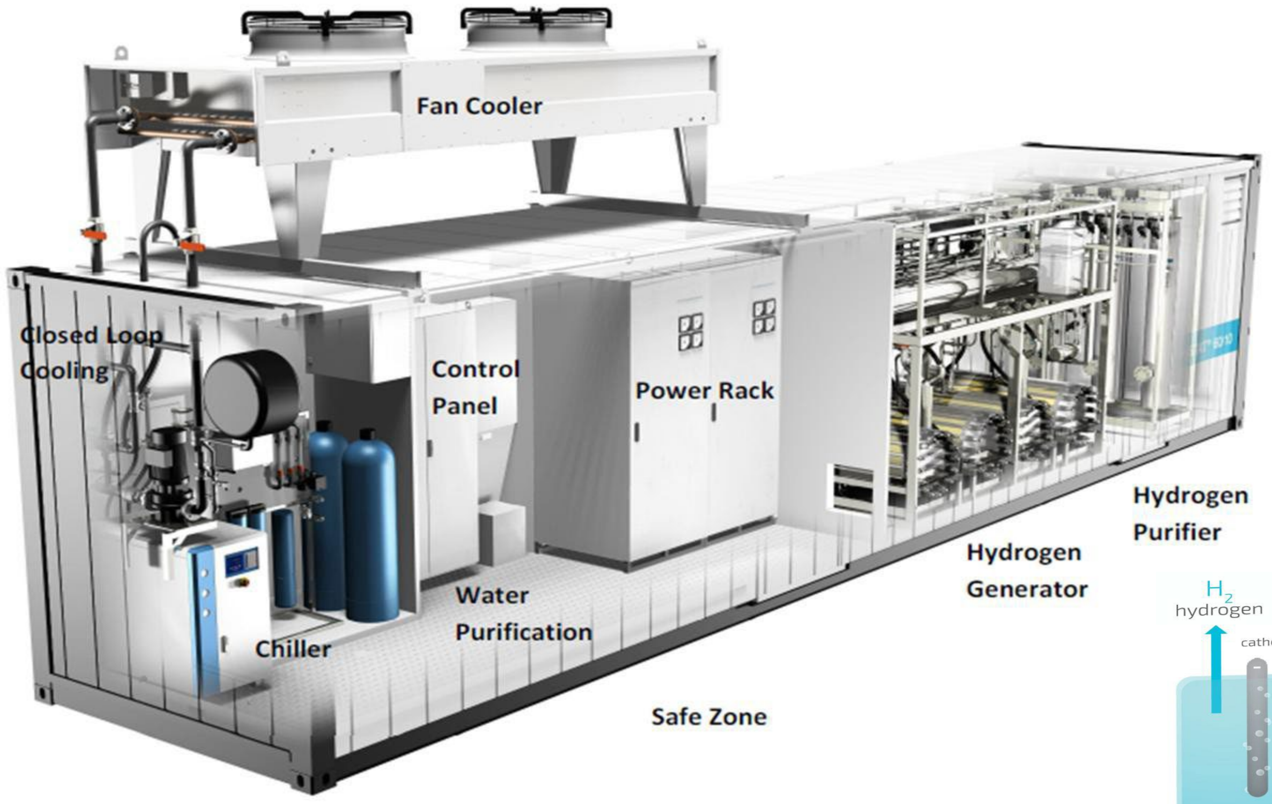
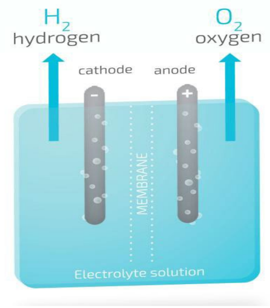
Electrolyser (H2 Generator)



ETIP Wind – Wind2H_2| Brussels (BE) | 21.02.2019



Electrolysers, when powered, split water (H_2O) into hydrogen & Oxygen. They are mainly:

- Alkaline electrolysers

  100°–150°C, ~70% efficient

- Polymer electrolyte membrane (PEM) electrolysers

  70-90°C, ~80% efficient

- Solid oxide electrolysers

  700-800°C, ~80+% efficient

Electrolysis Technologies

Alkaline Electrolysis

- Alkaline aqueous electrolyte (NaOH or KOH) solution with a typical concentration of 20–40 wt%
- Been around for >60 years
- Reliable proven technology

- **Proton Exchange Membrane**
  - Polymer electrolyte membrane
  - Compact
  - Wide working range (low-high power)

- **Solid oxide electrolyte**
  - Solid ZrxOy steam electrolysis
  - High temperature – high efficiency
  - Less flexible

- **Anion exchange membrane**
  - Alkaline polymer electrolyte
  - Little commercialization

Hydrogen Storage

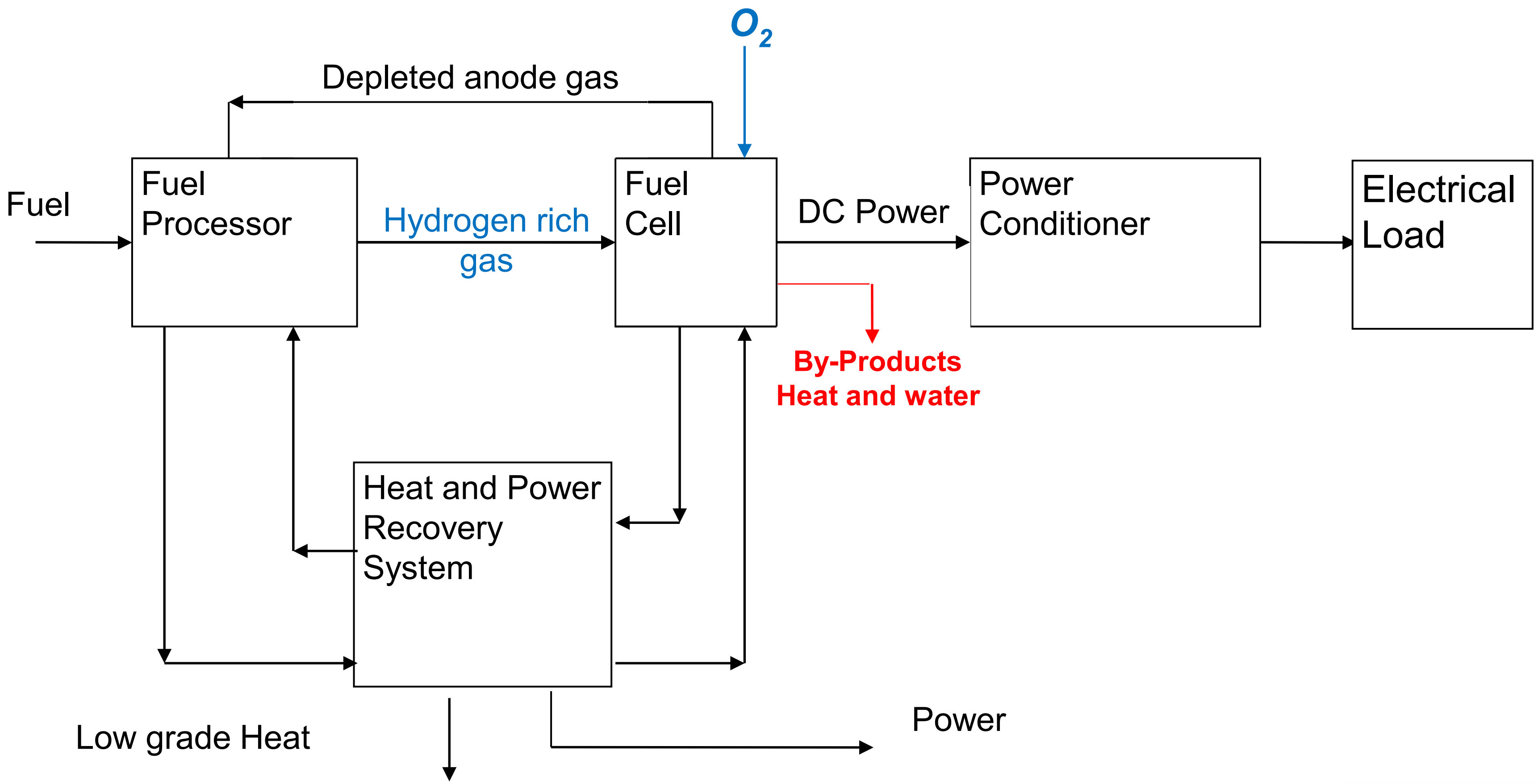
H2 Storage allows absorbing any access generation to be used during energy deficits, thus:

- Eliminating the variations in electrical demand
- Smoothing the renewables generation intermittency thus enabling their increased grid-integration reducing the emissions of fossil fuel generation.
- Allowing the transportation of the stored energy for use in remote areas

Fuel Cells (FC)

- Each fuel cell is composed of a membrane (electrolyte) sandwiched between two porous electrodes.
- A fuel cell stack is formed of a number of cells referred as Membrane-electrode assembly (MEA).
- The stack' voltage is determined by the number of cells, and stack current is determined by the active area of the cells.
- Other parts of a fuel cell system include pumps and blowers, compressors, cooling system, a power conditioning (voltage regulator to make the system DC output suitable for connection to an electrical load and sometimes DC/AC inverter).
- A fuel processing system is needed if the fuel cell supply is not pure hydrogen.
- A controller is needed to coordinate the parts of the system.
- In case of Polymer Electrolyte Membrane (PEM) FC, there is often a need to humidify one or both of reactant gases.

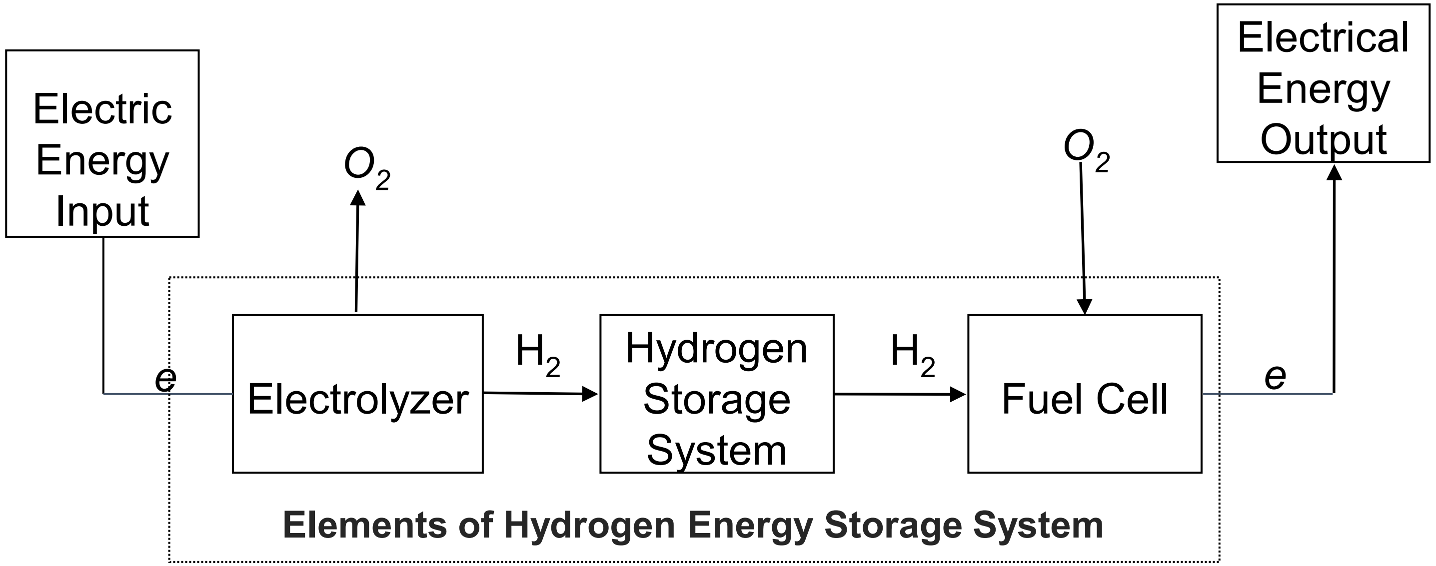
The fuel cell system consists in general of four sections as in Figure:



Hydrogen Energy Storage Systems (HESS)

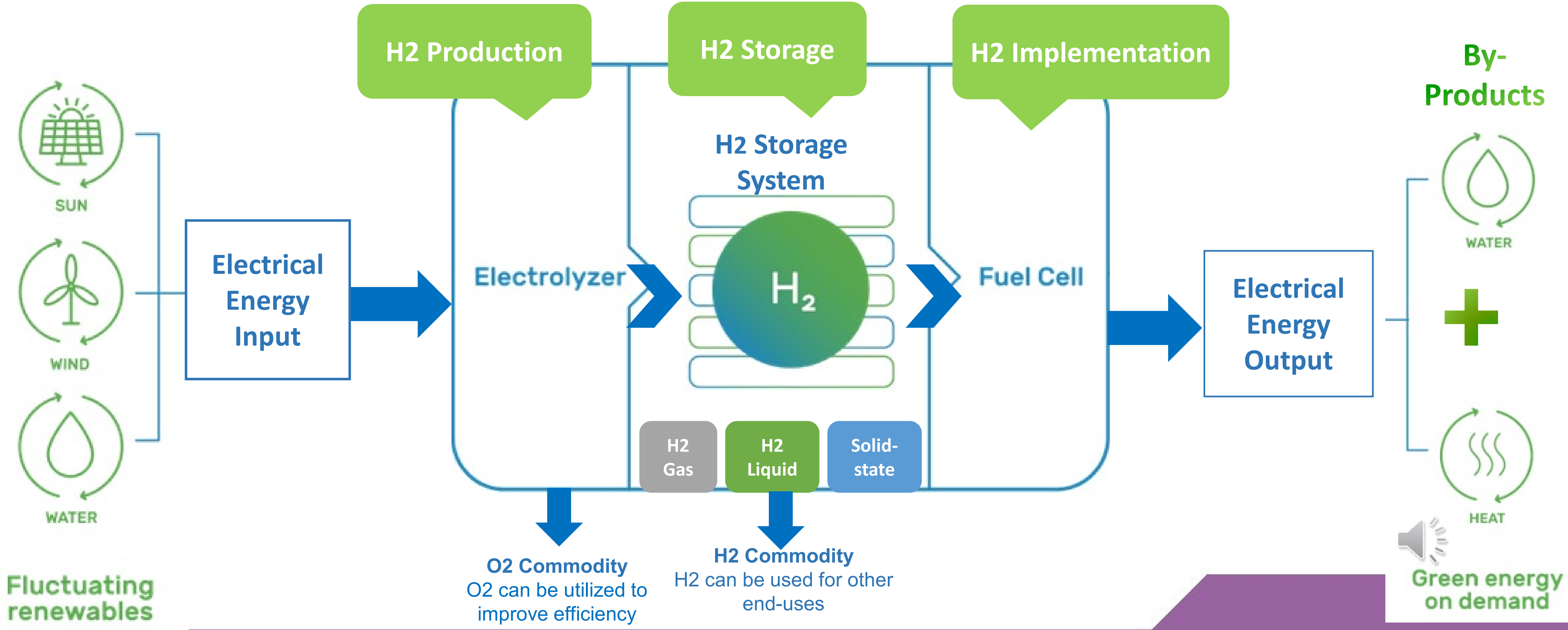
HESS allows storing the excess energy (during the grid off-peak hours or during excess renewable production) in the form of H2. The energy excess is used in powering an electrolyser to produce H2 from water electrolysis, which although still expensive, allows many applications:

- H_2 can be used in **fuel cells to generate electricity**
- H_2 can be **injected into existing gas grids** (it is mixable with other gases)
- H_2 can be used in many **industrial processes** (like fertilizer production)
- H_2 can be used as a **vehicle fuel**
- O_2 can also be **sold as a commodity**



e = electrical energy
H_2 = hydrogen gas
O_2 = Oxygen gas

Green Hydrogen Energy Storage Systems (HESS)

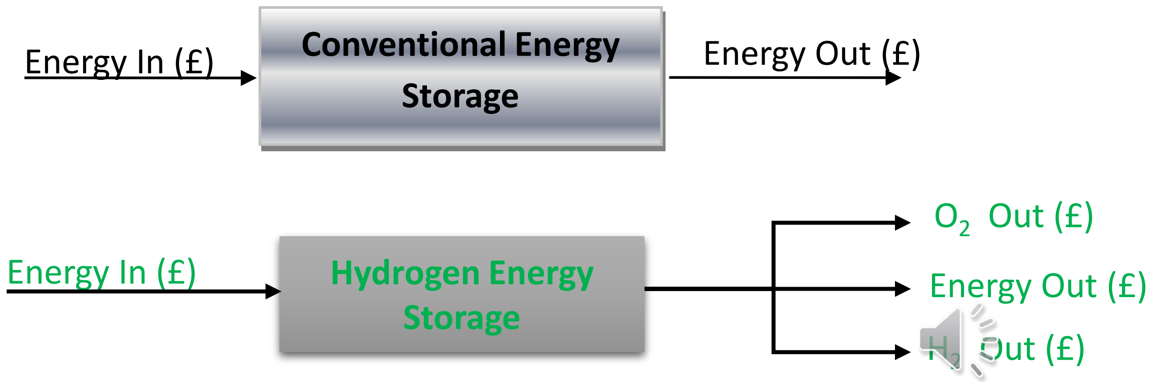


Efficiency of Hydrogen Energy Storage Systems

- All Energy Storage Systems have varying degrees of inefficiency (turn-around efficiency), with typical efficiency ranging from 45% to 80%.

- Hydrogen Energy Storage Systems has better efficiency because:
  - They utilize Electrolysis which has high efficiency
  - They utilize Fuel Cells of conversion efficiencies lot higher than that of combustion engines
  - Their efficiency can be further increased by:
    - Utilising the output heat from electrolysers & fuel cells in process heating
    - Selling the produced H2 and O2 gases as commodities thus increasing the system economic efficiency (3:1 increase in revenue options).

Possible Economic Revenue Streams for Hydrogen Energy Storage Compared to Conventional Energy Storage



Techno-Economic Assessment of Hydrogen Energy Storage (HES)

- Stored H2 can be used in a Fuel Cell to generate clean electricity with water & heat as the by-products.
- Stored H2 (when compressed at 700bar) has 3 times the specific energy (142 MJ/kg) of fuel oil (48 MJ/kg).
- Stored H2 can be used as an energy carrier delivered where it is needed.
- Stored H2 can deliver a fuel for making power or heat, or for fuelling transportation while absorbing the renewables intermittent power inputs.
- Implementing HES with renewables enables their increased integration, thus eradicating energy wasting & constraint payments
- HES allows an added stabilizing capability for the grid, thus reducing the need for spinning reserve and load shedding and reduce transmission & distribution burden.
- HES systems allows three possible economic revenue streams while conventional energy storage systems have only one possible revenue stream.

Renewable-Hydrogen Energy Systems Case Studies

Introduction

- The ongoing growth in global energy demands and the associated catastrophic climate change with the increased greenhouse gas (GHG) emissions have **accelerated the need for maximizing the implementation of more renewable energy sources with offshore wind as the top source in the UK**.

- Renewable energy sources have a **great potential, but their fluctuating and intermittent nature hinder** their increased integration, thus requiring energy storage.

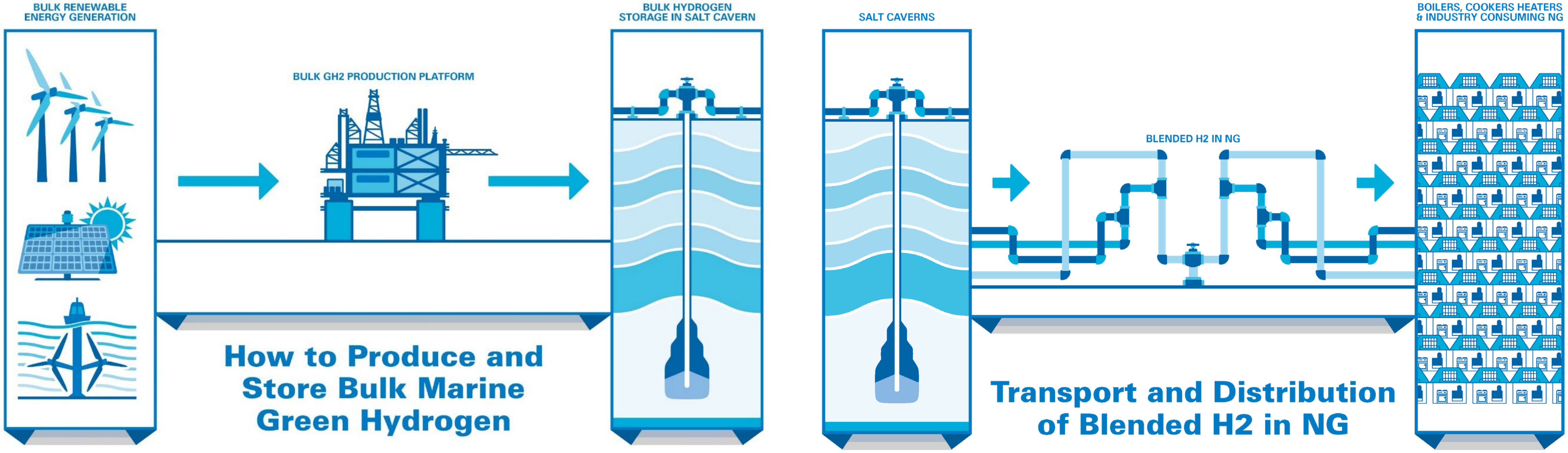
- While batteries, compressed air, flywheels or capacitors are suited for short-term storage of electricity, **long-term storage could be realized with hydrogen as energy vector.**

- Renewable-hydrogen energy storage systems can be implemented for **enabling more renewables grid-integration and can decarbonise heating, transport and industrial applications**.

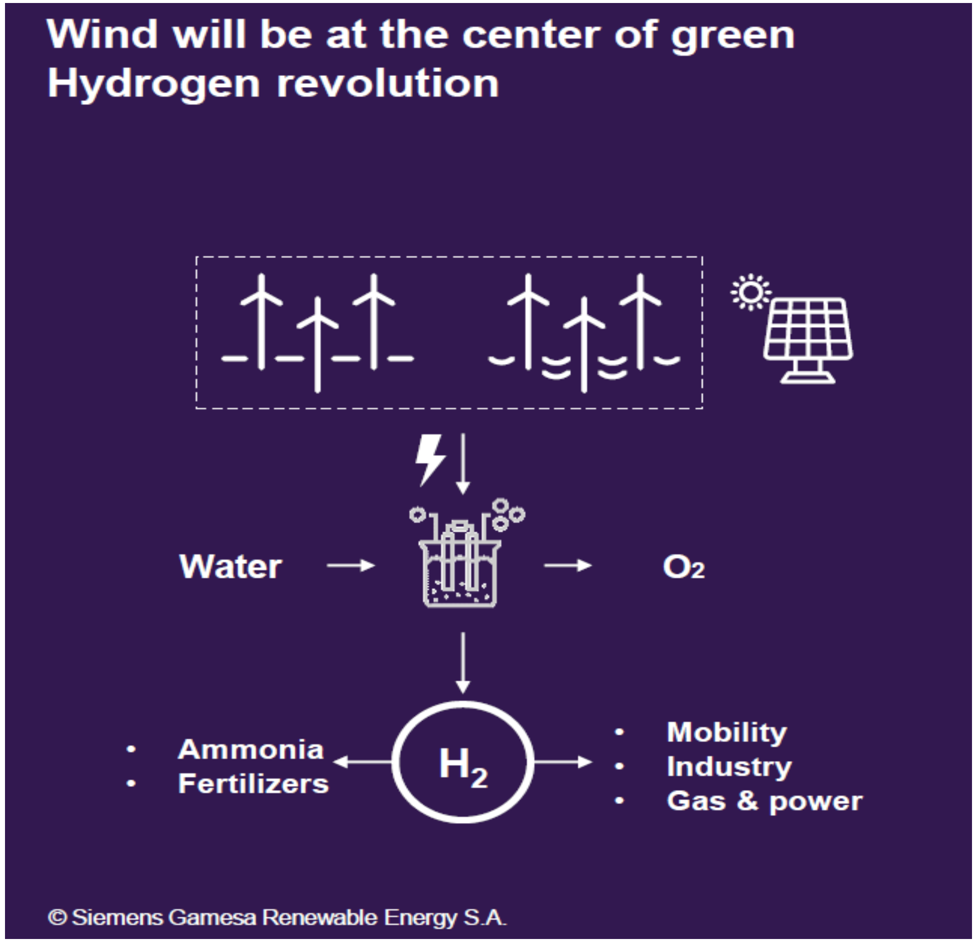
- Renewable-hydrogen applications are increasing with the **falling costs of renewable power**.

- **To fully unlock the potential of renewable-hydrogen, costs of hydrogen technology should be reduced through large-scale implementations**.

Large-Scale Green Hydrogen Production & Storage



Wind Green Hydrogen



Renewable H2 by integrating electrolyzer into existing Wind farms

- **Offshore Wind H2 projects** strongly grow with significant potential expected from 2030 with the North Sea as the most promising area, combining both good wind resources and strong potential demand for H2
- **Onshore large-scale Wind H2 projects** are expected from 2026 onwards
- **Onshore large-scale Hybrid (Wind + PV) H2 projects** are expected in countries with favourable resources (Australia, Chile) and will constitute a **low-cost source for H2 export**
- **Globally announced Offshore H2 projects** (+20 GW) **and Onshore H2 projects** (+ 30 GW) .

Solar Green Hydrogen

- The conversion of solar energy into a clean fuel (H_2) is the most promising technology for future large quantities generated in a clean and sustainable manner.
- H2 can be produced by using the solar energy heat (thermochemical), light (photoelectrochemical or photocatalytic) or electricity (electrolysis).
- Thermochemical splitting of water is the most direct method for using solar energy to derive hydrogen from water is one-step; however, remain with challenges.
- Photocatalytic splitting of water into H_2 and O_2 needs a photo-semiconductor able to efficiently absorb solar energy and then to split the molecule in an indirect way because pure water does not absorb solar radiation.
- Electrolysis utilises the solar electricity to power the electrolyser which splits the water.

Cost of Green Hydrogen

- **Green H2** is **currently more expensive** than conventional H2 produced from fossil fuels
- **Cost of green H2 is falling rapidly** due to combined effects of **reduced electrolyzer cost** and **reduced renewable power costs**
- **Costs associated with CO2 emissions** from fossil fuels could be considered to further **improve the competitiveness of green H2**
- Renewable-H2 **will compete in the next 5 years** with fossil fuels
- Wind-H2 will allow **wind farms with expiring feed-in tariffs/incentives to identify new revenue streams.** Integrating Electrolysers into wind farms will:
    - **Allow CAPEX reduction** by replacing high cost HV infrastructure with pipes network
    - **Increase system efficiency** due to lower HV electrical loses
    - **Increase plant load factor** as electrolyzer load is more flexible than electrical network requirements

Case Study 1 (Power to Power): Lam Takhong Wind Hydrogen Hybrid Project Thailand

- Use the curtailed energy from 24 MW wind farm with limited injection capacity
- Implement 1 MW PEM electrolyzer, 3 MWh (10 hours) of compressed hydrogen storage (250 bar), and 300 kW PEM fuel cell
- Use the hydrogen through a 300-kW fuel cell to power the new energy center

Case Study 2 (Power-to-Gas): Direct injection of hydrogen in high-pressure natural gas grid Germany

- Feed hydrogen into the medium-pressure distribution natural gas pipeline at 40-70 bar with compression.
  - Implement 1x HyLYZER®-200-30 (PEM, single cell stack design) with all peripherals to produce 200 Nm^3/h H_2 (power: 2.4 MW)

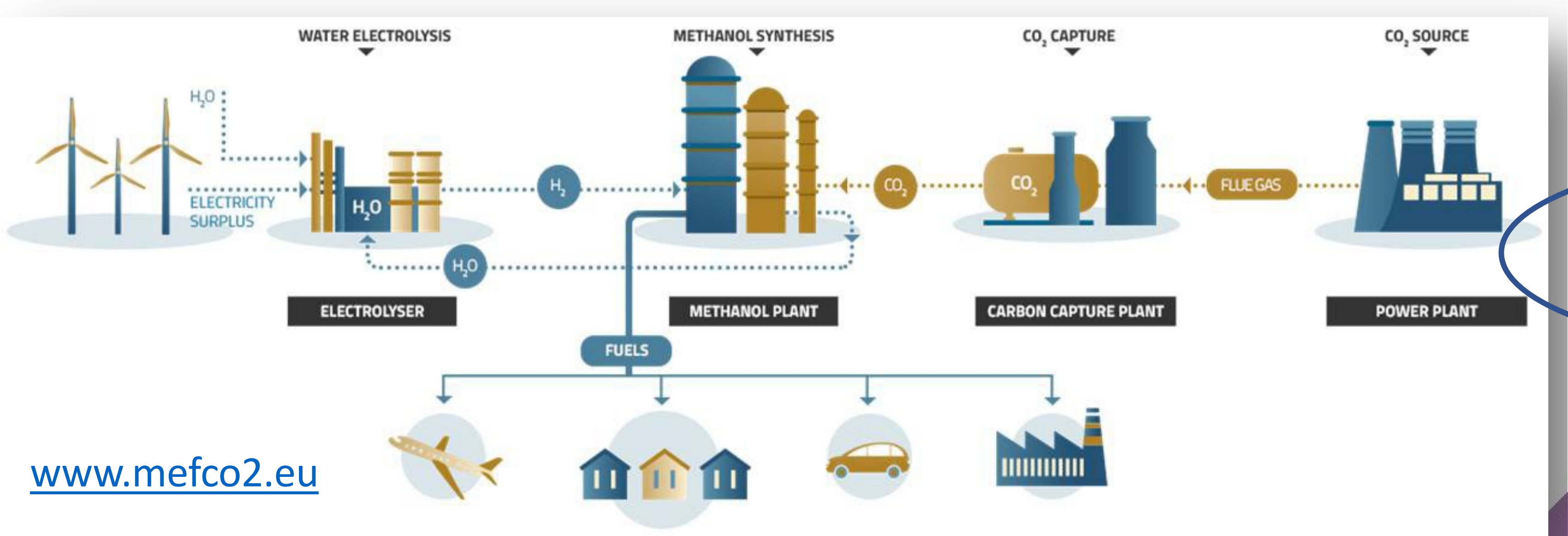
www.w2g-energy.de

2.4 MW PEM Electrolyser Direct Injection

Case Study 3 (Power-to-Methanol): Niederaußem Germany

- Produce **green methanol** as energy vector from captured CO_2 and the hydrogen produced using surplus renewable energy.

- Implement 1x HyLYZER®-200-30 (PEM, single cell stack design) with all peripherals to produce 200 Nm^3/h H_2 (power: 1 MW)



www.mefco2.eu

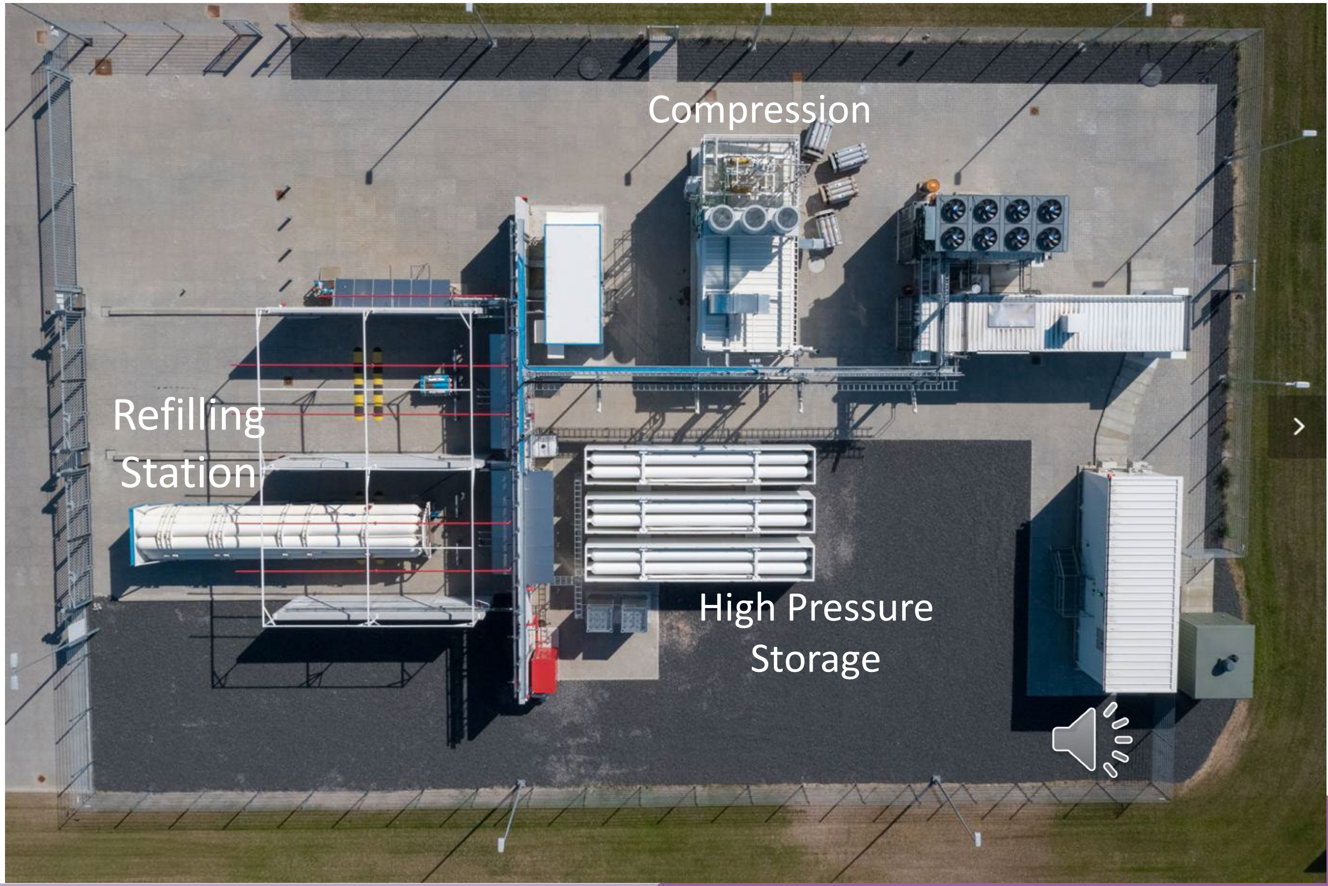
1MW PEM Electrolyser
CO2 Capture Plant
Methanol Plant

Case Study 4 (Deliver H2 for Refueling Stations & Industry)

HyBalance, Denmark

- Implement 1x HyLYZER®-230-30 (PEM, dual cell stack design) with all peripherals to produce 230 Nm^3/h H2 (power: 1.2 MW)
- Validate innovative delivery processes for hydrogen fuelling stations at high pressure and for industrial client (via dedicated pipeline)

More information: www.hybalance.eu



Case Study 5 (Energy Balancing): Highly flexible Electrolysers, Norway

- A 45 MW wind park implementing 1x HyLYZER®-500-30 (PEM) with all peripherals to produce 400 Nm³/h H2 (power: 2.5 MW).
- Demonstrate enhanced wind integration through hydrogen storage
- Demonstrate multiple control systems and remote operation (difficult access)

More information: www.haeolus.eu

Case Study 6 (Utilizing Curtailed Renewable Capacity): The BIG HIT Project, Orkney/Scotland

- The Orkney Islands have over 50 MW of installed wind, wave and tidal capacity and produce over 100% of their electricity demand from renewables on an annual basis; however, the renewables electricity output is often limited by grid constraints leading to reduced output and less income.

- BIG HIT utilise this curtailed capacity instead to produce ‘green’ hydrogen by electrolysis and this hydrogen is transported across the islands for mobility, heat and power end-uses.

- Two PEM electrolysers (2MW) are used in the islands of Eday and Shapinsay to produce hydrogen that is stored as high-pressure gas in 5 tube trailers. Hydrogen, as an energy-storage medium can be transported to mainland Orkney, or consumed locally, or can be stored to be converted later into heat and power.

- A 75-kW fuel cell is used to convert the stored H2 to heat and power for several harbour buildings, marina and 3 ferries (when docked) in Kirkwall. Additionally, a hydrogen refuelling station in Kirkwall fuels 5 Symbio hydrogen fuel cell road vehicles for Orkney Islands Council.

Case Study 7 (Power-to-Power and Fuel): The HydroGlen Project (Glensaugh Aberdeenshire)

1.Renewable Generators (Solar PV and Wind)

2.Grid Connection with import/export

3.Battery (for short term storage of renewables electricity and grid-balancing)

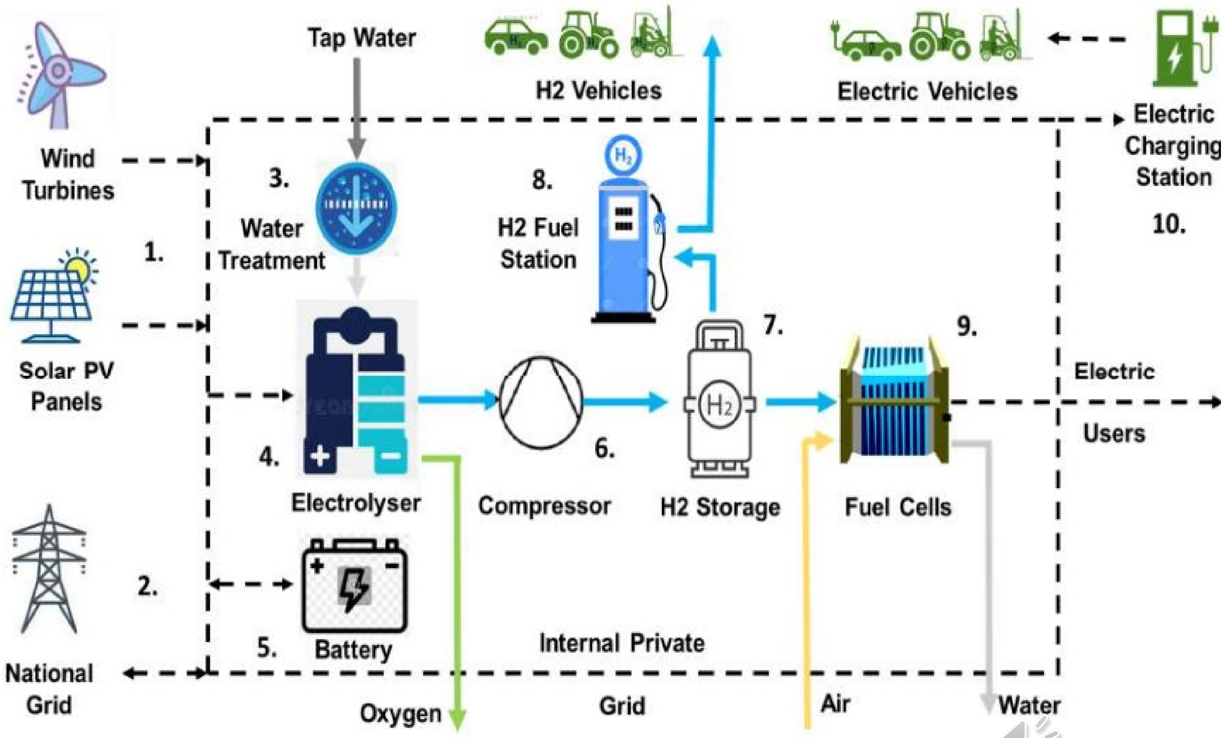
4.PEM Electrolyser producing H2 at higher pressure (30 barg)

5.H2 Compressor (to 200 barg)

6.H2 Storage (modular and scalable, 200 barg gas bottles)

7.Hydrogen refuelling station typically operating at 900 barg discharging to vehicle fuel tank at 700 or 350 barg. Refuelling a Hydrogen Fuel Cell Electric Vehicle (FCEV) takes 3-5 minutes like petrol or diesel.

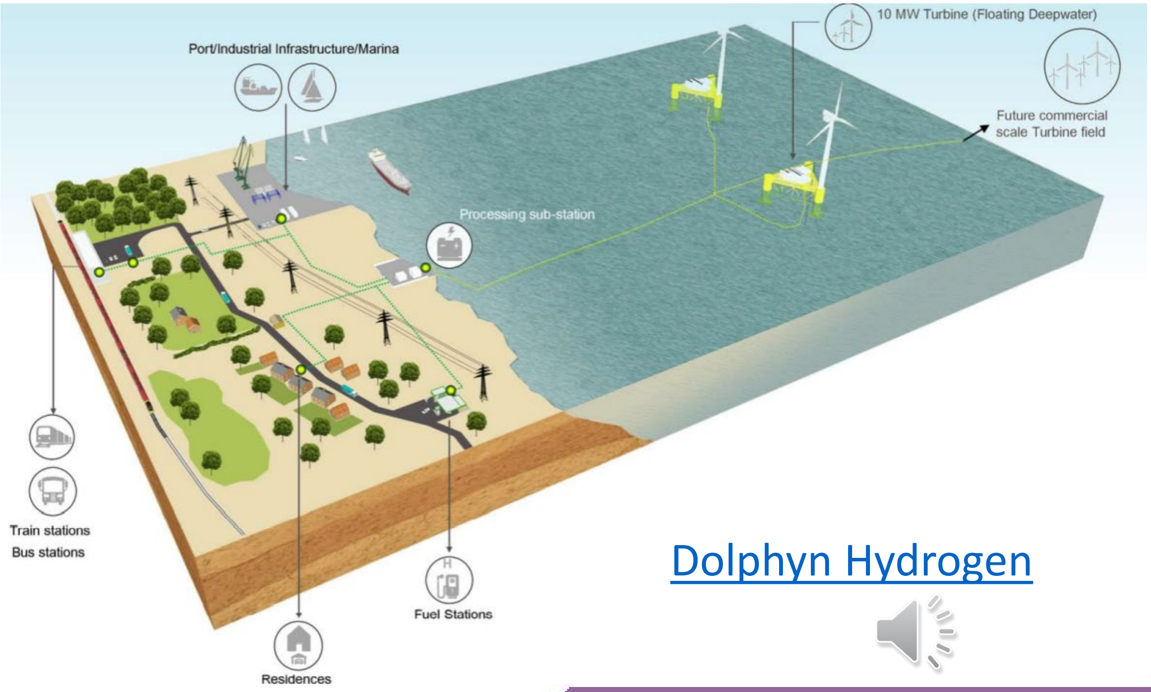
8.Hydrogen fuel cells for additional power generation by reconverting hydrogen back to electricity.



[ERM Dolphyn and Source Energie announce plans to develop Gigawatt scale "green hydrogen" floating wind sites in the Celtic Sea](#)

Case Study 8 (Wind Power-to-Green H2 fuel and Desalinated Water): The ERM Dolphyn Project Scotland

- Floating Structures with wind turbines located 60 km off the Pembrokeshire coast, west of Milford Haven (>10m/s average wind speed) to support decarbonisation
- Off-grid power generation system & Standby power generation system
- Combines desalination and hydrogen production on a floating wind platform.
- On-board fresh-water and Green H2 production
- H2 export to shore via pipeline
- Saves 6 million tonnes of Carbon emissions/year
- Creates high-quality jobs

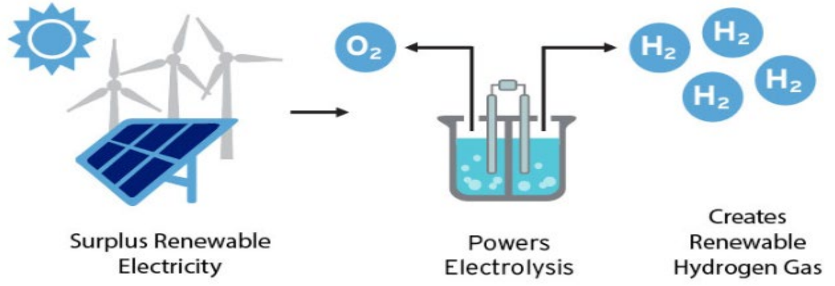


[Dolphyn Hydrogen]

Case Study 9 (Solar Power-to-Power Small-Scale Grid-Connected Building Decarbonization): The Farmhouse Research Project, Scotland

This project aimed decarbonising a grid-connected farmhouse while avoiding its grid power import/export.

- A 24kW/h Solar PV capacity is installed to supply the farmhouse power needs during summer, and the excess in its summer generation is stored in the form of Green H2 to be utilized during winter to reduce/eliminate grid power import/export.
- An electrolyser was sized based on the excess in solar generation during summer for the given PV size and location. H2 storage tanks are sized based on the generated H2 from electrolyser, the storage pressure, and on the storage period.
- The proposed PV-H2 system was simulated to demonstrate the H2 production over the different months based on the PV excess supplied to the electrolyser.



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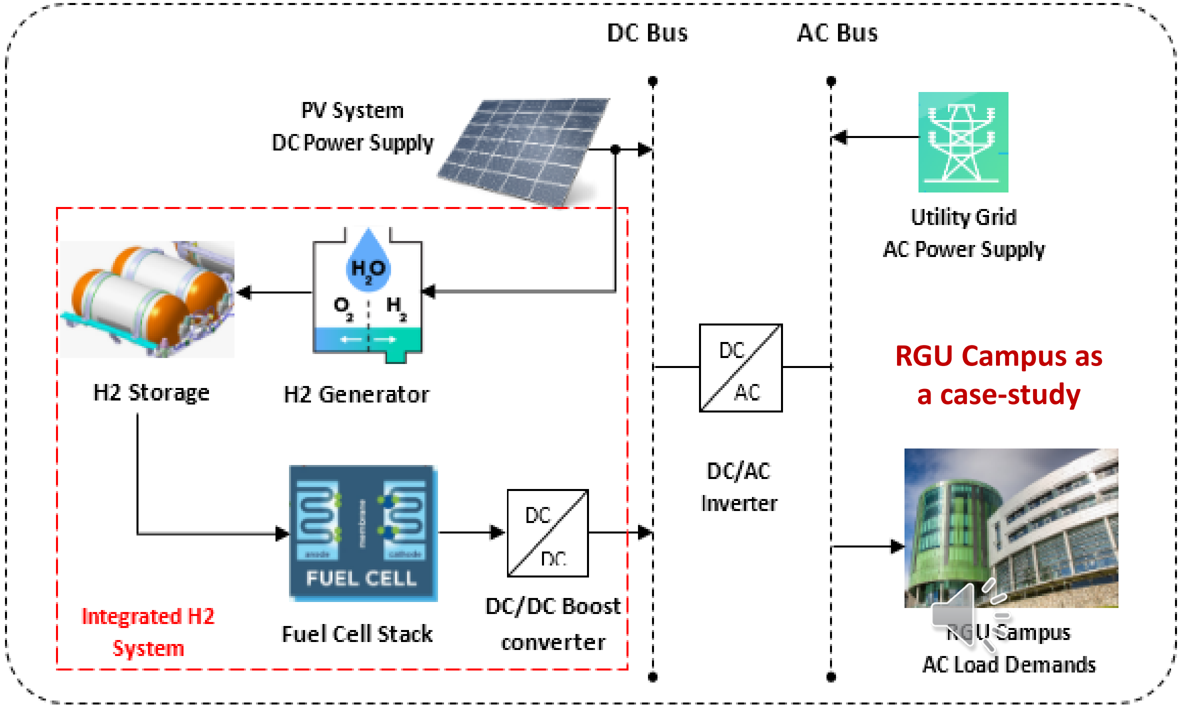
Case Study 10 (Solar Power-to-Power Large-Scale Grid-Connected Building Decarbonization): RGU Campus Research Project, Scotland

This project aims developing an energy optimization tool for realizing a Zero-Carbon Hydrogen-Based Grid-Connected Building-Scenario to be implemented on any grid-connected building

Research Project Objectives:

- Size the PV Capacity needed to minimize the building GHG based on the building annual energy demands
- Size the H2 electrolyzer and storage needed to complement the Solar capacity and mitigate its intermittency
- Develop an energy management model for achieving the optimal scheduling scenario for the H2 generation, storage and utilization in fuel cell together with the PV and the grid
- Develop a simulation-model for the proposed scenario
- Identify the economic and environmental benefits of the proposed scenario



Proposed Zero-Carbon Hydrogen-based Grid-connected Building Scenario

Conclusion

Hydrogen is a key player in the world clean energy transition and major contributor to the UK Net Zero Future. H2 will play a pivotal role in achieving an affordable, clean and prosperous economy.

For Hydrogen to play such a key role, the following is needed:

- Technology breakthroughs to reduce costs across the entire supply chain
- Long Term Strategy
- Favourable Government Policies
- Development of Local Skilled Workforce and Service Infrastructure
- Further Research, Analysis and Modelling that allows the effective deployment of hydrogen across different sectors

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Thank you!