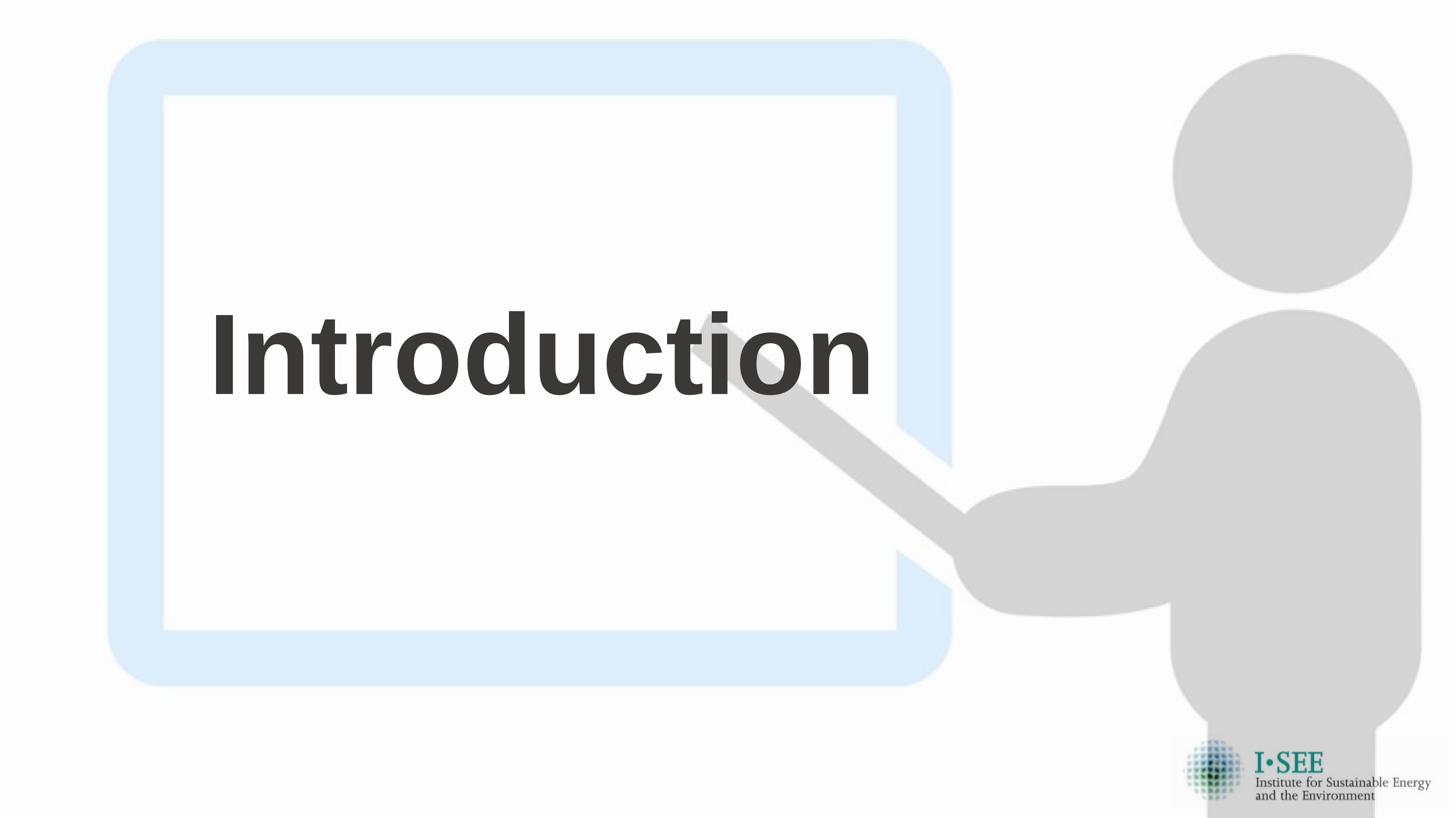
The Future of Sustainable Hydrogen (Energy)

Tim Mays

Professor of Chemical and Materials Engineering
Director, Institute for Sustainable Energy and the Environment (I•SEE)
UKRI Hydrogen Research Challenges Co-ordinator

cestjm@bath.ac.uk



Introduction

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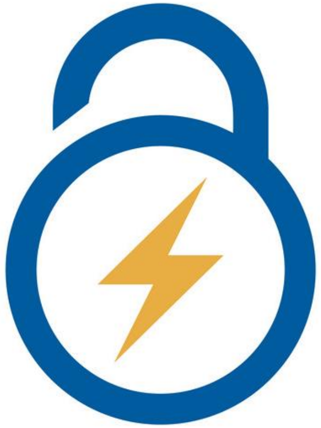
Scope

- *NB: Not, at this stage, a detailed analysis or manifesto*

This seminar is an overview of sustainable hydrogen and hydrogen-related technologies for energy systems and industry to support the UK's drive for secure Net Zero 2050.



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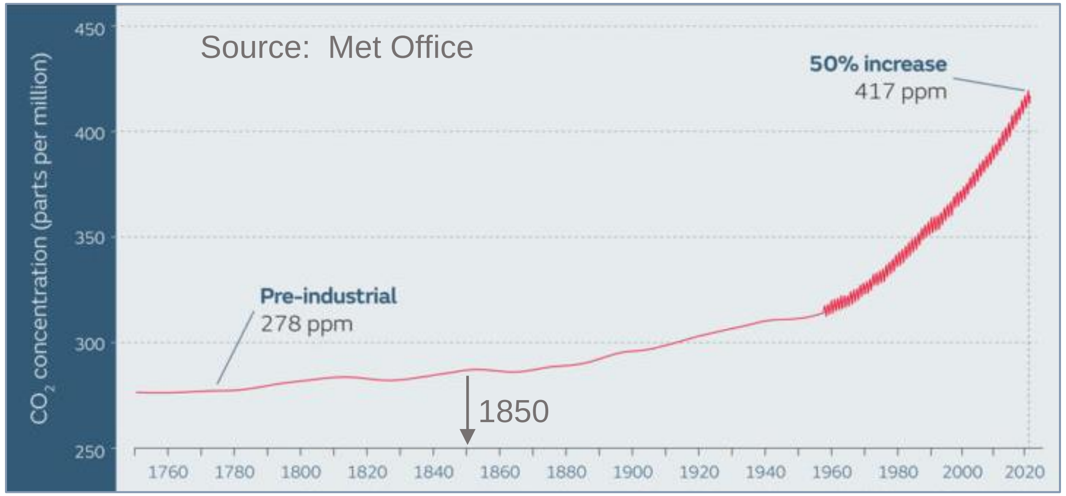
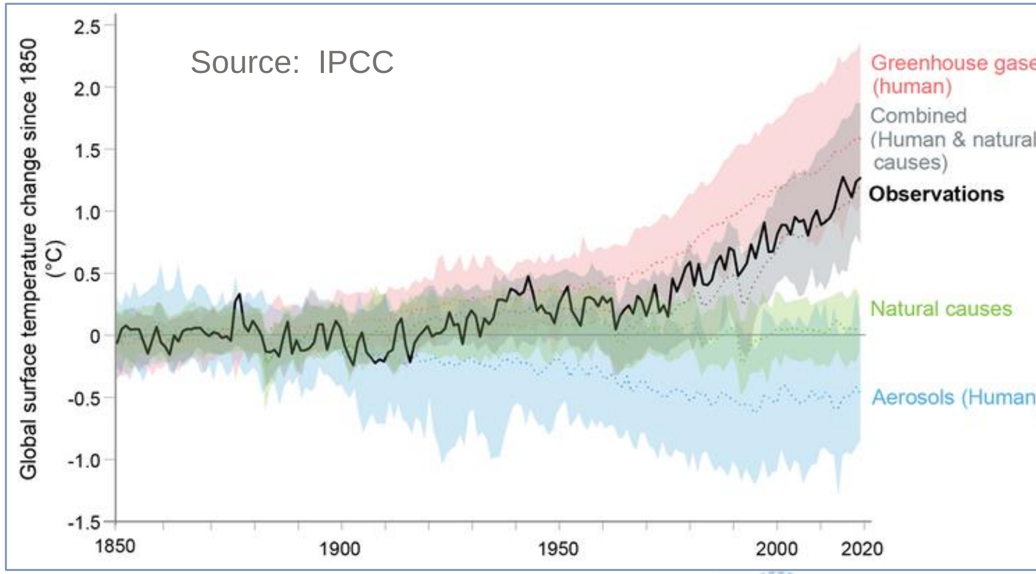
Context

- More and (on average) richer people globally leading to increased demand for energy and industrial products.
- Increased CO_2 emissions to air from declining fossil fuels leading to a global warming crisis.
- Challenges to security of supply.
- **Hypothesis:** Hydrogen has an important role to play in delivering low carbon and secure energy and industrial products.





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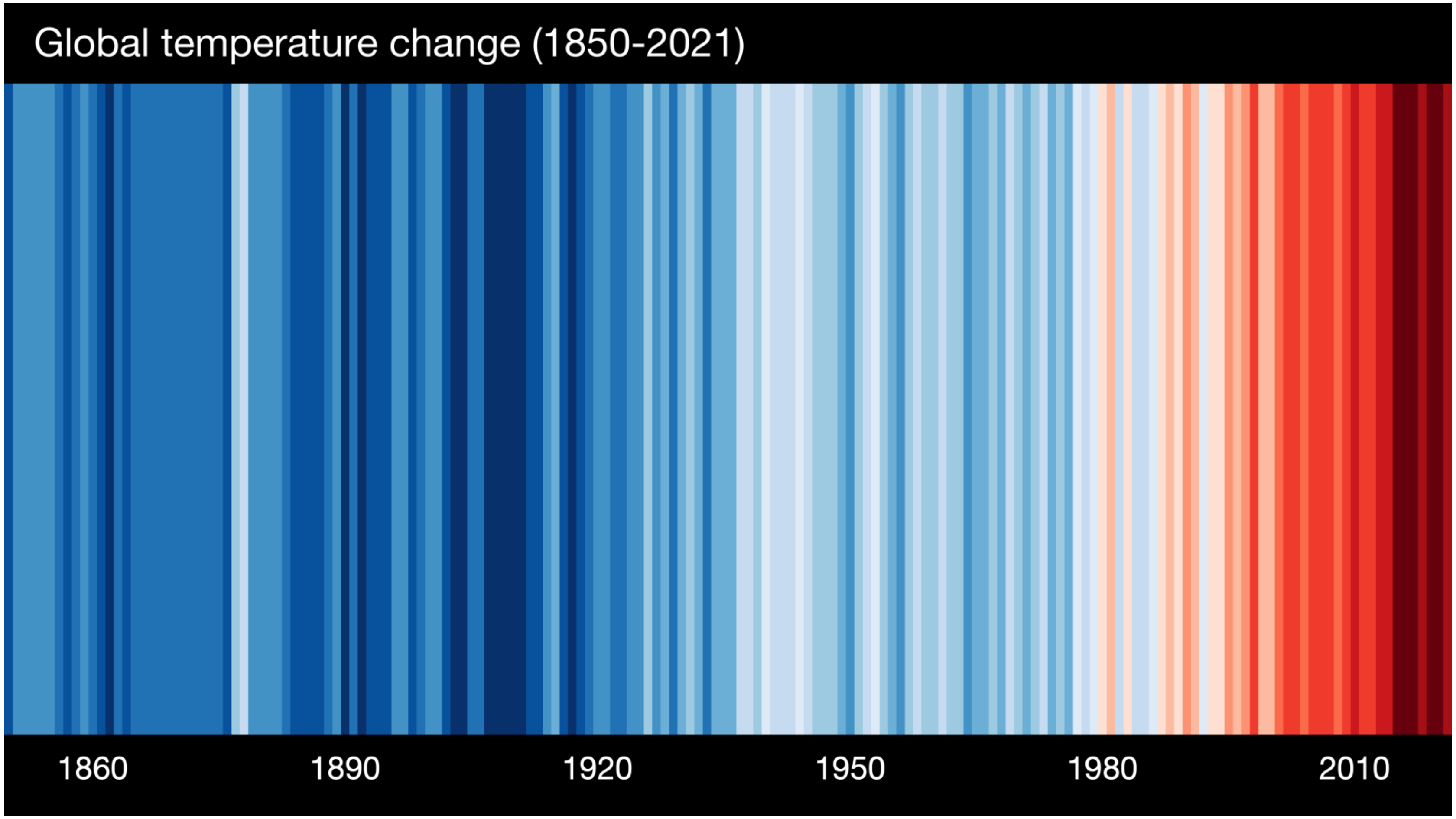
Climate Stripes



Source: https://showyourstripes.info/l/globe (Professor Ed Hawkins, University of Reading)

Global Initiative

- The **Paris Agreement** is a legally binding international treaty on climate change. It was adopted at COP21 in Paris, on 12 December 2015 and entered into force on 4 November 2016.

- Its goal is to limit global warming to well below 2 ºC, preferably to 1.5 ºC, compared to pre-industrial levels.

- To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-21st century.

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

Net Zero UK

STATUTORY INSTRUMENTS

2019 No. 1056

CLIMATE CHANGE

The Climate Change Act 2008 (2050 Target Amendment) Order 2019

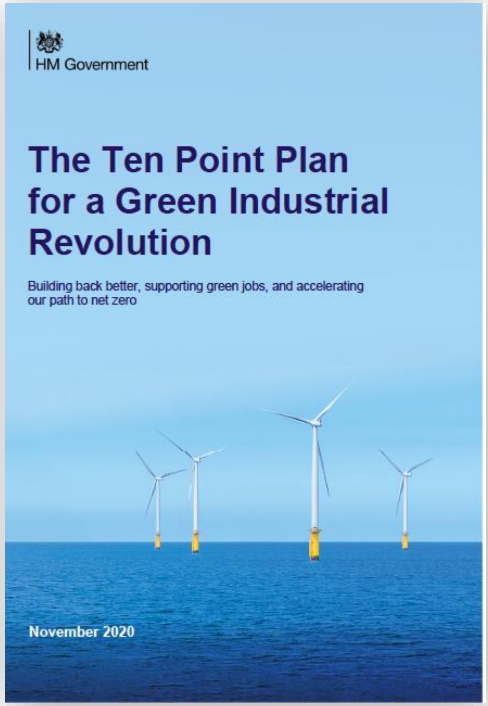
Citation and commencement

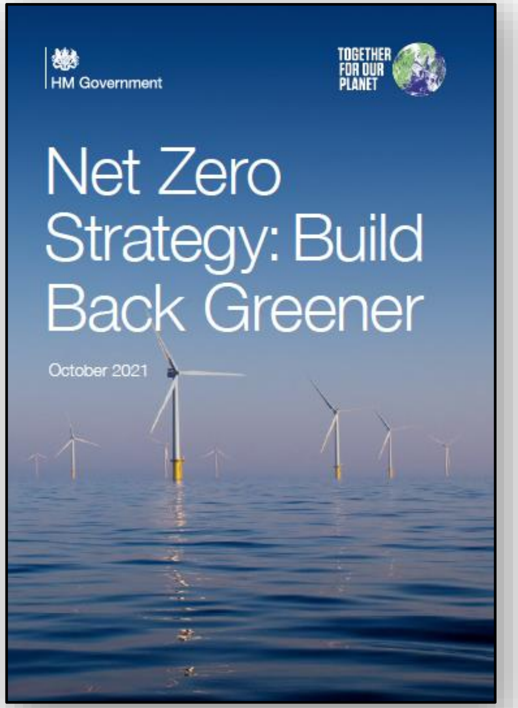
1. This Order may be cited as the Climate Change Act 2008 (2050 Target Amendment) Order 2019 and comes into force on the day after the day on which it is made.

Amendment of the target for 2050

2.—(1) Section 1 of the Climate Change Act 2008 is amended as follows.

(2) In subsection (1), for "80%" substitute "100%".





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UK Energy Strategy

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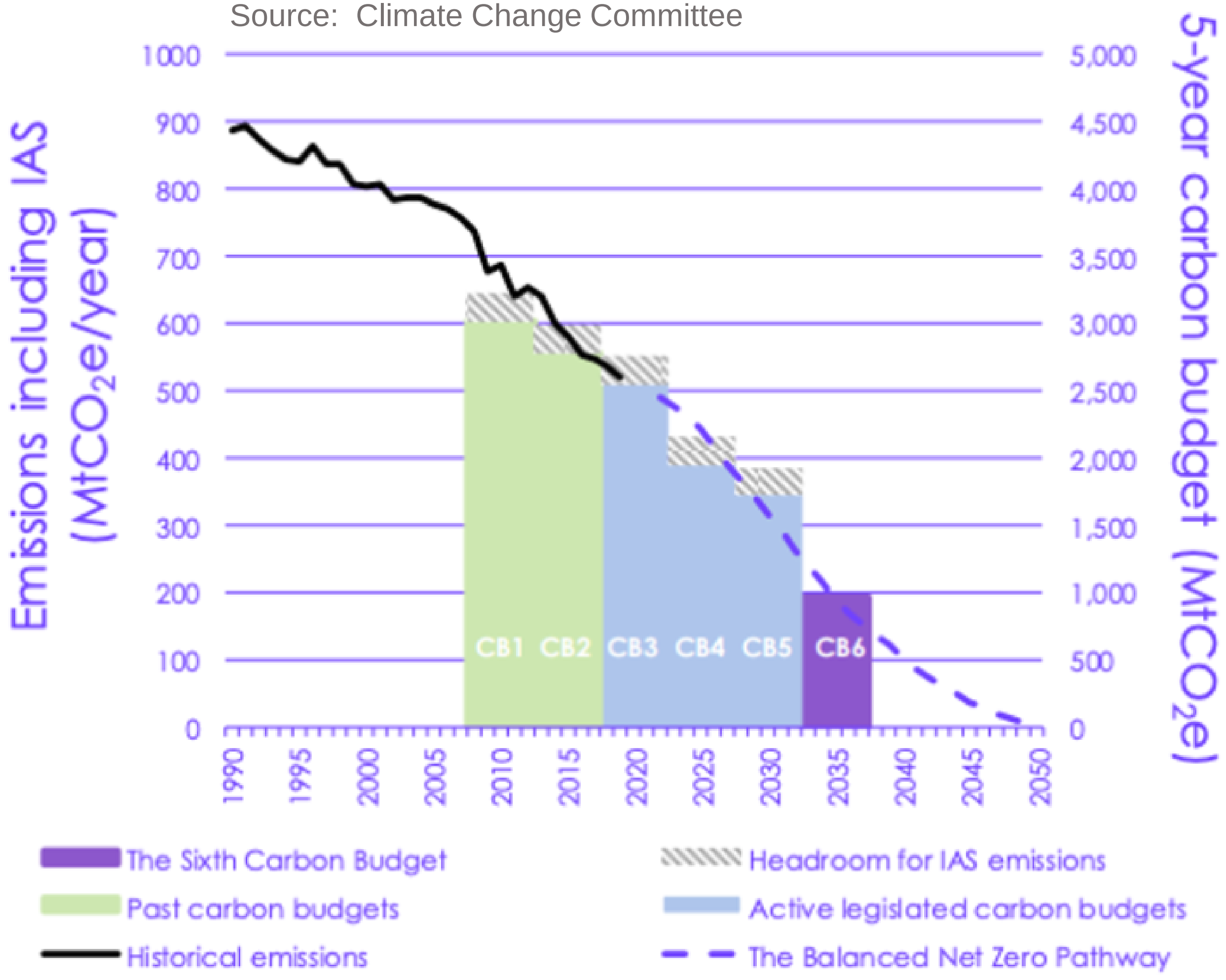
UK Carbon Budgets

Source: Climate Change Committee



The Ten Point Plan for a Green Industrial Revolution

Point 1
Advancing Offshore Wind

Point 2
Driving the Growth of Low Carbon Hydrogen

Point 3
Delivering New and Advanced Nuclear Power

Point 4
Accelerating the Shift to Zero Emission Vehicles

Point 5
Green Public Transport, Cycling and Walking

Point 6
Jet Zero and Green Ships

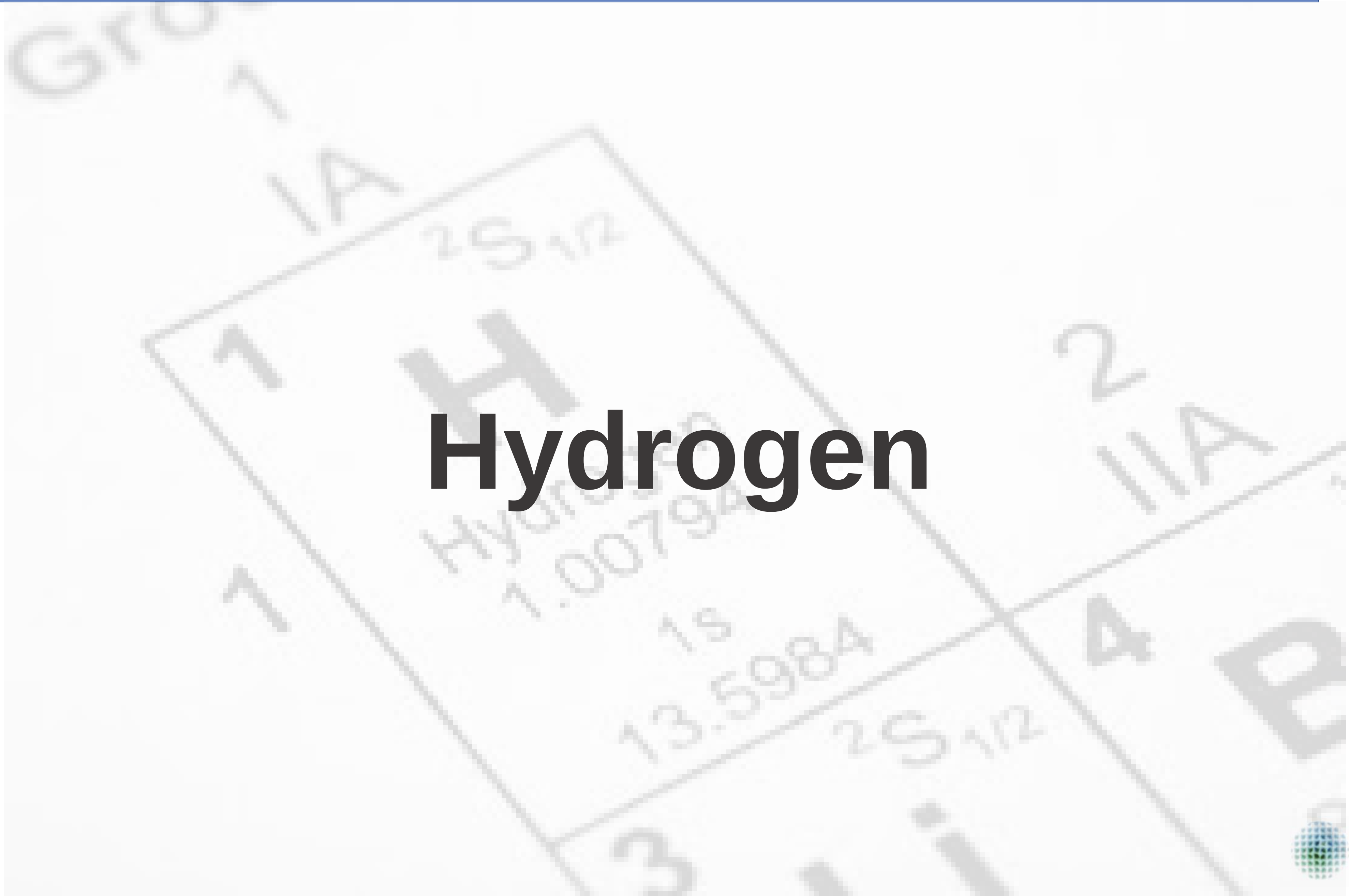
Point 7
Greener Buildings

Point 8
Investing in Carbon Capture, Usage and Storage

Point 9
Protecting Our Natural Environment

Point 10
Green Finance and Innovation

Hydrogen



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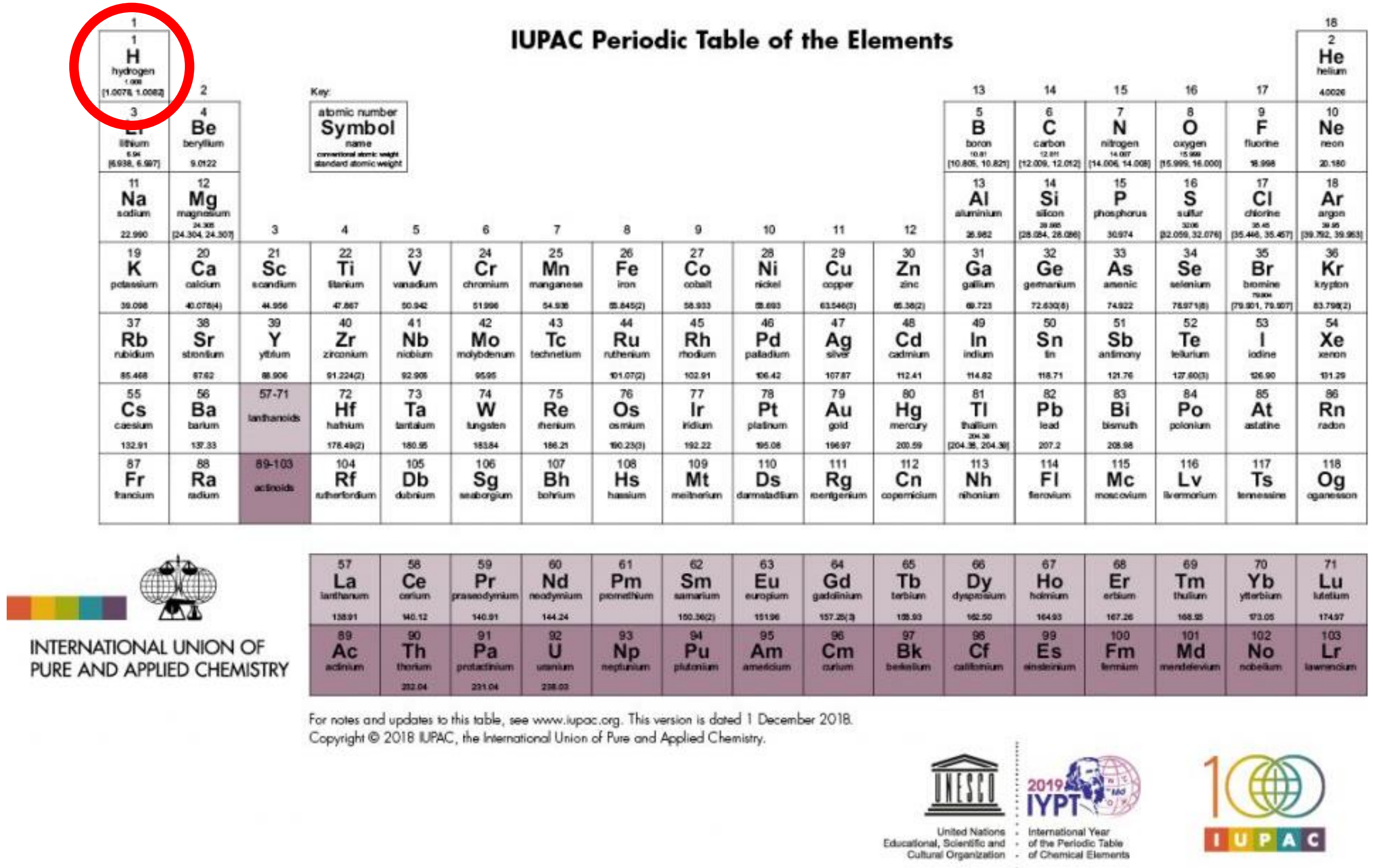
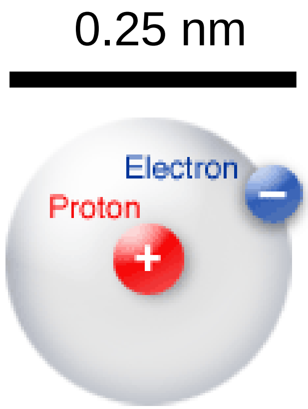
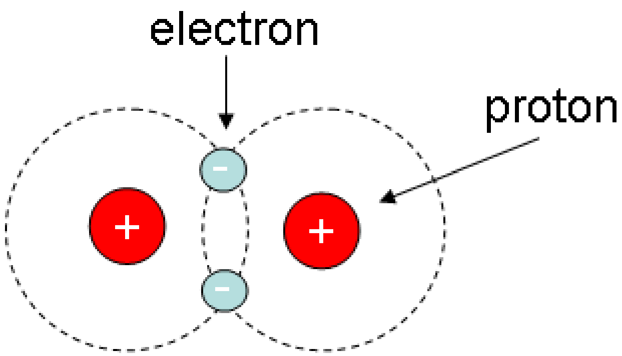
Number One Element

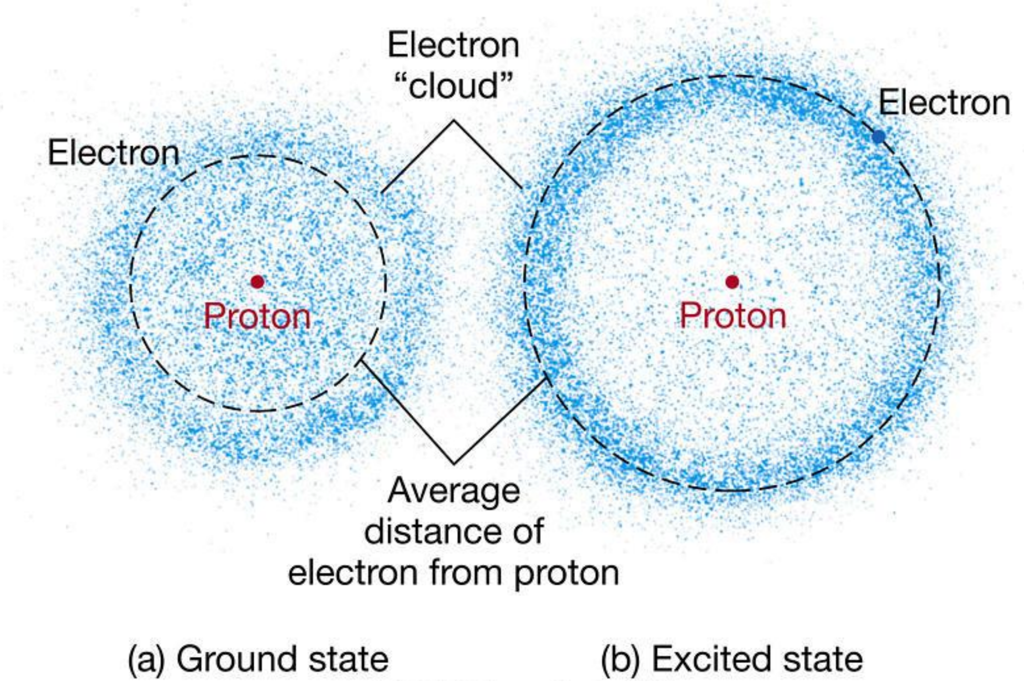


Atomic and Molecular Structure



Simple model of a hydrogen atom, H, (above) and di-hydrogen or molecular hydrogen, H_2, (below) (Bohr, 1913)

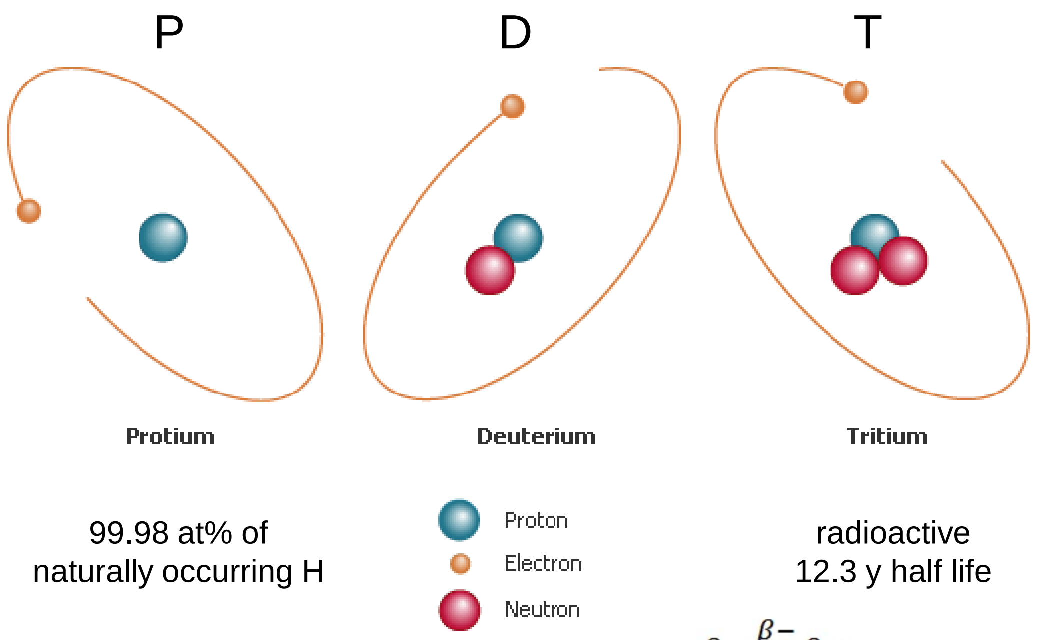




More accurate models of hydrogen atoms from quantum mechanics (Pauli, 1925; Schrödinger,1926)

A Dozen Molecular Hydrogens !

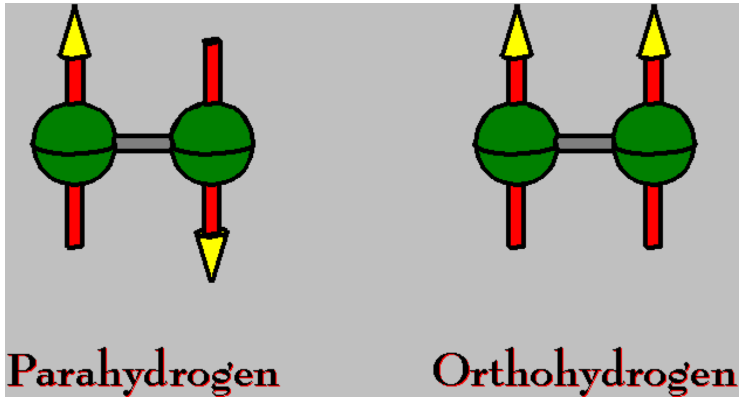
Hint: Start with *para*-PP



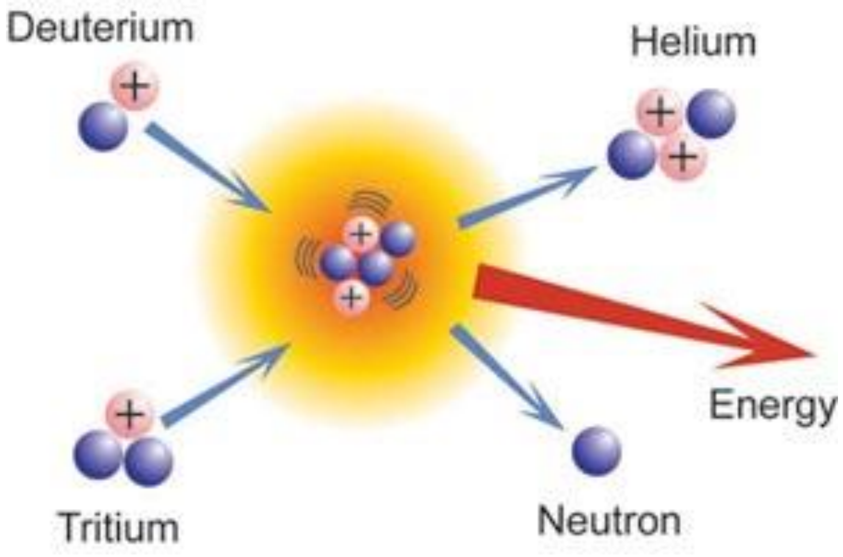
99.98 at% of naturally occurring H

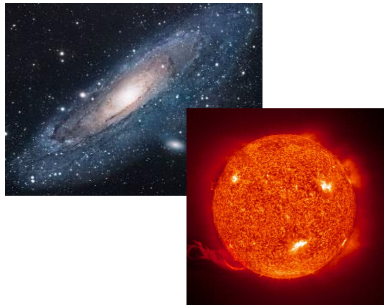
radioactive
12.3 y half life

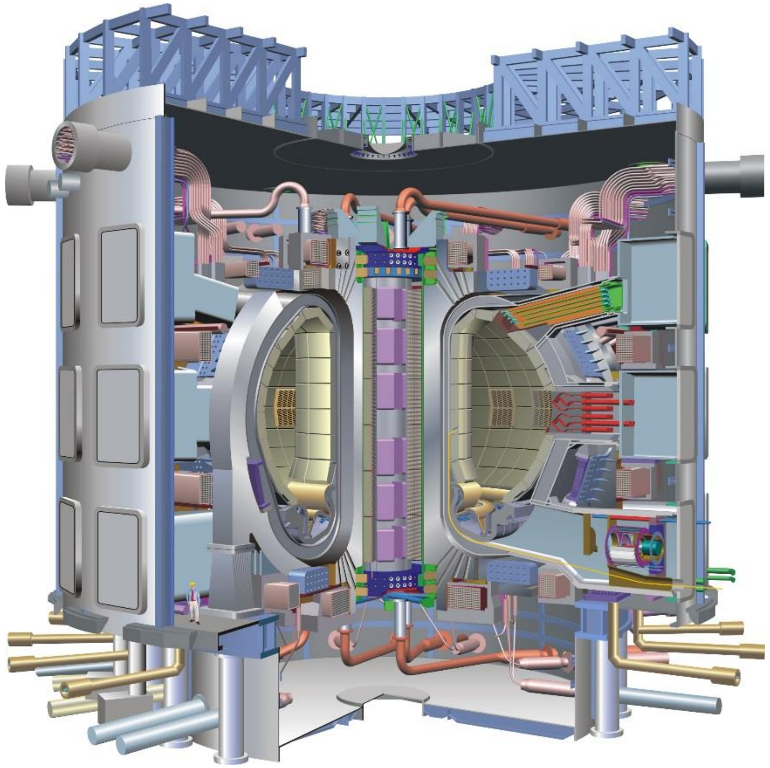
$$^{3}_{1}T \xrightarrow{\beta-} {}^{3}_{2}He + e^{-} + \bar{\upsilon}_e$$



Nuclear Fusion Energy







International Thermonuclear Experimental Reactor (ITER) Caderache, SW France

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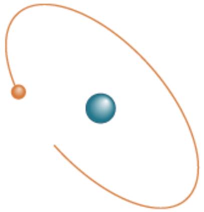
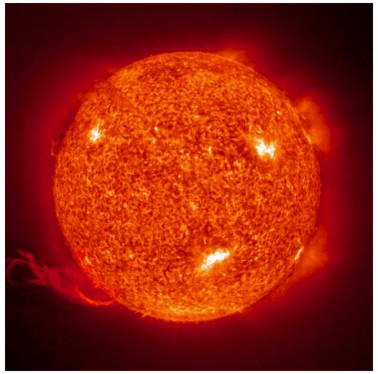
Universal Occurrence

- Consisting of the simplest, smallest and lightest of all atoms, hydrogen …



  - … was the first element formed in the Big Bang 13.8 billion years ago …

    - … and remains the commonest element in the observable Universe (75 % by mass, 90 % by number of atoms).

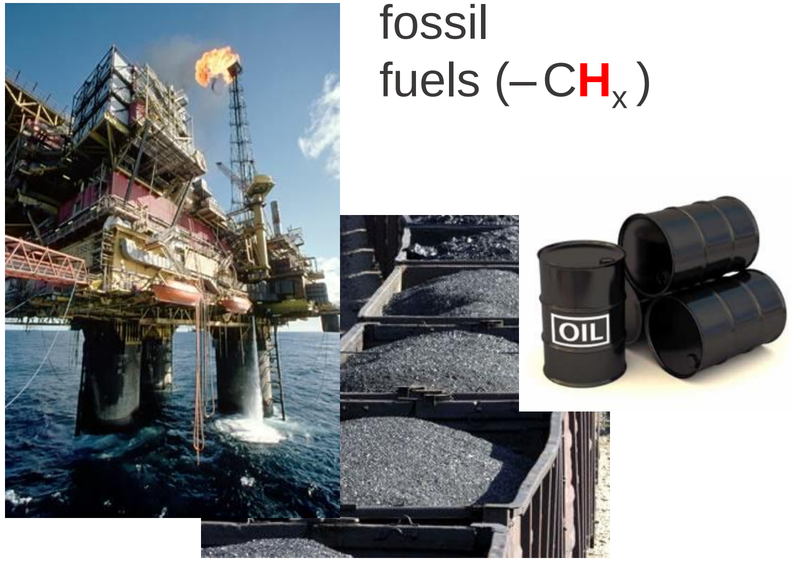


Terrestrial Occurrence

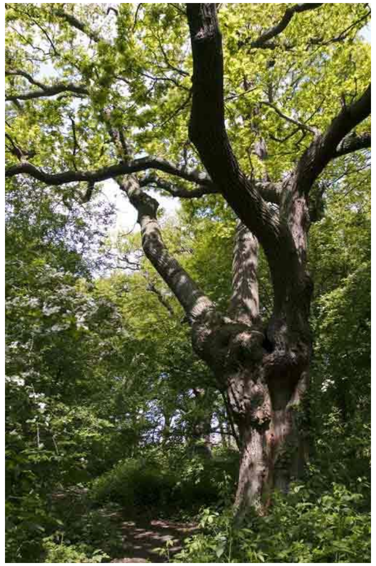
- Hydrogen is the third commonest element on the Earth's surface but almost all of it is contained in chemical compounds

water ($\mathbf{H}_2O$)

~10^{18} m^3



fossil fuels ($–C\mathbf{H}_x$)



biomass ($–C\mathbf{H}_{2x}O_x$)

~10^{15} kg (dry)

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Key Facts

- In ambient conditions free hydrogen is a colourless, odourless, tasteless, highly-flammable molecular gas (*normal*-H_2); it is an asphyxiant in very high concentrations
- Hydrogen combines with oxygen to produce water and (a lot of) energy (French: *hydrogène*, Greek: *hydro* = water, *genes* = to beget)
- In ambient conditions density of gaseous H_2 is 0.08 g L^{-1} (air is 1.2 g L^{-1})
- Normal boiling point is -253 °C (20 K)
  Density of liquid hydrogen (LH2) is ~70 g L^{-1} (water is 1,000 g L^{-1})
- Normal melting point is -259 °C (14 K)
  Density of solid hydrogen (SH2) is ~90 g L^{-1} (ice is 917 g L^{-1})
- I kg H_2 contains about the same energy as 3 kg petrol
- H_2 costs about 3x the cost of methane used to make it

- 10 kg of **water** in a filled 10 L household bucket
- 0.7 kg of **LH2** in a filled 10 L household bucket

Chemical Energy

hydrogen + oxygen → water + energy

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

- **Energy = 120 – 142 MJ kg^{-1} heat (combustion)**

  = 1.23 V electrical potential + 24 MJ kg^{-1} heat (fuel cell)

- Only material product of above reaction is water
  Compare: hydrocarbon + oxygen → water + carbon dioxide + …

- A lot of energy per unit mass of hydrogen
- Compare: 40 – 55 MJ kg^{-1} for combustion of hydrocarbons

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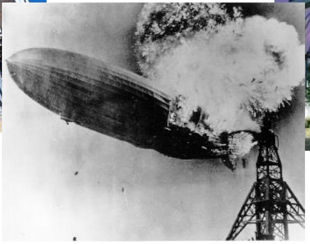
History

18th / 19th centuries CE Boyle, Cavendish, Lavoisier, de Rivaz, Grove

town gas


20th / 21st centuries CE ammonia synthesis, Hindenburg, oil processing, hydrogen bomb, space shuttle, Honda FCX Clarity, …



Literature

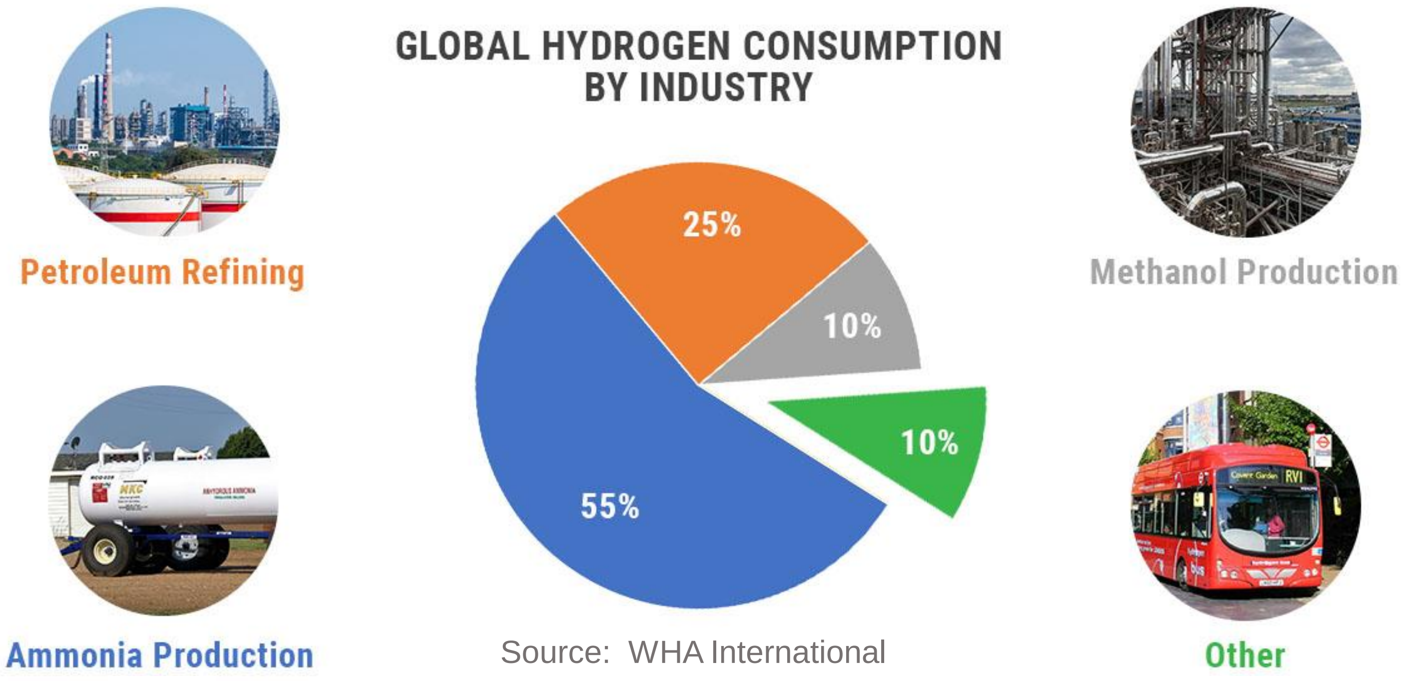
Jules Verne
The Mysterious Island (1874)

“Yes, but water decomposed into its primitive elements,“ replied Cyrus Harding, "and decomposed doubtless, by electricity, which will then have become a powerful and manageable force, …”

Hydrogen Now

Globally pa …

- H_2 demand ~90 Mt
- Cf. 2,000 Mt pa natural gas
- Currently, H_2 is produced mainly from fossil fuels, resulting in ~900 Mt CO_2 emissions
- Cf. 35,000 Mt pa



Source: WHA International

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Hydrogen Futures

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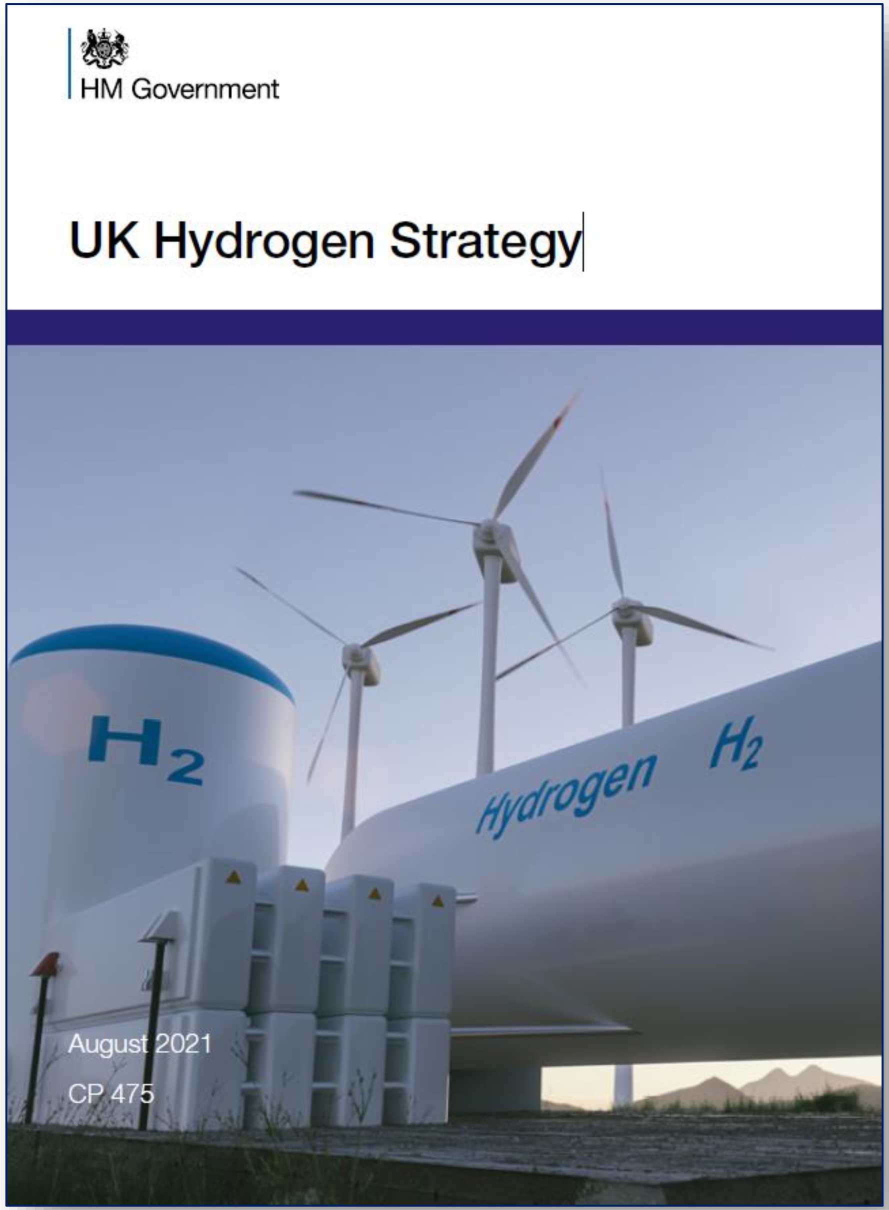
HM Government
UK Hydrogen Strategy
H2
Hydrogen
H2
August 2021
CP 475

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Government Plans

Driving the growth of low carbon hydrogen could deliver...

Support for up to 8,000 jobs by 2030, potentially unlocking up to 100,000 jobs by 2050 in a high hydrogen net zero scenario	Over £4bn of private investment in the period up to 2030	Savings of 41MtCO_2e between 2023 and 2032, or 9% of 2018 UK emissions

Policy impacts

- Aiming for 5GW Hydrogen production capacity by 2030 in partnership with industry.
- Lower carbon heating and cooking with no change in experience for domestic consumers through hydrogen blends and reducing the emissions of the gas used by up to 7%.

Target Milestones

2021	Publish our Hydrogen Strategy and begin consultation on Government's preferred business models for hydrogen
2022	Finalise hydrogen business models
2023	Work with industry to complete testing necessary to allow up to 20% blending of hydrogen into the gas distribution grid for all homes on the gas grid
2023	By 2023 we will support industry to begin hydrogen heating trials in a local neighbourhood
2025	We hope to see 1 GW of Hydrogen production capacity
2025	Will support industry to begin a large village hydrogen heating trial, and set out plans for a possible pilot hydrogen town before the end of the decade

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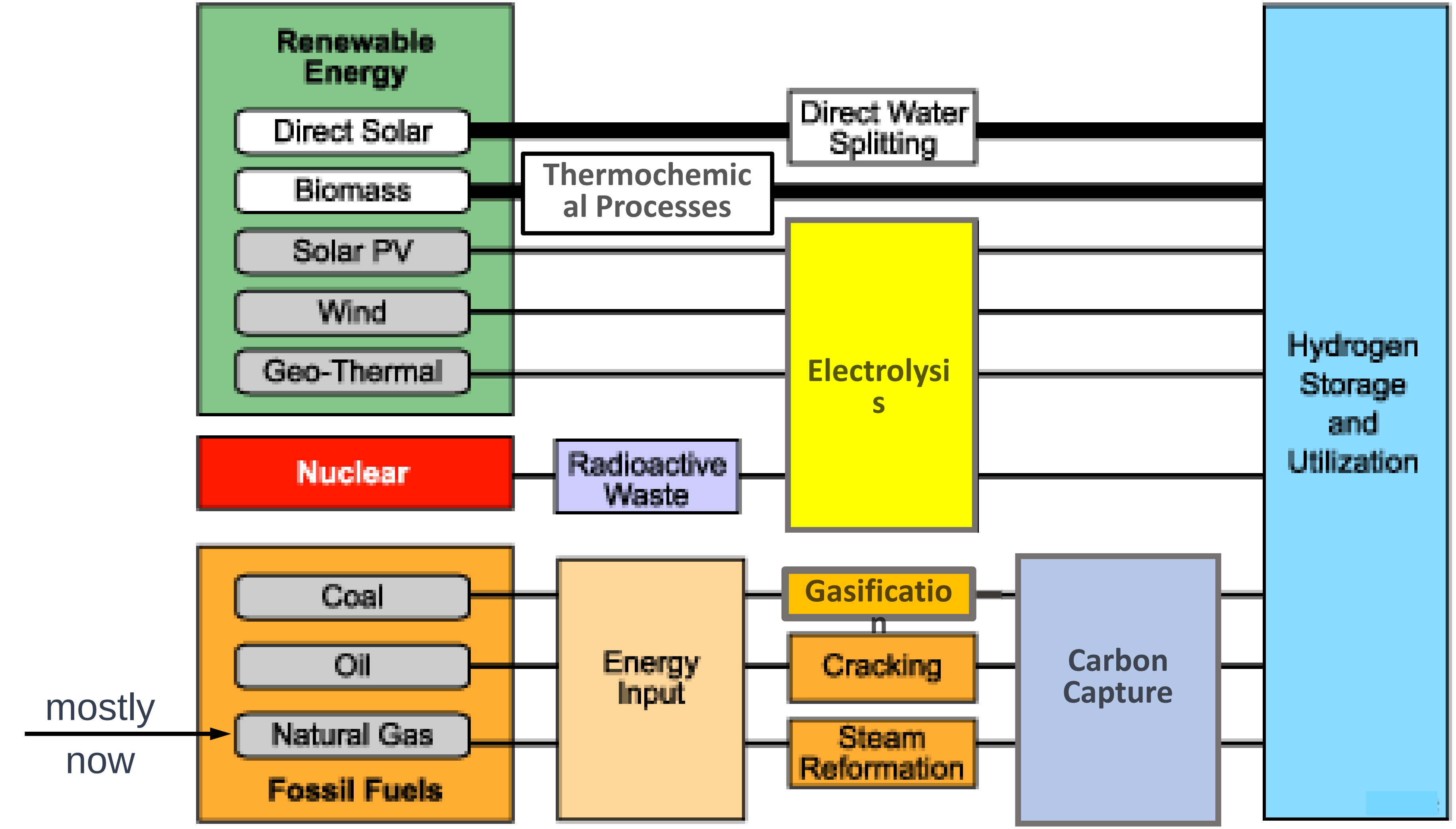
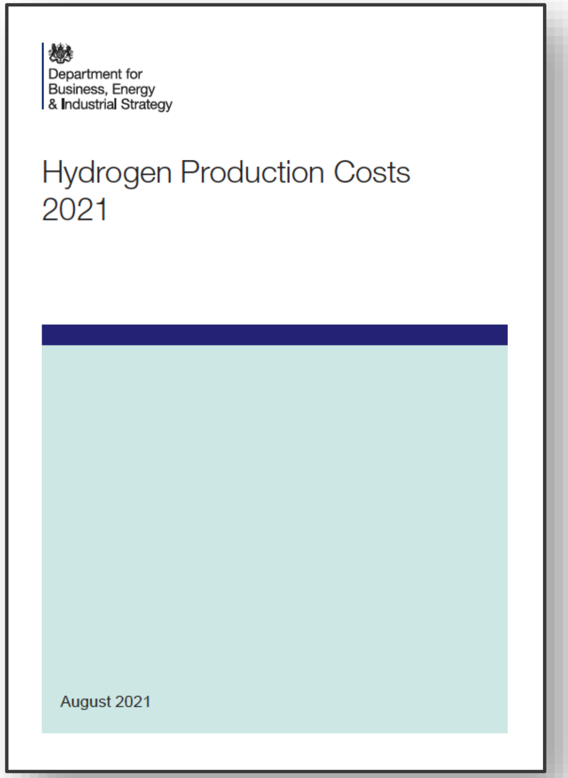
Hydrogen Production



Source: (After) Florida Solar Energy Center



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Hydrogen Colours

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

Source: Global Energy Infrastructure

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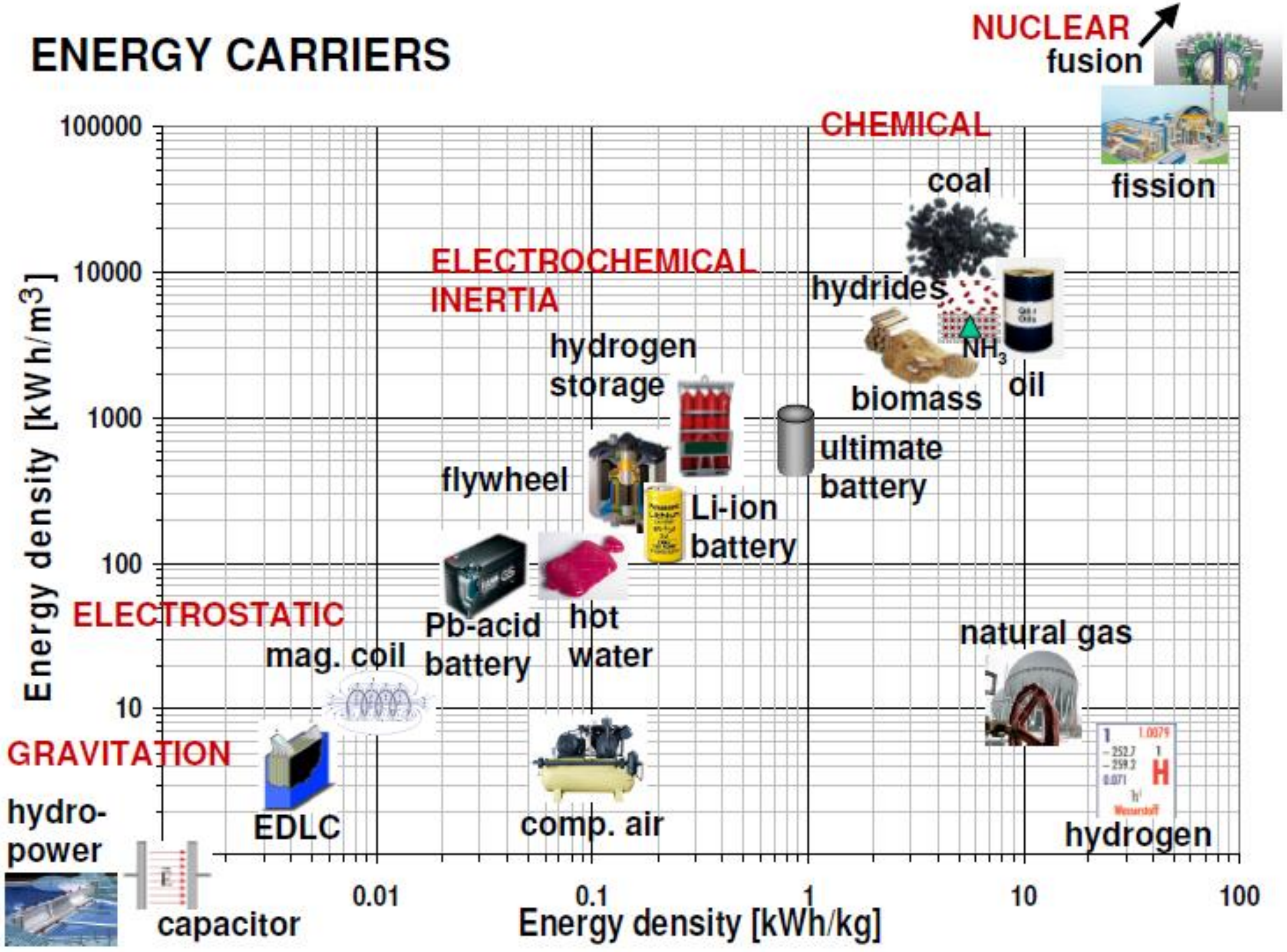
Storage and Distribution



Source: Züttel, et al, 2010

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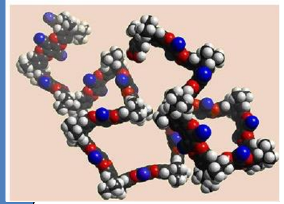
Storage and Distribution

Physical

molecular or di-hydrogen, H_2

Liquid and / or solid
Compressed gas
Containment in porous solids



Chemical

atomic, ionic, covalent hydrogen

solid / liquid / gas or vapour carriers

H^0

$H^{\pm d}$

H-X

Pt

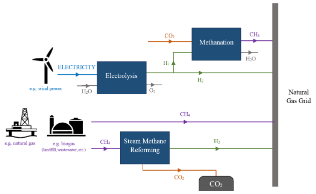
MgH_2

$LiBH_4$

NH_3

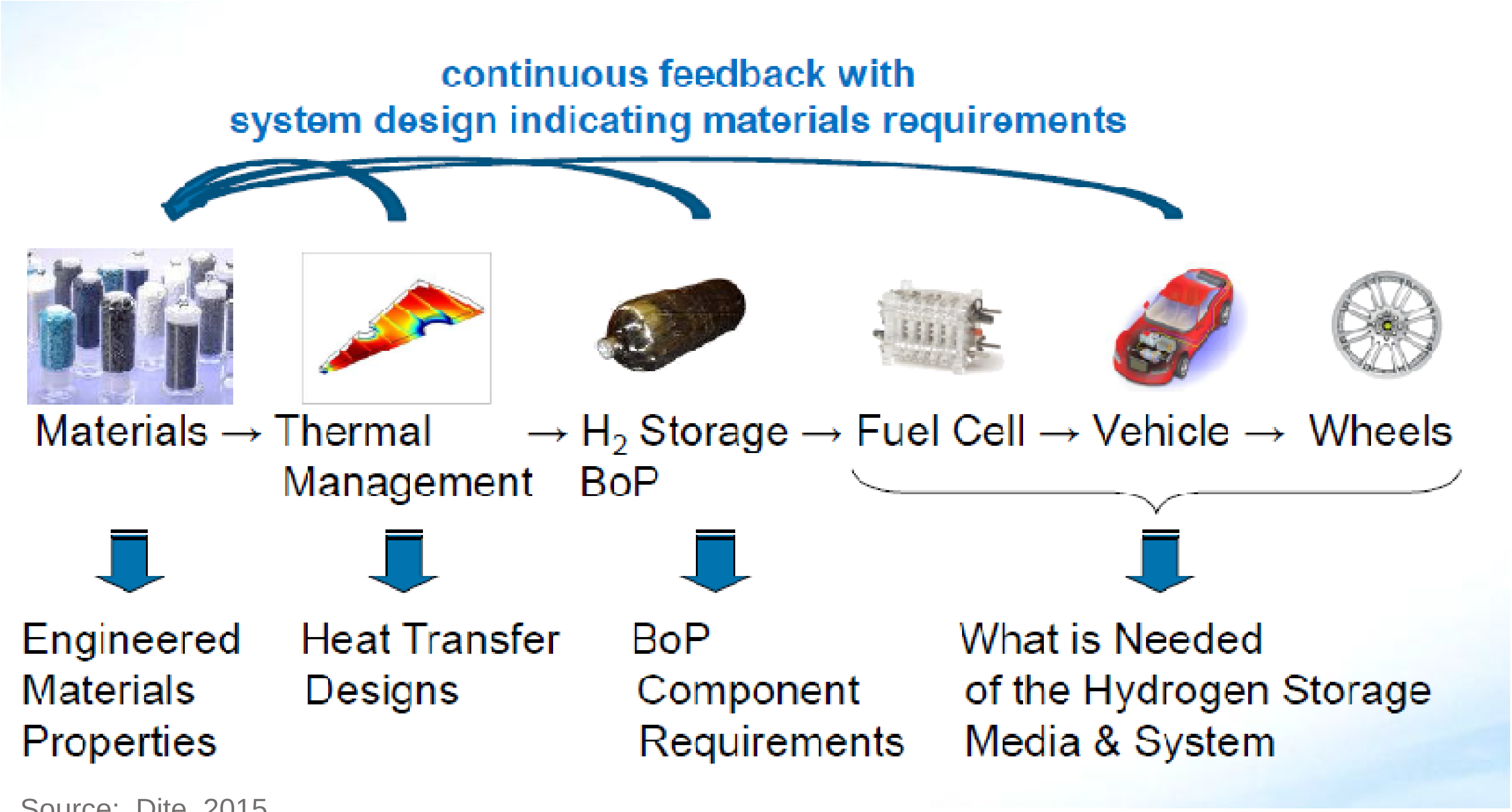
Also …

Subterranean / submarine geological storage



Blending

Storage and Distribution



Source: Dite, 2015

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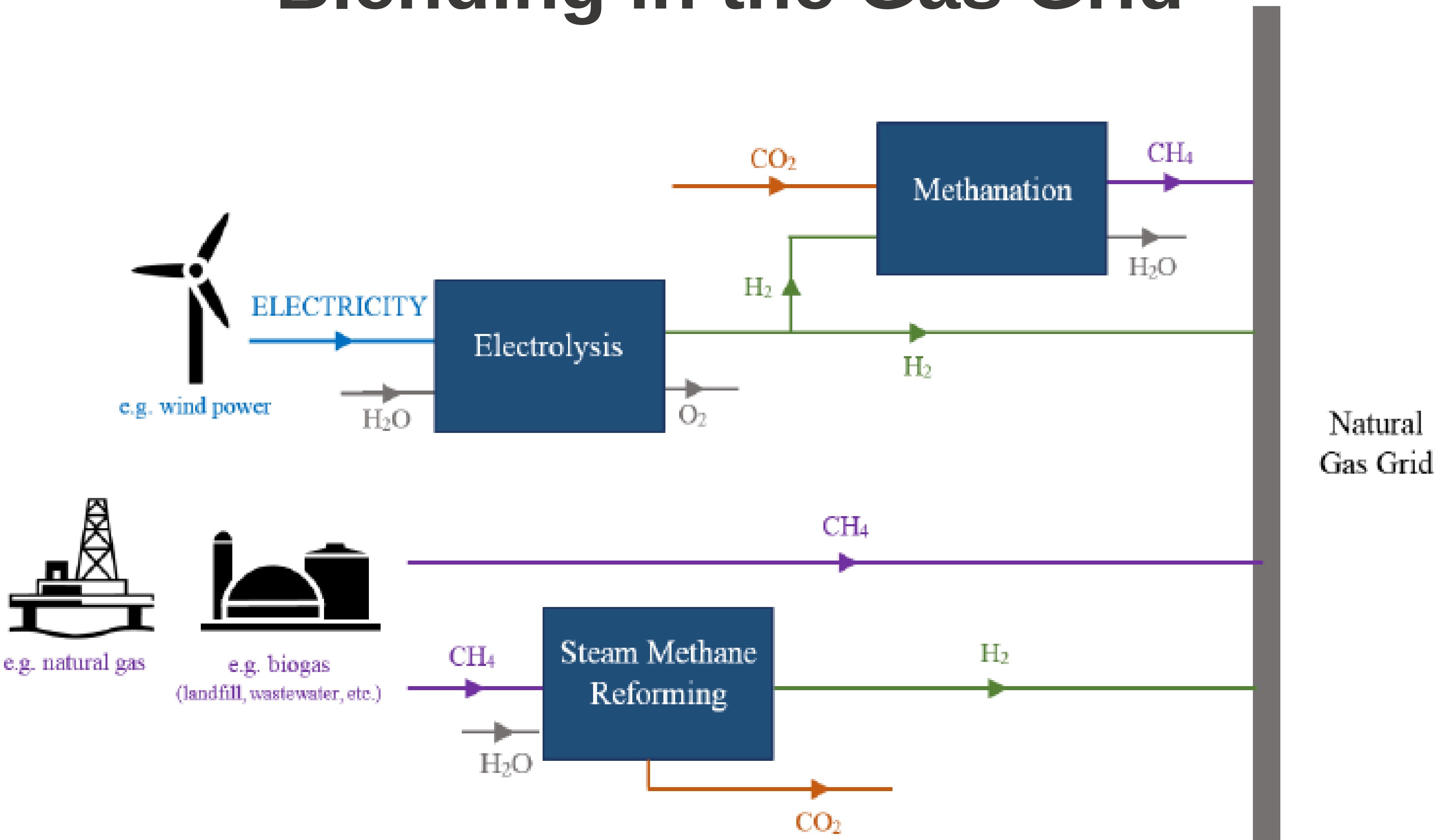
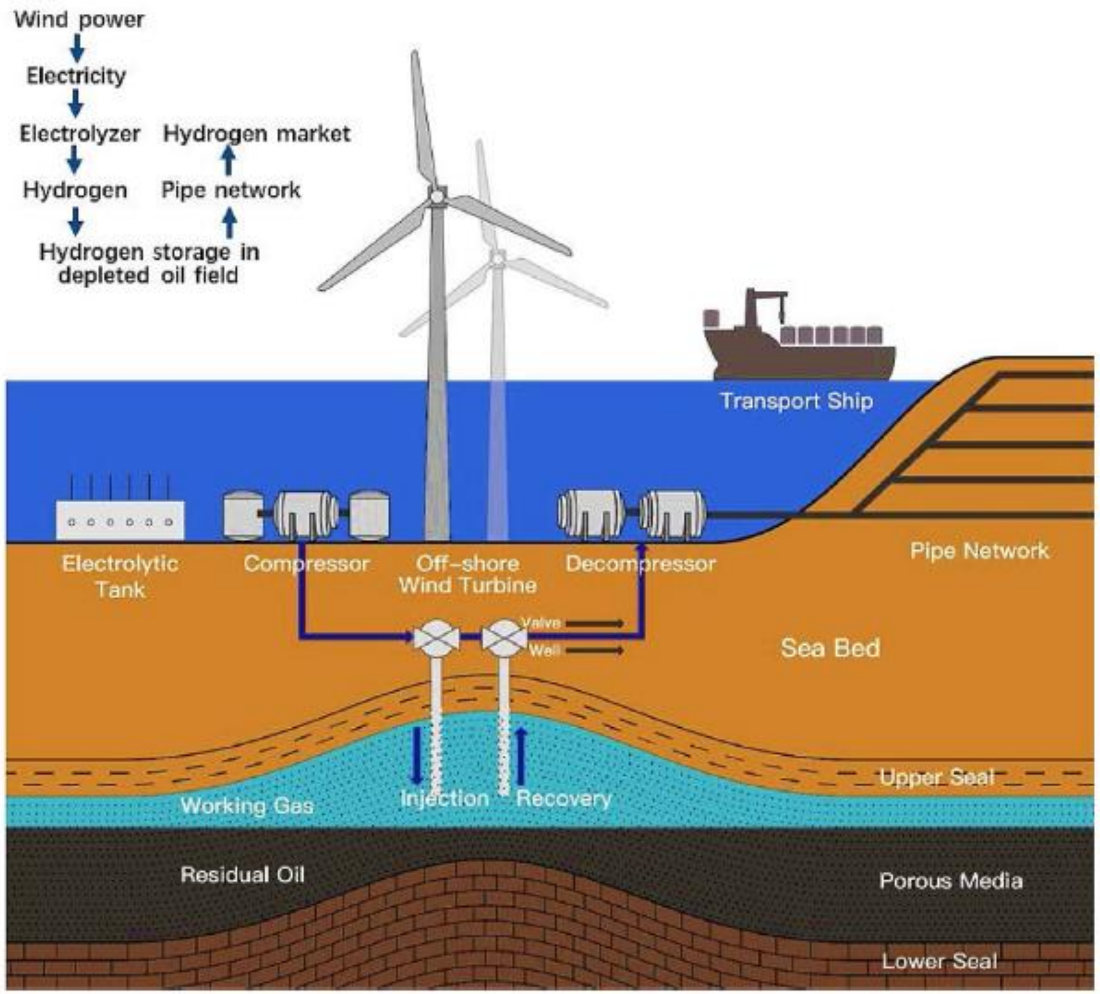
Blending in the Gas Grid



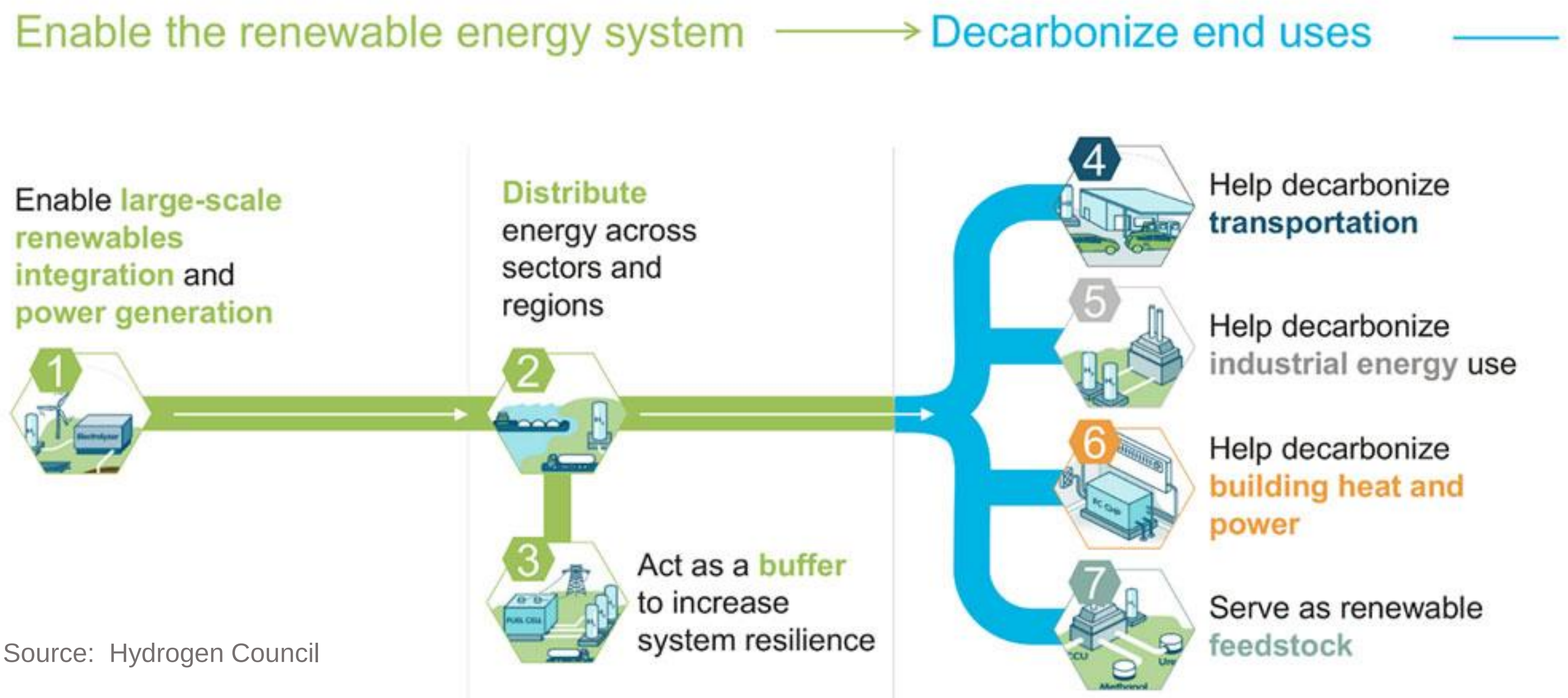
Source: (After) Quarton and Samsatli, 2018

Geological Storage



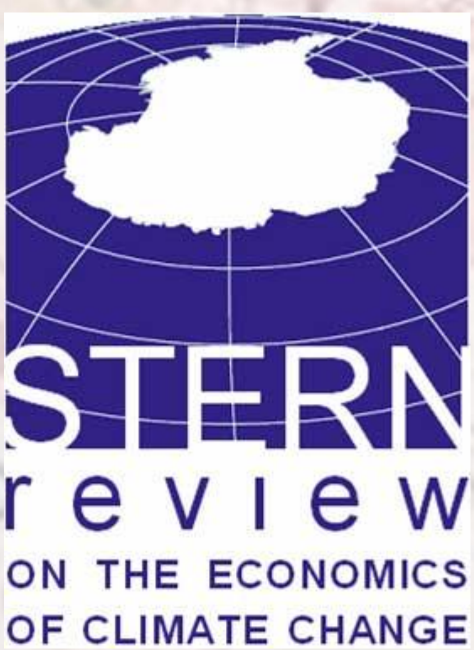
Source: Song, et al., 2021

Hydrogen Uses



Source: Hydrogen Council

Economics



- Energy security means the provision of affordable energy to society on demand.
- Hydrogen and hydrogen energy systems are currently expensive.
- But can we afford NOT to use hydrogen and other sustainable energy technologies?
- The Stern Review (2006) claims that investment of 1 % of GDP pa to manage climate change should be set against a likely 20 % reduction in GDP pa if we do nothing (UK GDP pa ~£2T).

Safety

- Hydrogen release will disperse quicky in the open but will be an issue in confined spaces
- Hydrogen has wide flammable range 4 % - 75 %
- Range for natural gas is 4 % - 15 %
- Range for gasoline is 1.4 % - 5.6 %
- Very low ignition energy
- Potential for detonation
- Very hot, nearly invisible flame
- Evidence of spontaneous ignition from venting
- Chemicals industry has been using hydrogen safely on a large scale for many years.
- Regulations, codes and and standards will need to be adapted to new uses

People

- Awareness of energy and climate change is widespread
- But not so with hydrogen which to many – even policymakers – has negative associations, e. g., with the H-bomb, the Hindenburg and “danger”
- Hydrogen is better known in some areas (e. g., Teeside, S Wales) where there are visible and well-known hydrogen activities
- Need for clear and accessible information on hydrogen energy, and understanding by and reassurance of both the public and policymakers
- Need education and training to support new technologies

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The Ten Point Plan for a Green Industrial Revolution

The Roles of Hydrogen

✓ **Point 1**
Advancing Offshore Wind

Point 2
Driving the Growth of Low Carbon Hydrogen

✓ **Point 3**
Delivering New and Advanced Nuclear Power

✓ **Point 4**
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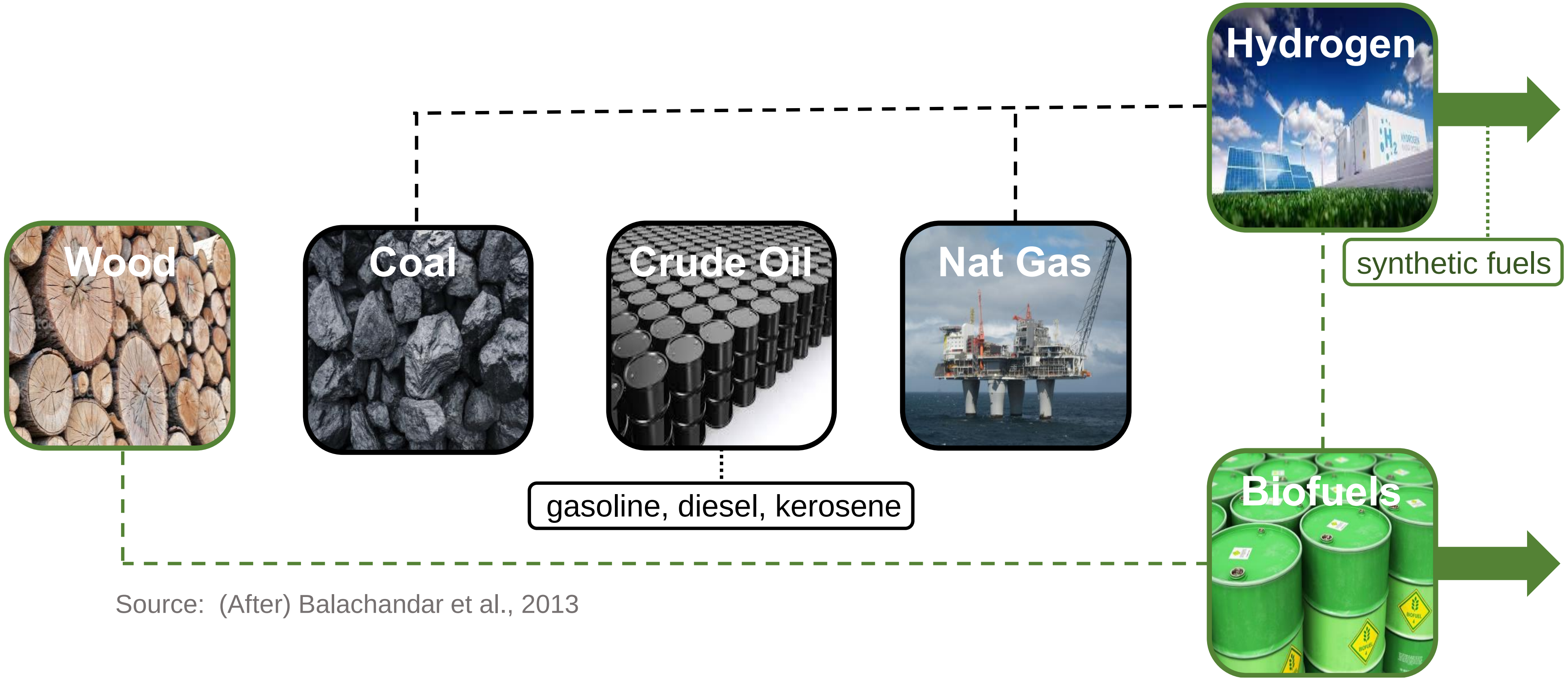
Evolution of Chemical Fuels



Source: (After) Balachandar et al., 2013

Time, phase (solid, liquid, gas), H-C ratio

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Penultimate Word

nature

19 February 2004 Volume 427 Issue no 6976

Leapfrogging the power grid

The desire to mitigate climate change, and opportunities to empower consumers in the developed and developing worlds, all point towards a need for less-centralized energy generation. It's time to further boost hydrogen research.

Hydrogen as a widely used energy carrier is essential and inevitable. Scientists, technologists, governments and philanthropists should do much more to hasten its arrival.

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Thank You