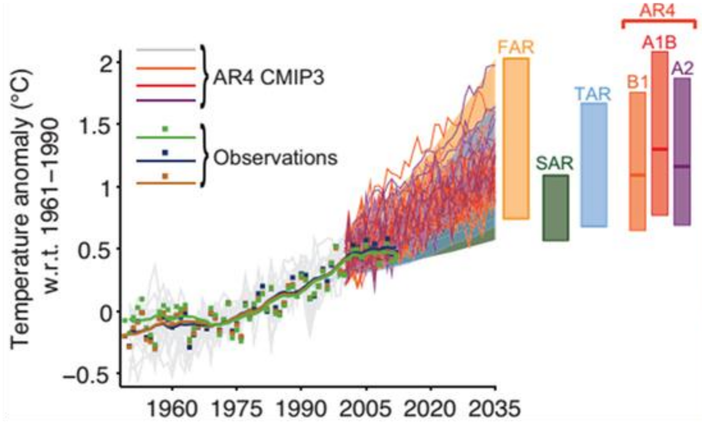
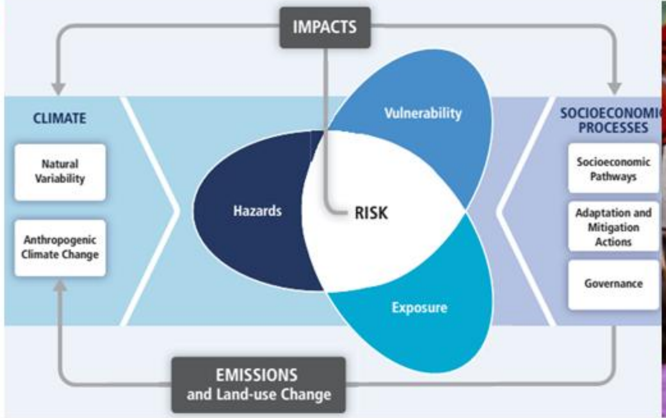


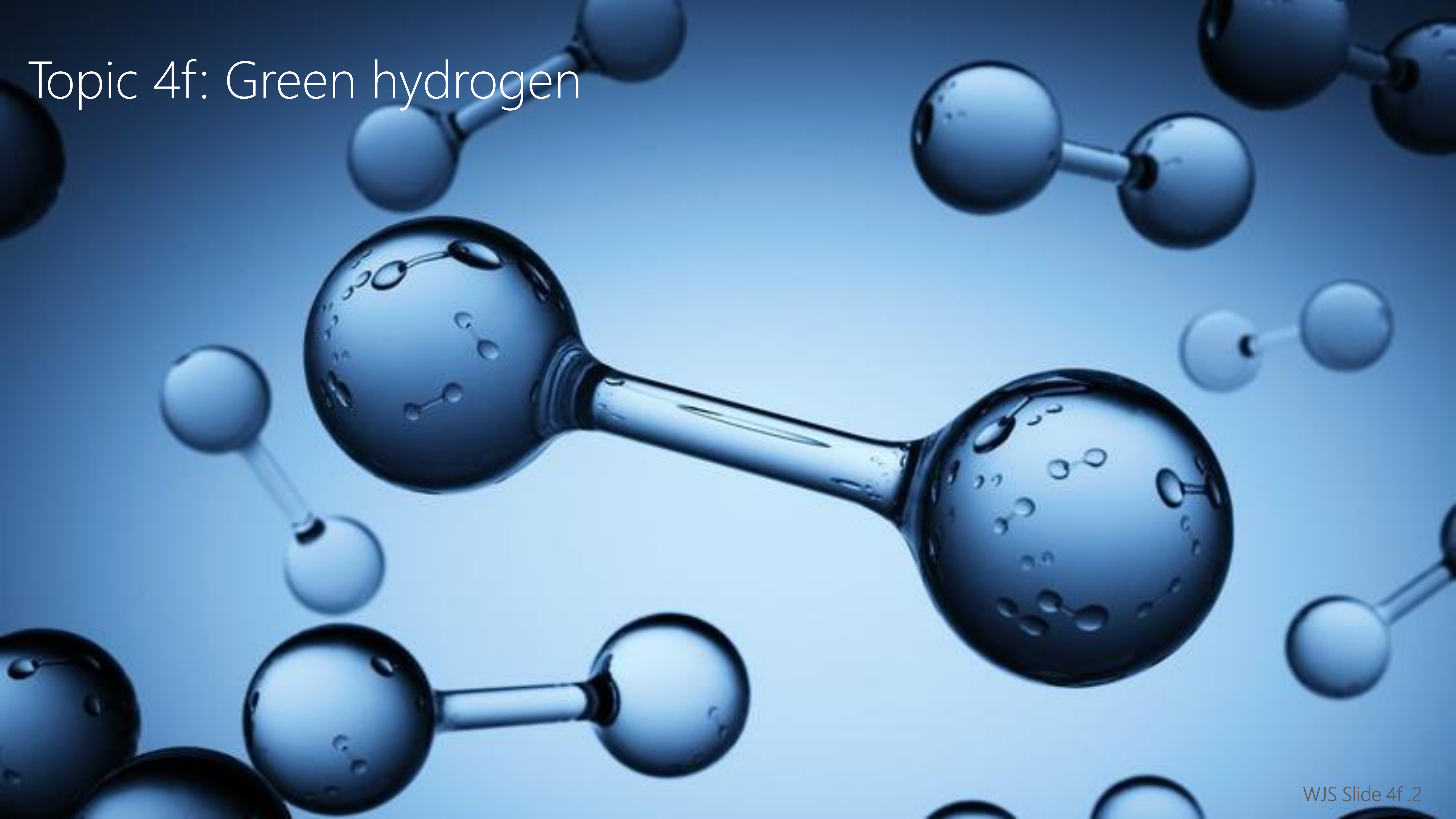


Energy Systems & Climate Change





Topic 4f: Green hydrogen



Some characteristics of hydrogen

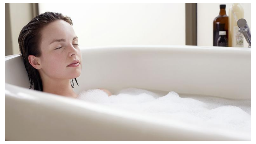
Most abundant element in the universe

Very high energy per unit mass (~3 x oil, ~2 x natural gas)

Produces zero CO_2 when burned – only warm water

Most abundant element in the universe ....but it's always stuck to something else (e.g. C, or O)

Very high energy per unit mass (~3 x oil, ~2 x natural gas) ....but very low per unit volume (about 1/3,000 of oil)



Produces zero CO_2 when burned – only warm water ....but do you really want to burn it?

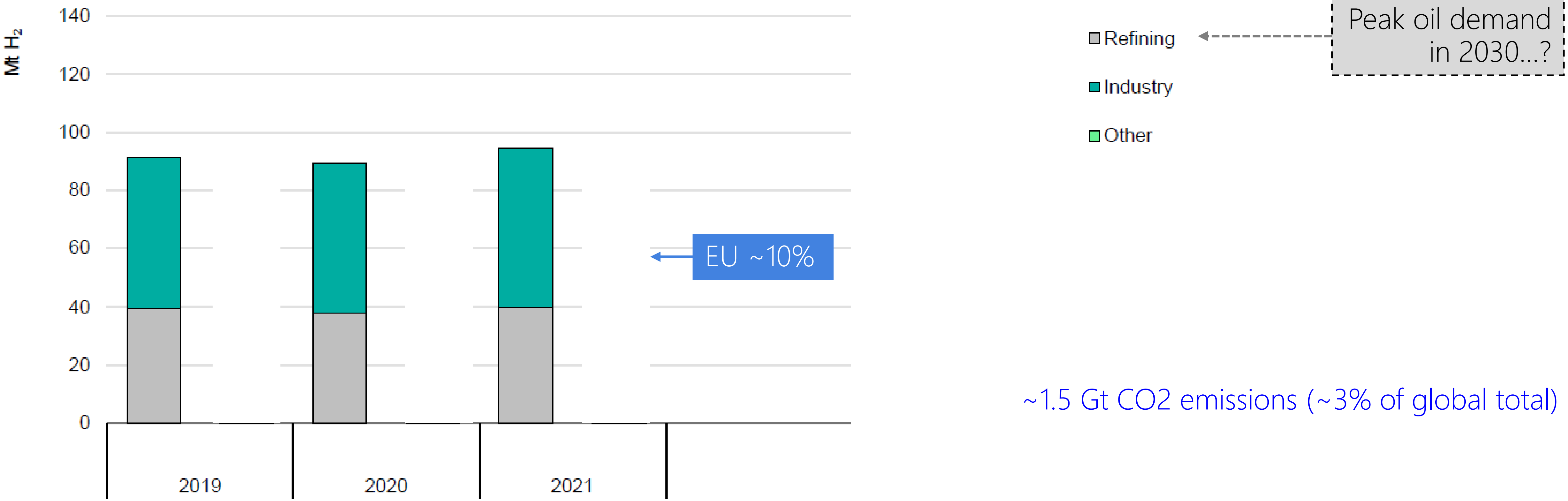
Fire: high flammability range, low ignition energy, invisible flame

What is it used for, currently?

~100 Mt used annually

~60% Industry and ~40% Refining

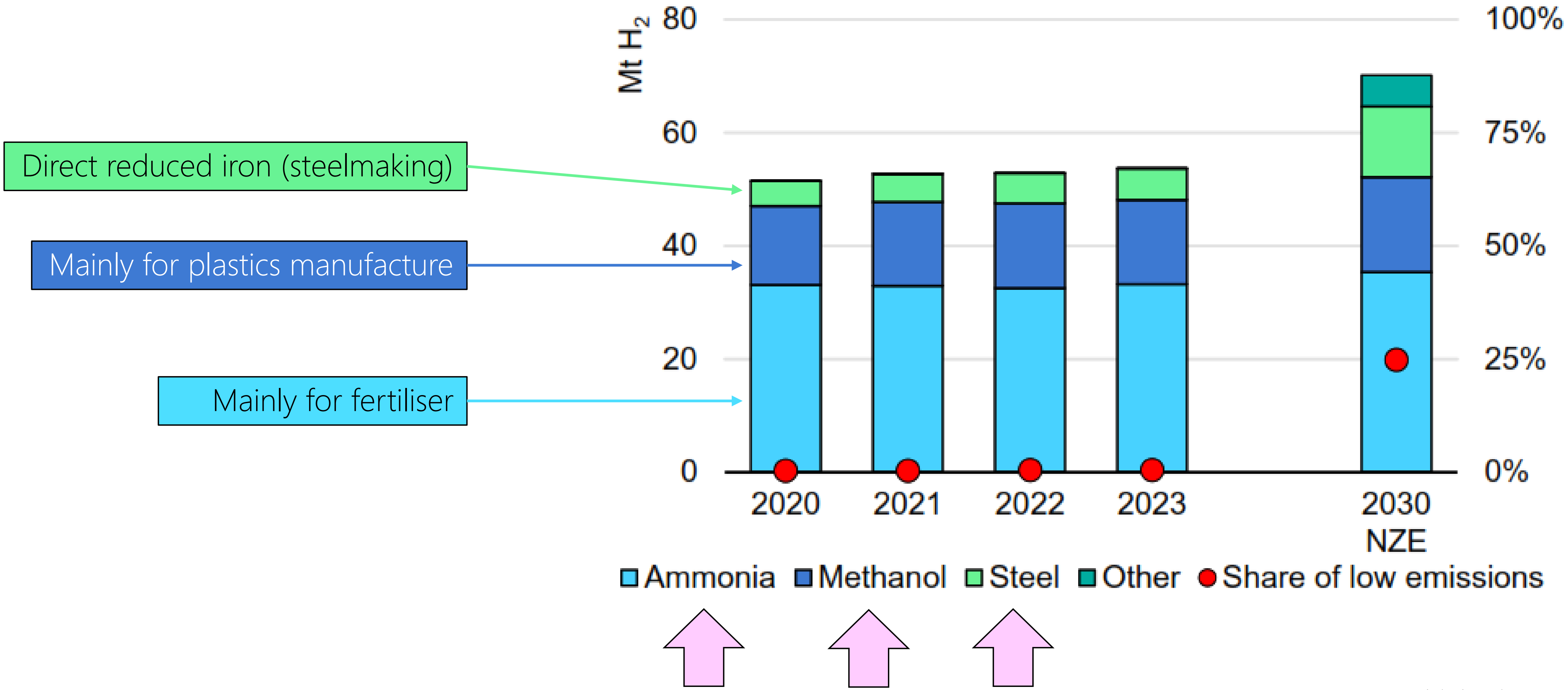
Hydrogen demand by sector and by region in the Stated Policies and Announced Pledges scenarios, 2019-2030



~1.5 Gt CO2 emissions (~3% of global total)

Notes: Mt H_2 = million tonnes of hydrogen; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. *Other* includes transport, buildings, power generation sectors and production of hydrogen-derived fuels and hydrogen blending.

Source: IEA (2022). Global Hydrogen Review 2022



Source: IEA (2024). Global Hydrogen Review 2024

How is it made, currently?

Topic 4f: green hydrogen

From fossil fuels

$$CH_y + (+ H_2O) \rightarrow H_2 (+ CO_2 + CO + C)$$

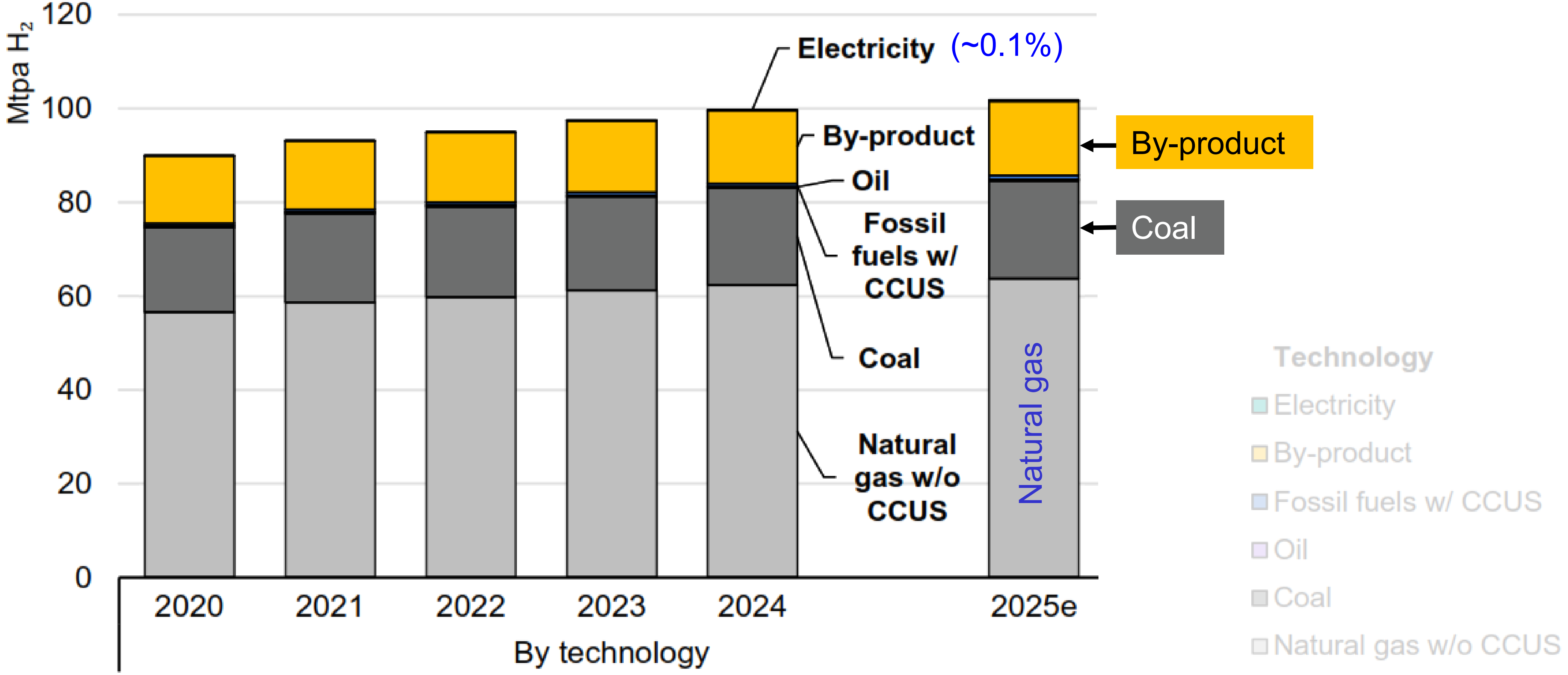
reforming / gasification / pyrolysis

From water

$$H_2O + \rightarrow H_2 + O_2$$

electrolysis

Figure 3.1 Hydrogen production by technology and by region, 2020-2025e



Source: IEA (2025). Global Hydrogen Review 2025

Steam-methane reforming (uses natural gas)

Two principal reactions:

$CH_4 + H_2O + \text{heat} \rightarrow CO + 3H_2$ (Steam-methane reforming)

$CO + H_2O \rightarrow CO_2 + H_2 + \text{heat}$ (Water-gas shift)

Overall reaction: $CH_4 + 2H_2O + \text{heat} \rightarrow 4H_2 + CO_2$

minimum energy requirement: $41.23\ \text{kJ.mol}^{-1}$ of H_2 = $20.5\ \text{MJ.kg}^{-1}$ of H_2 (+ 100 MJ from CH_4)

(LHV of H_2 = $120\ \text{MJ.kg}^{-1}$)

CO_2: at best $\frac{44}{8} = 5.5 \frac{\text{kg}_{CO2}}{\text{kg}_{H2}}$ $\left(\text{In practice}, \approx 9^{*} \frac{\text{kg}_{CO2}}{\text{kg}_{H2}}\right)$ 10-12^

H_2O: at best $\frac{36}{8} = 4.5 \frac{\text{kg}_{H2O}}{\text{kg}_{H2}}$ $\left(\text{In practice}, \approx 16-40^{**} \frac{\text{kg}_{H2O}}{\text{kg}_{H2}}\right)$ 16-40

**Source: IEA (2024). Global Hydrogen Review 2024, p89 ^Including upstream emissions *Direct emissions, Source: IEA (2024). Global Hydrogen Review 2024, pp208-209

Topic 4f: green hydrogen

Coal gasification

Two principal reactions: $3C + O_2 + H_2O + \text{heat} \rightarrow 3CO + H_2$ (Coal gasification)

$3CO + 3H_2O \rightarrow 3CO_2 + 3H_2 + \text{heat}$ (Water-gas shift)

Overall reaction: $3C + O_2 + 4H_2O + \text{heat} \rightarrow 4H_2 + 3CO_2$

CO_2: at best $\quad \dfrac{3 \times 44}{8} = 16.5 \dfrac{\text{kg}_{\text{CO2}}}{\text{kg}_{\text{H2}}} \quad \left(\text{In practice}, \approx 21^{*} \dfrac{\text{kg}_{\text{CO2}}}{\text{kg}_{\text{H2}}}\right)$ 22-26[1]

H_2O: at best $\quad \dfrac{4 \times 18}{8} = 9 \dfrac{\text{kg}_{\text{H2O}}}{\text{kg}_{\text{H2}}} \quad \left(\text{In practice}, \approx 26 - 46^{**} \dfrac{\text{kg}_{\text{H2O}}}{\text{kg}_{\text{H2}}}\right)$ 26-46

*Source: IEA (2024). Global Hydrogen Review 2024, pp208-209. [1]Including upstream **Source: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review15/sa039_elgowainy_2015_o.pdf

Water electrolysis

Overall reaction: $2H_2O_{(l)}$ + **electricity** $\rightarrow 2H_{2\,(g)} + O_{2\,(g)}$

minimum energy requirement: $h_f^o =$ 2(-285.83) kJ.mol^{-1} $\rightarrow$ 2(0) + 0 kJ.mol^{-1}

571.66 kJ $\rightarrow$ 4.032 g_{H2} = 141.79 MJ.kg^{-1} (= HHV H_2)

141.79 MJ.kg^{-1} of H_2 = 39.39 kWh$_e$ .kg^{-1} of H_2

(electrolyser efficiency ranges 60% – 90%, implying 44 – 66 kWh$_e$ in practice)

CO_2: at best $0\,\dfrac{\mathrm{kg_{CO2}}}{\mathrm{kg_{H2}}}$ $\left(\text{In practice,} \approx 0\ -40^{*}\dfrac{\mathrm{kg_{CO2}}}{\mathrm{kg_{H2}}}\right)$ 0-40

H_2O: at best $\dfrac{36}{4} = 9\,\dfrac{\mathrm{kg_{H2O}}}{\mathrm{kg_{H2}}}$ $\left(\text{In practice,} \approx 40 - 70^{**}\dfrac{\mathrm{kg_{H2O}}}{\mathrm{kg_{H2}}}\right)$ 40-70

Source: IEA (2024). Global Hydrogen Review 2024, *pp208-209.*

***Source: IEA (2024).* Global Hydrogen Review 2024, *p89*

Topic 4f: green hydrogen

From fossil fuels

Blue hydrogen

Technology: Natural gas reforming + CCUS gasification +CCUS
Energy source: Natural gas, coal
GHG emissions: Low

Turquoise hydrogen

Technology: Pyrolysis
Energy source: Natural gas
GHG emissions: Solid carbon (by-product)

From water

Yellow hydrogen

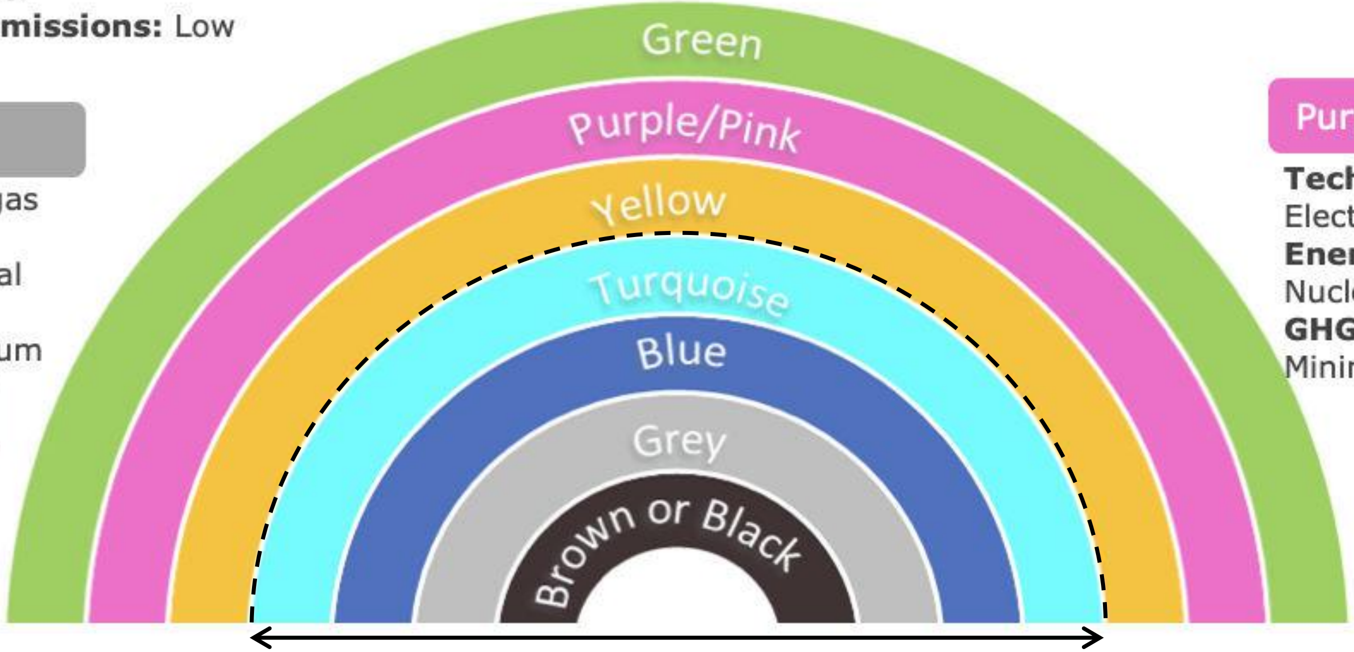
Technology: Electrolysis
Energy source: Mixed-origin grid energy
GHG emissions: Medium

Grey hydrogen

Technology: Natural gas reforming
Energy source: Natural gas
GHG emissions: Medium

Brown/Black hydrogen

Technology: Gasification
Energy source: Black/ brown coal (lignite)
GHG emissions: High



From fossil fuels

Purple/Pink hydrogen

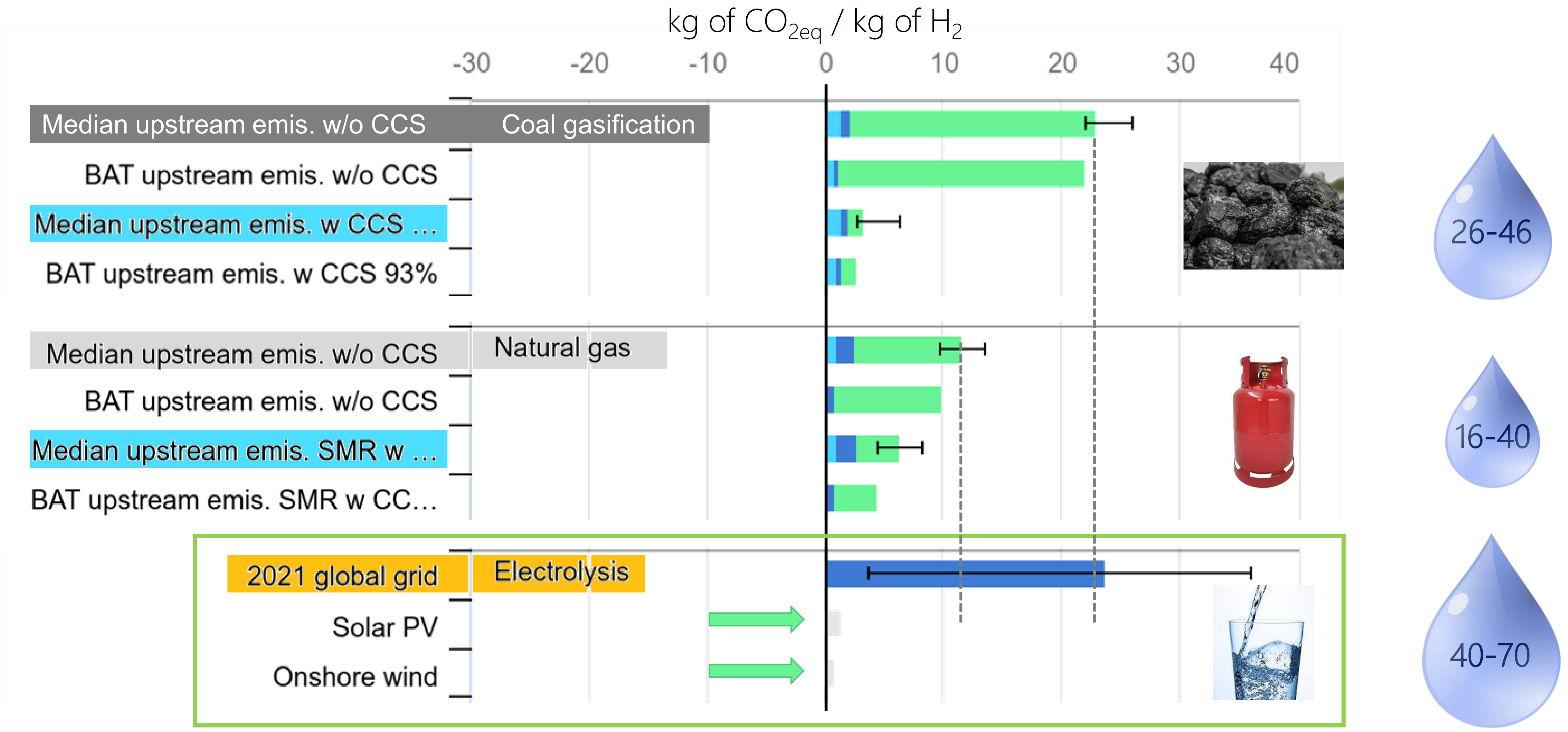
Technology: Electrolysis
Energy source: Nuclear
GHG emissions: Minimal

Green hydrogen

Technology: Electrolysis
Energy source: Wind, Solar, Hydro, Geothermal
GHG emissions: Minimal

Source: https://www.tecnicasreunidas.es/articulo/hydrogen-present-and-future-part-2/

Comparing the CO_2-intensity of hydrogen production routes



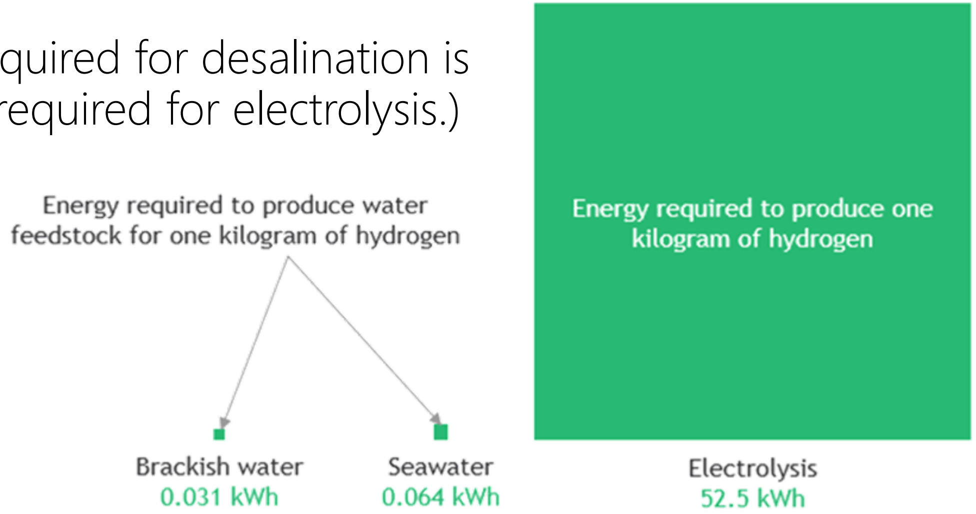
Source: Adapted from https://www.iea.org/data-and-statistics/charts/comparison-of-the-emissions-intensity-of-different-hydrogen-production-routes-2021

Can we use seawater for electrolysis?

Yes, in principle (*e.g.* see link below).

Seawater desalination is a proven technology, with relatively low costs and energy consumption.

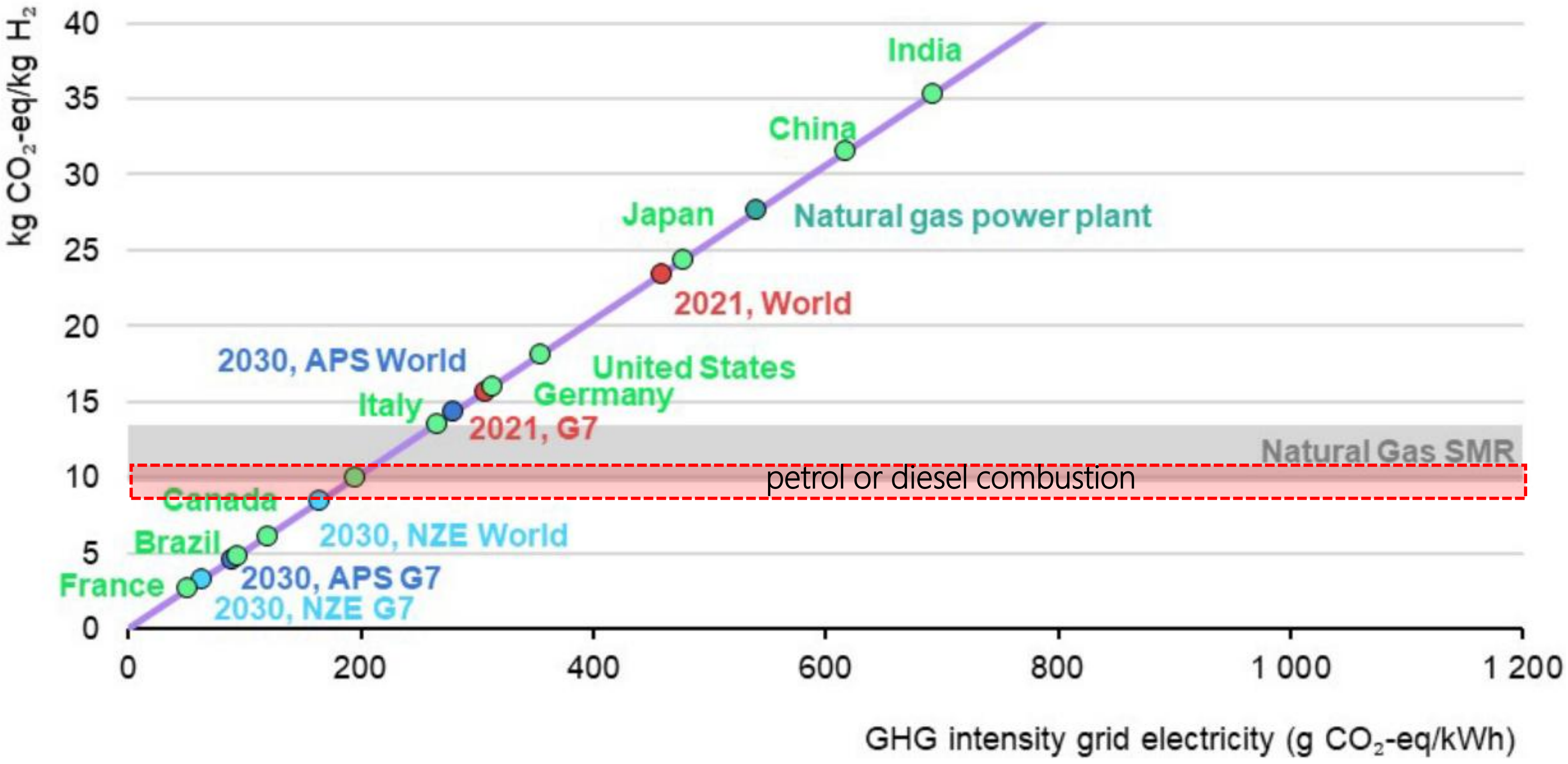
(The energy required for desalination is ~0.2% of that required for electrolysis.)



In practice, it probably makes more sense to source pure water from a dedicated seawater purification plant.

https://www.weforum.org/stories/2023/09/seawater-electrolysis-a-hydrogen-revolution-or-technological-dead-end-here-are-the-numbers/

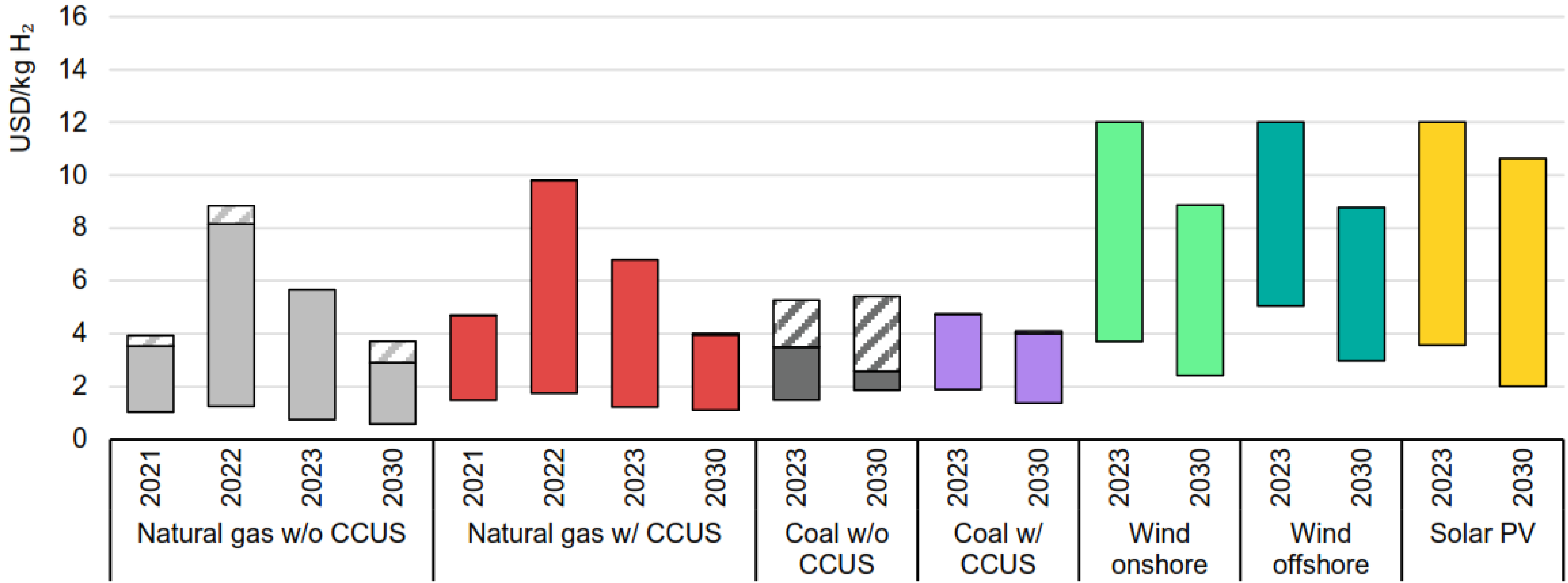
Impact of the CO_2-intensity of grid electricity on hydrogen production by electrolysis



Source: IEA (2023). Towards hydrogen definitions based on their emissions intensity, *p50.*

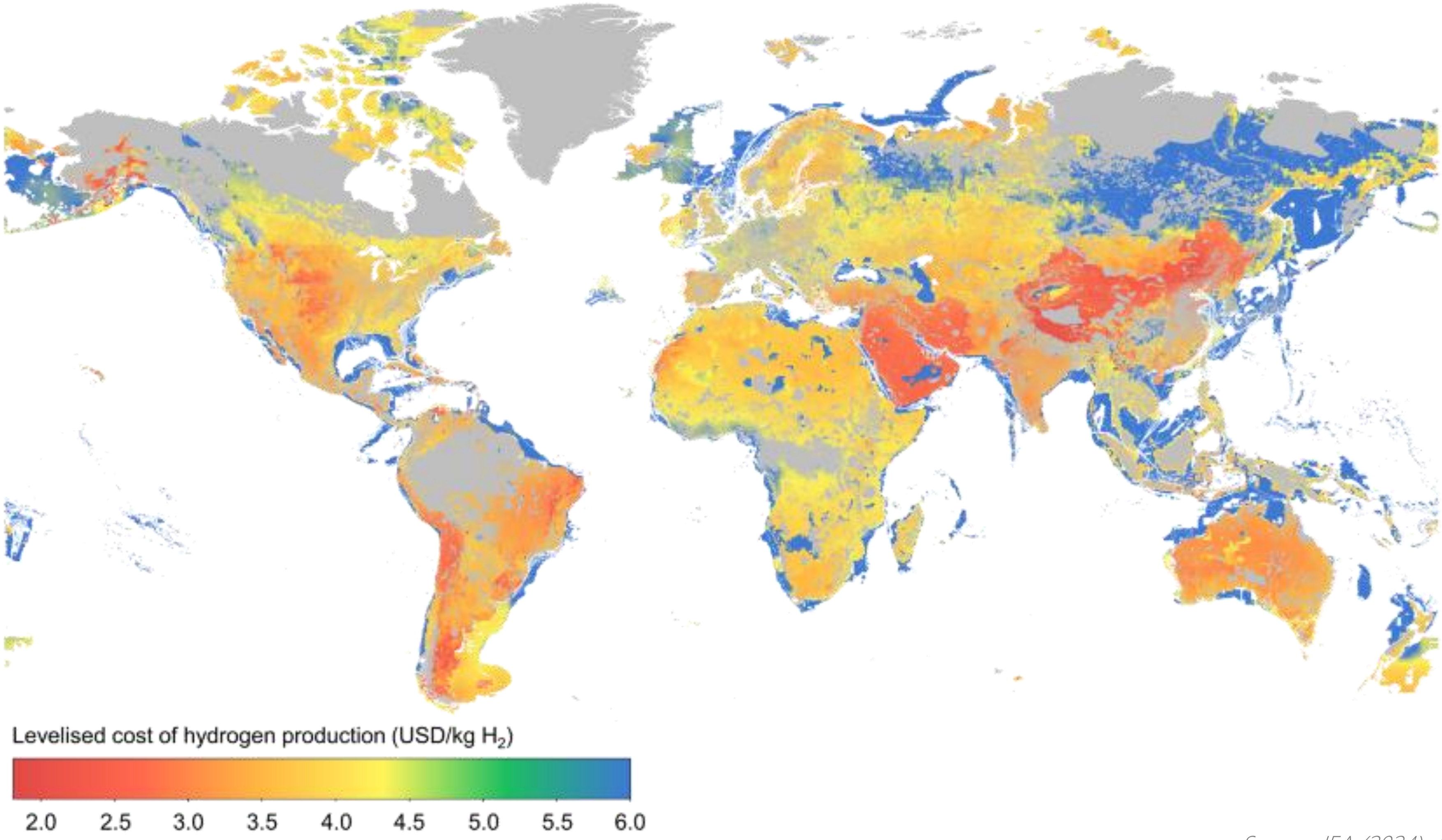
How much does it cost?

Figure 3.11 Hydrogen production cost by pathway, 2023, and in the Net Zero Emissions by 2050 Scenario, 2030



Source: IEA (2024). Global Hydrogen Review 2024

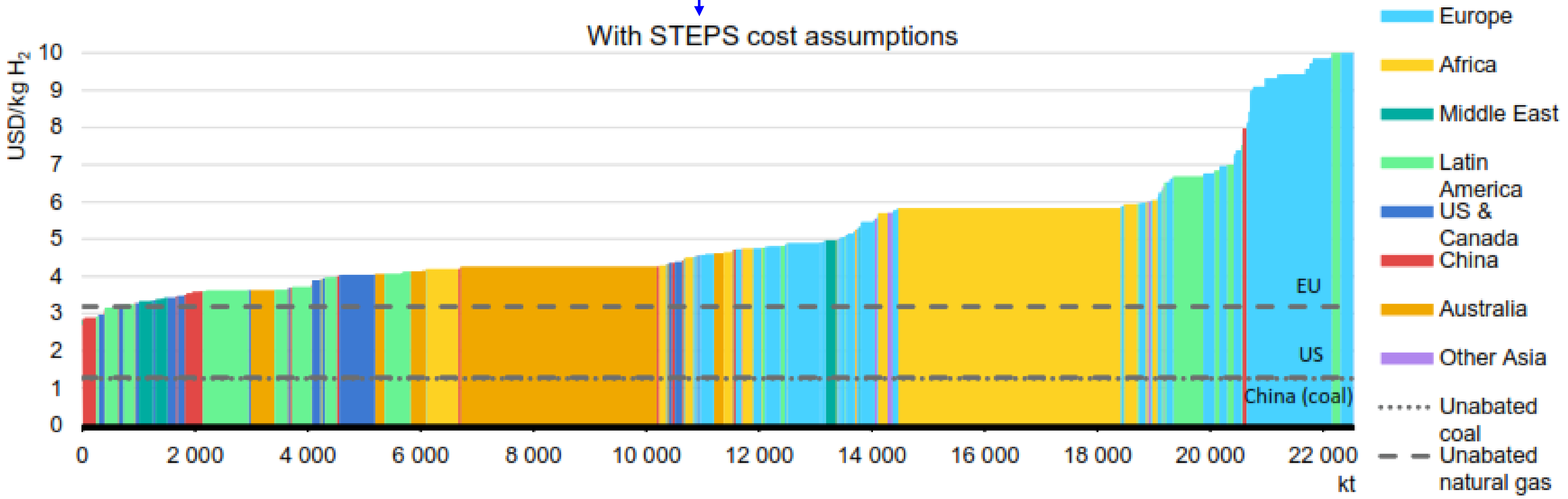
Figure 3.13 Hydrogen production cost from hybrid solar PV and onshore wind, and from offshore wind in the Net Zero Emissions by 2050 Scenario, 2030



Source: IEA (2024). Global Hydrogen Review 2024

Figure 3.12 Production cost curve of solar PV- and wind-based hydrogen production from announced projects, and production cost from unabated fossil fuels,

IEA "stated policies" scenario



Source: IEA (2024). Global Hydrogen Review 2024

Why the new (again) interest?

Why green hydrogen?

Replace grey H_2 in existing applications

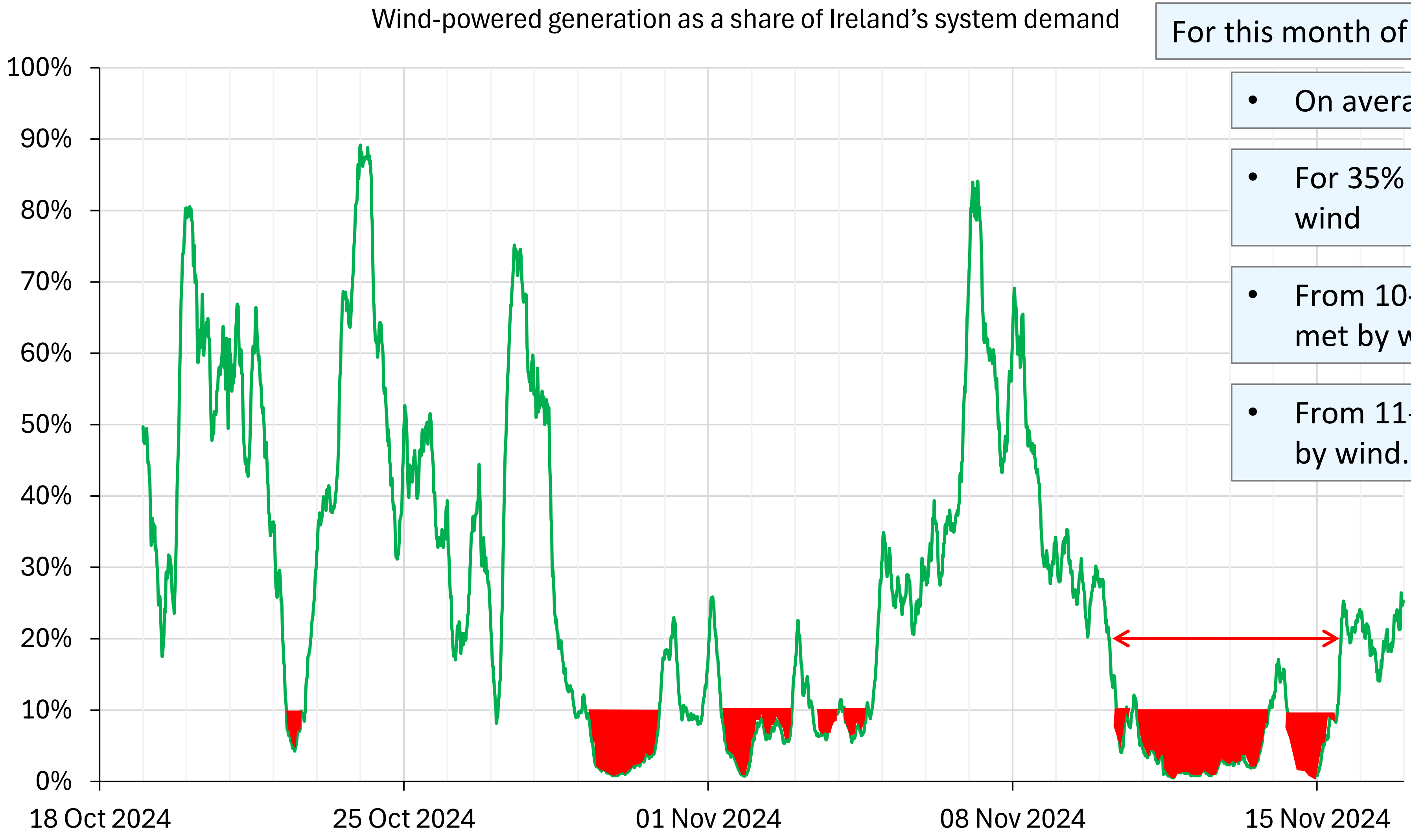
- "Hard to abate" sectors
- Reduce global CO_2 emissions by ~3%

For long-duration energy storage (LDES)

- Help to integrate variable renewables (VRE)
- Reduce global CO_2 emissions by ~40% – 80%
  - Increased use of VRE for electricity generation
  - Increased electrification of industry, transport

The vision: using green hydrogen to integrate VRE

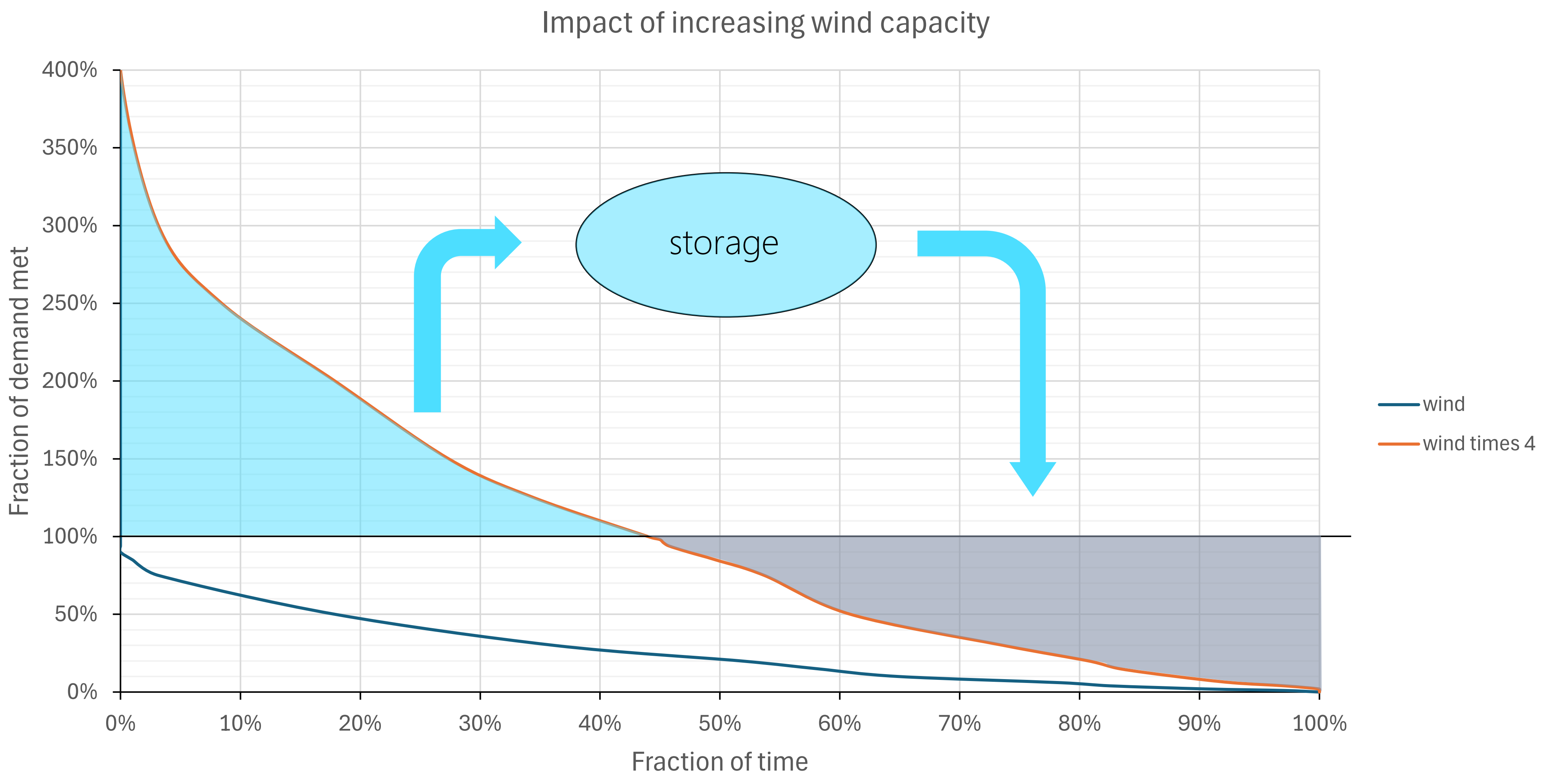
The trouble with Variable Renewables is, they're variable…



For this month of data:

- On average, 26% of demand met by wind
- For 35% of time, <10% of demand met by wind
- From 10-15 November, <20% of demand met by wind
- From 11-13 November, <2% of demand met by wind…

Raw data: EirGrid Smart Dashboard (https://www.smartgriddashboard.com/#roi/demand)



Raw data: EirGrid Smart Dashboard (https://www.smartgriddashboard.com/#roi/demand)

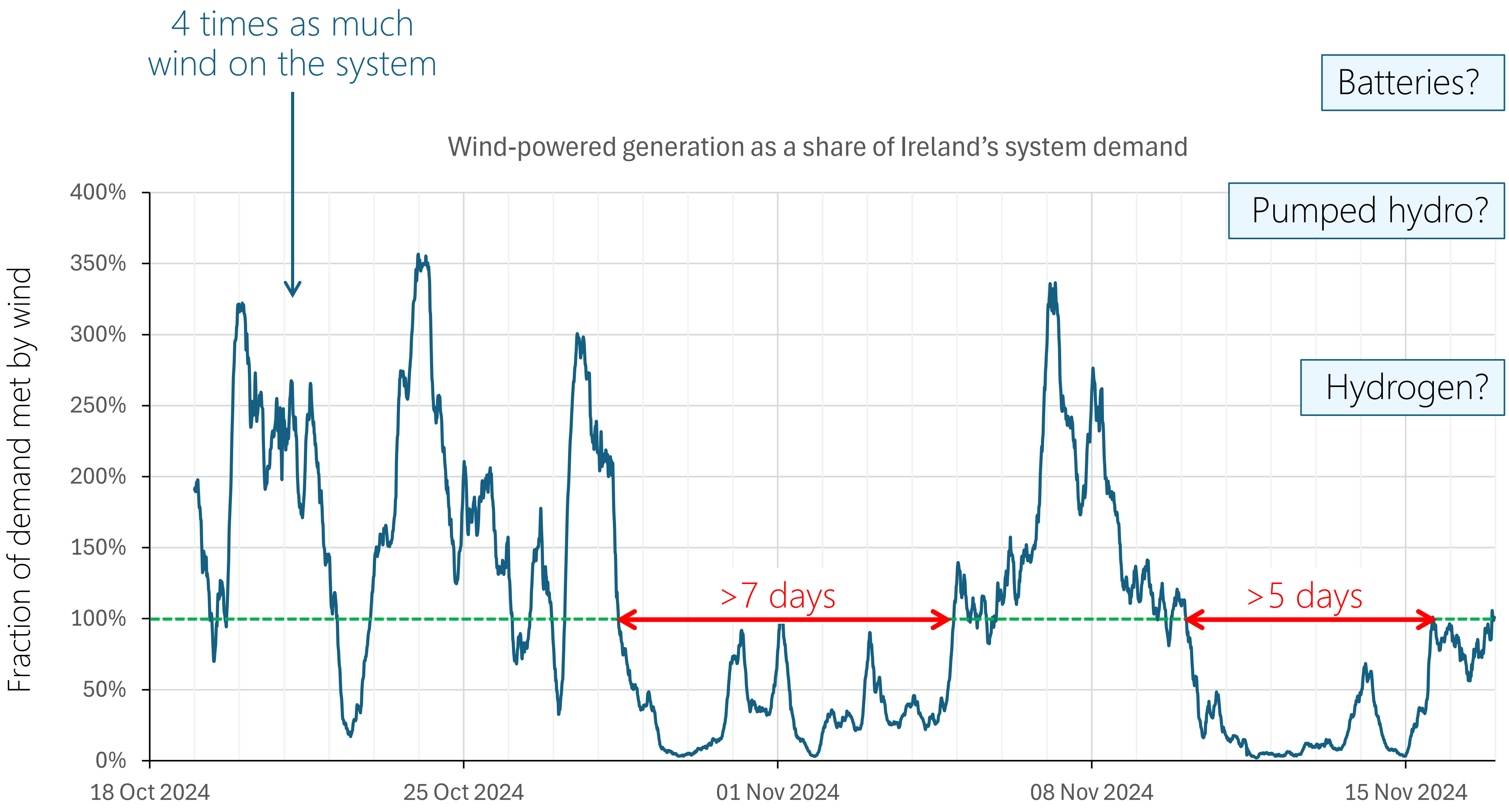
Topic 4f: green hydrogen

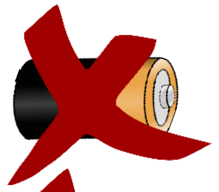
What kind of storage could we use?

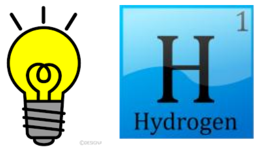
Batteries?

Pumped hydro?

Hydrogen?







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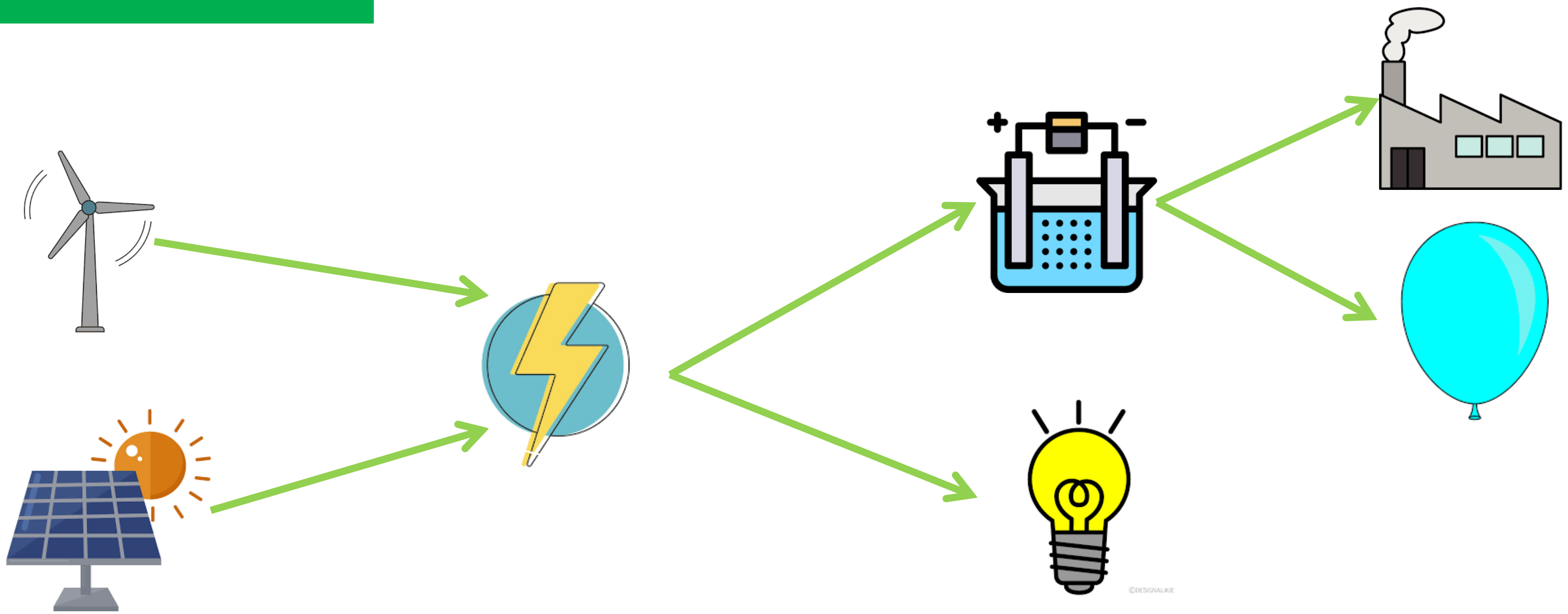
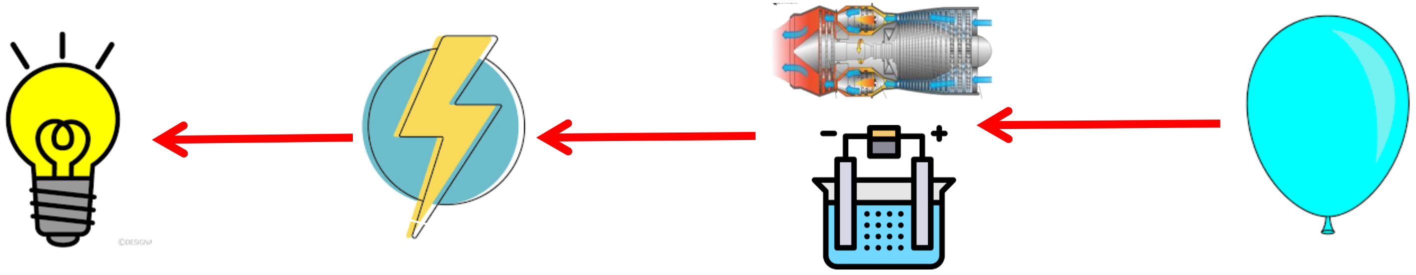
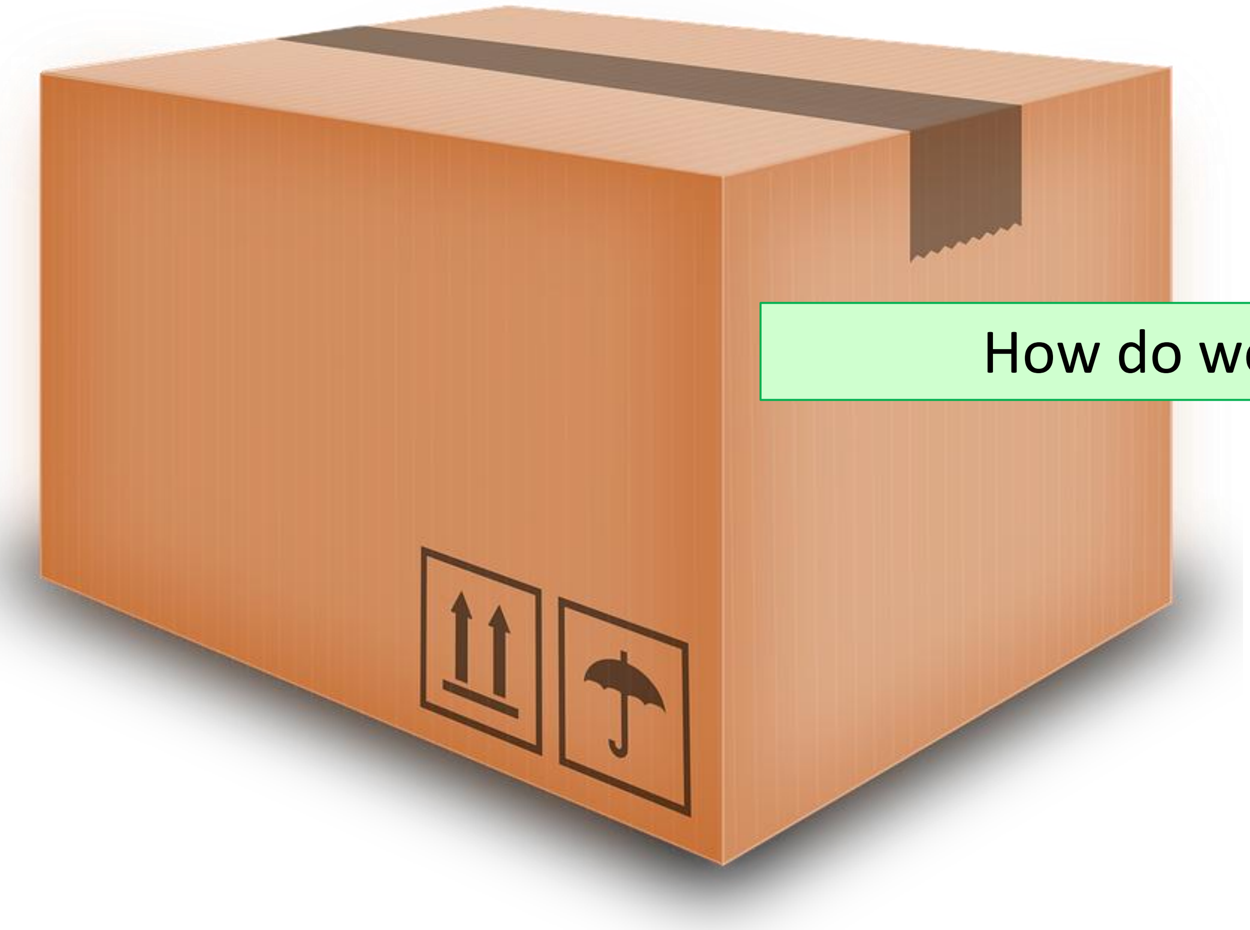
When the sun is shining
and/or
the wind is blowing:

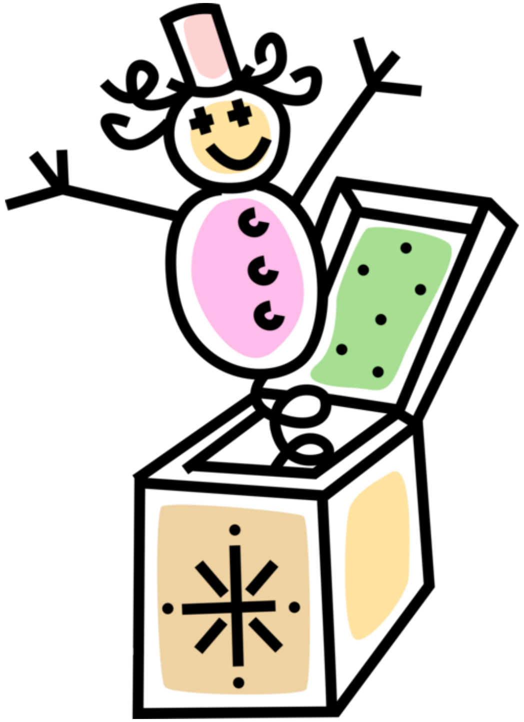


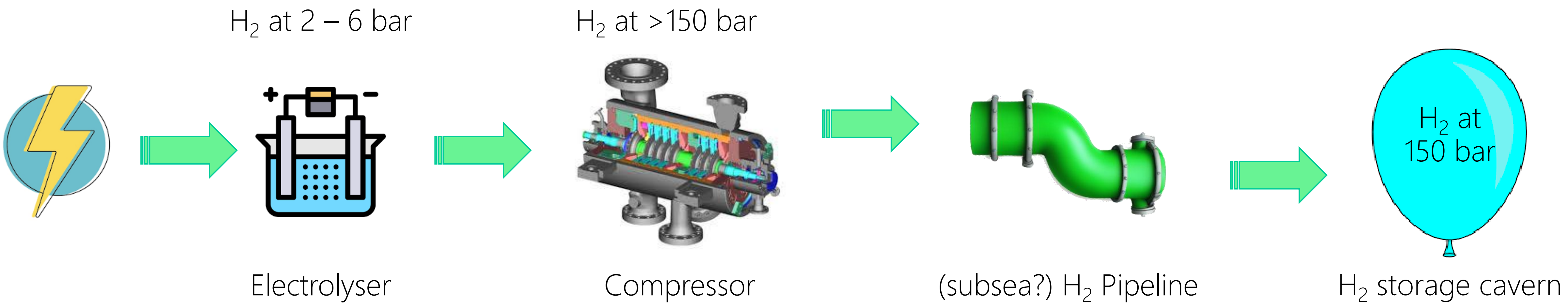
When it's dark
and/or
the air is calm:





How do we store it?

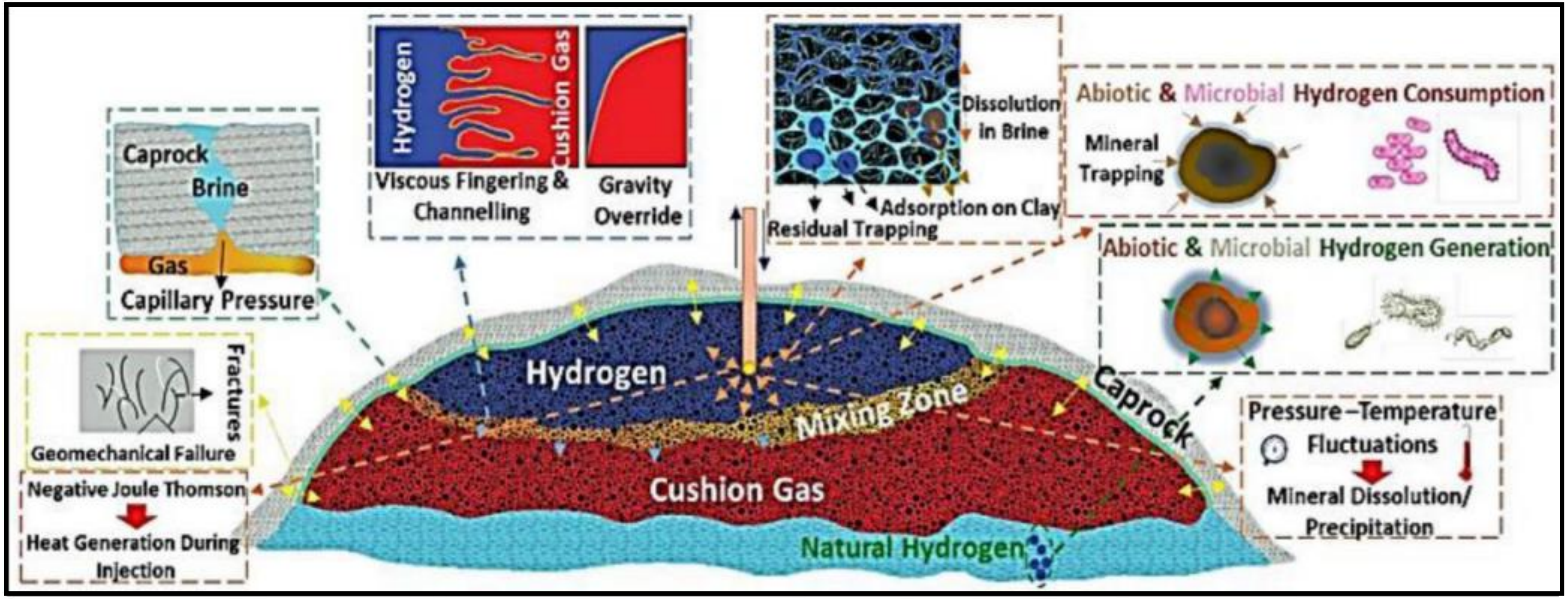




H_2 at 2 – 6 bar
H_2 at >150 bar
H_2 at 150 bar
Electrolyser
Compressor
(subsea?) H_2 Pipeline
H_2 storage cavern

Some challenges with underground storage of hydrogen

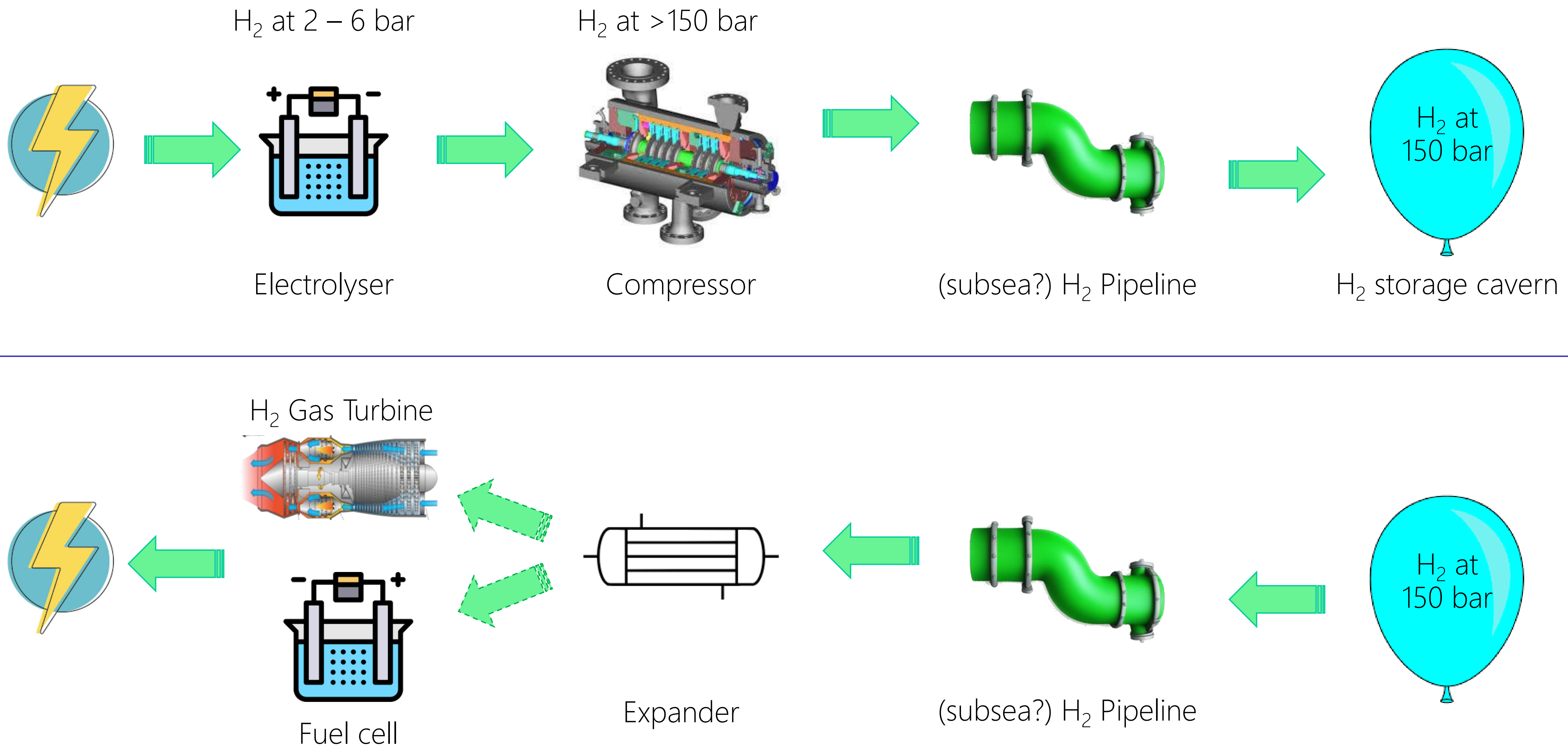
Include cushion gas



Physical, Geochemical, and Microbial Issues Associated with Underground Storage Systems (Muthukumar, P., et al., 2023)

How do we reconvert it to electricity?

Topic 4f: green hydrogen



Topic 4f: green hydrogen

When the sun is shining
and/or
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When it's dark
and/or
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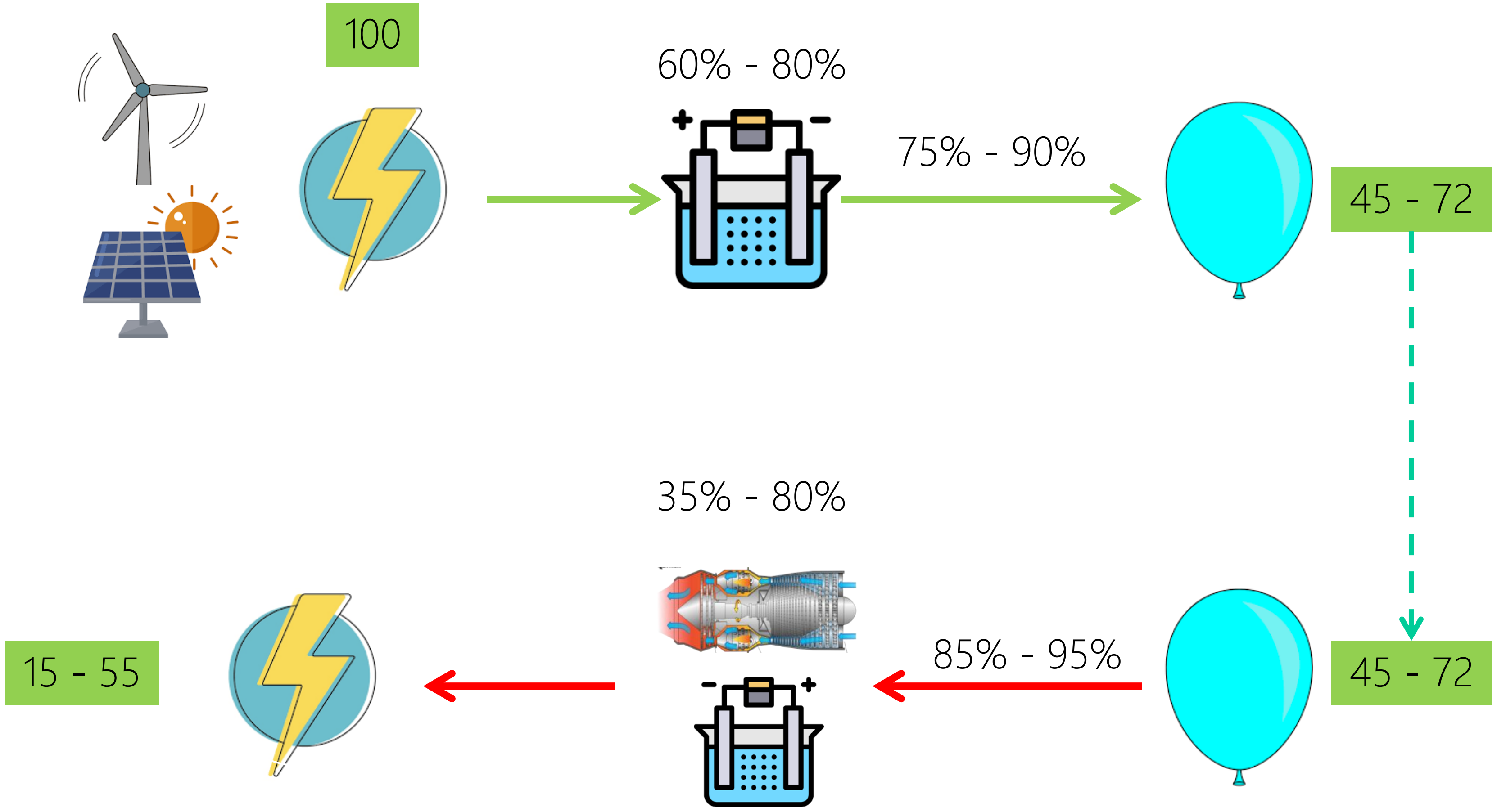
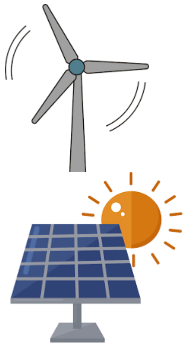


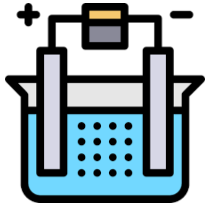
Round-trip efficiency (electricity > hydrogen > electricity) = 15% - 55%

(losses = 45%-85%)

Summary

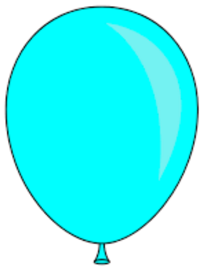
Topic 4f: green hydrogen





- Green hydrogen could (in principle) eliminate CO_2 emissions from hydrogen manufacture.
- This would reduce global CO_2 emissions by ~2 %
- However:
  - Much of the associated technology is new
  - Capital costs are high
  - O&M costs are unknown
  - Hydrogen transport is VERY challenging, and expensive.
- Hence, green hydrogen is currently 3-10 times more expensive than fossil hydrogen.

- Green hydrogen could (in principle) facilitate transition to a VRES-based electricity system.
- However:
  - All of the above, plus…
  - …round-trip efficiency is low







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