Atmospheric & climate impacts of hydrogen: what leakage means for industry

Nicola Warwick

University of Cambridge,
National Centre for Atmospheric Science, UK

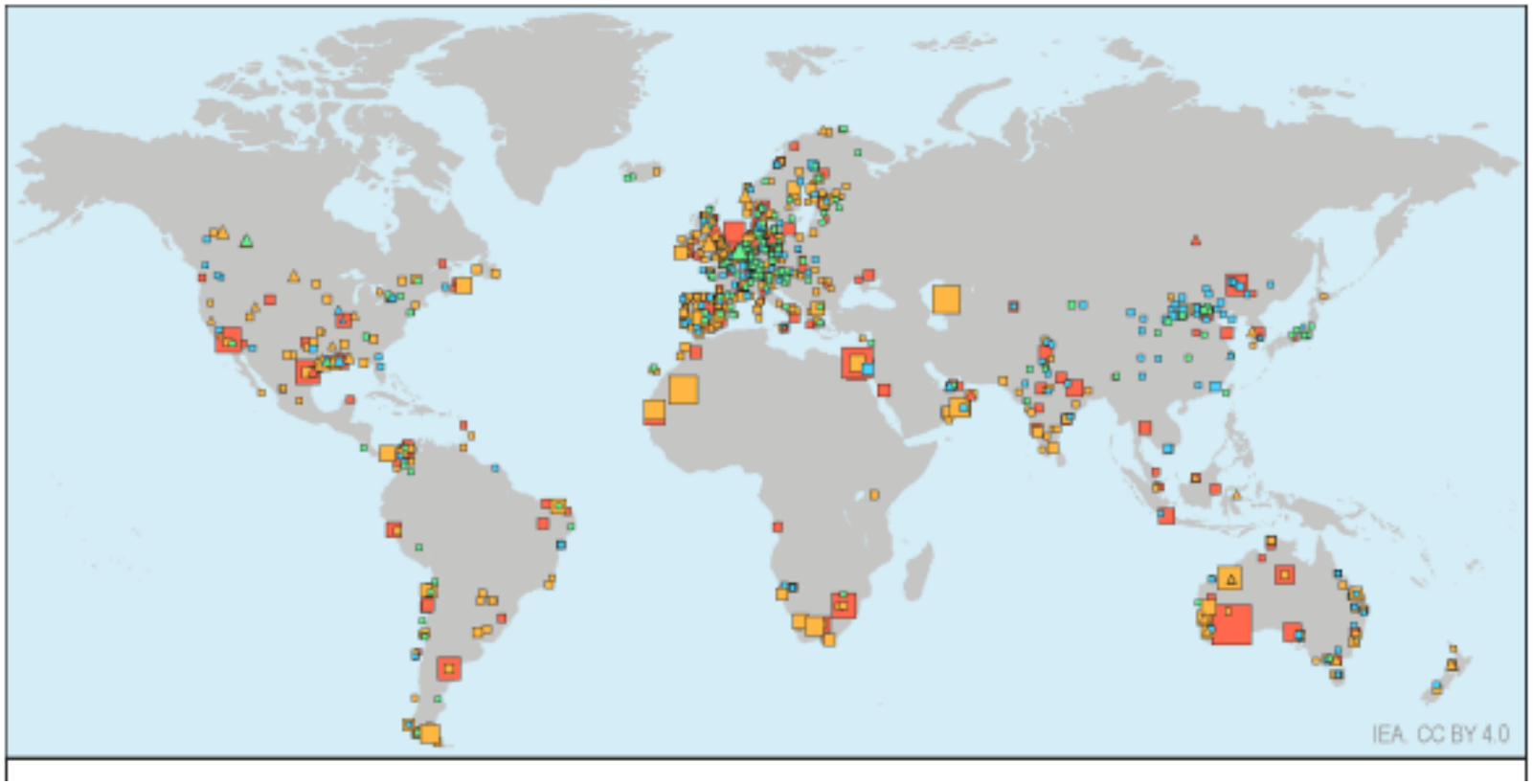
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Stockholm



National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF CAMBRIDGE

Global Hydrogen energy



Map of low emission hydrogen projects, IEA, Global Hydrogen Review, 2023

Rapid strategic growth: 17 → 60+ national strategies since 2021

Pivoting to heavy industry, moving from policy planning to site infrastructure

Rapid industrial scaling makes understanding hydrogen's full atmospheric impact increasingly important

The colours of hydrogen: production and emissions







FEEDSTOCK & PROCESS	**Natural gas (SMR)**	**Natural gas (SMR + CCS)**	**Water + Renewable Power**
DIRECT CO_2 EMISSIONS	**High**	**Reduced (80-95% captured)**	**Zero direct emissions**
KEY ATMOSPHERIC RISK	**High CO_2 footprint**	**Dual leakage risk: H_2 leaks & upstream methane leaks**	**Climate benefits depend on H_2 leakage rates**



- As industry scales up hydrogen infrastructure, unmonitored leakage can erode climate benefits

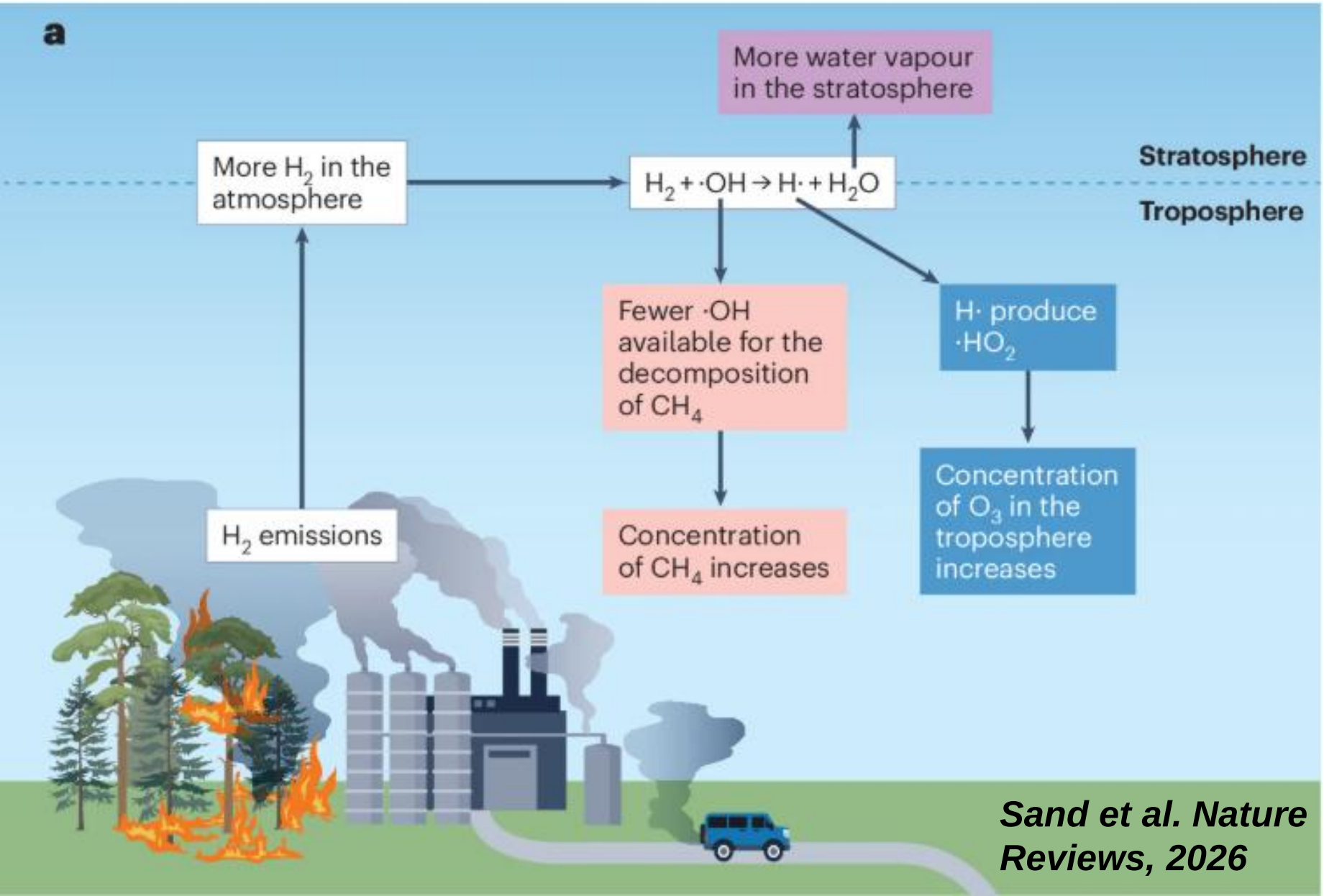


Dr Graeme Pearman
(Univ of Melbourne)



Prof. Michael Prather
(UC Irvine)

Hydrogen's indirect impacts on climate



Sand et al. Nature Reviews, 2026

Hydrogen itself traps no heat.

Impact comes entirely from chemical reactions increasing **methane, ozone** and **stratospheric water vapour.**

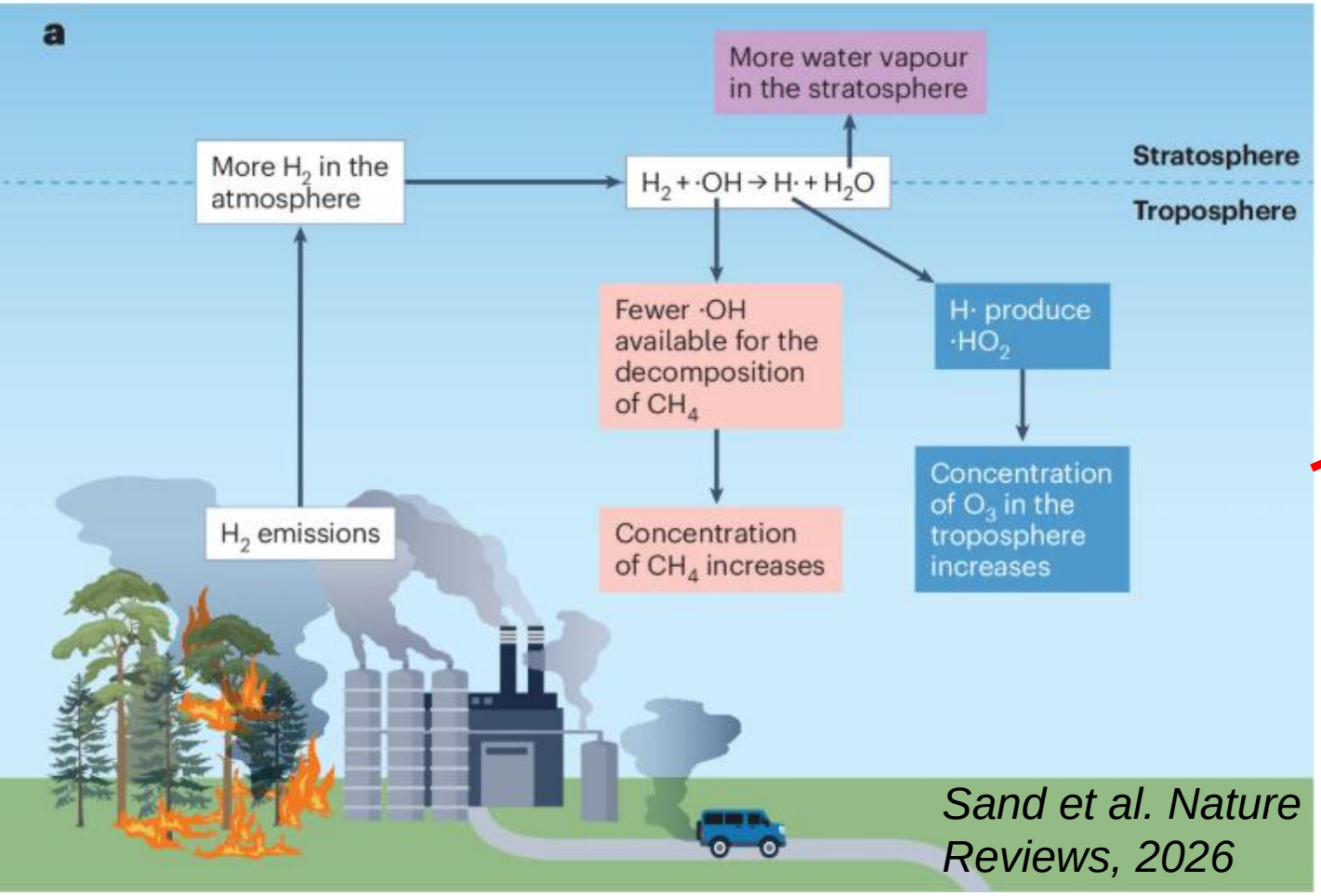
The Global Warming Potential (GWP) allows comparisons of the global warming impacts of different gases

- Their ability to absorb energy
- How long the gases stay in the atmosphere
- Compares **1 kg** of a gas to **1 kg of CO_2** – over a given time

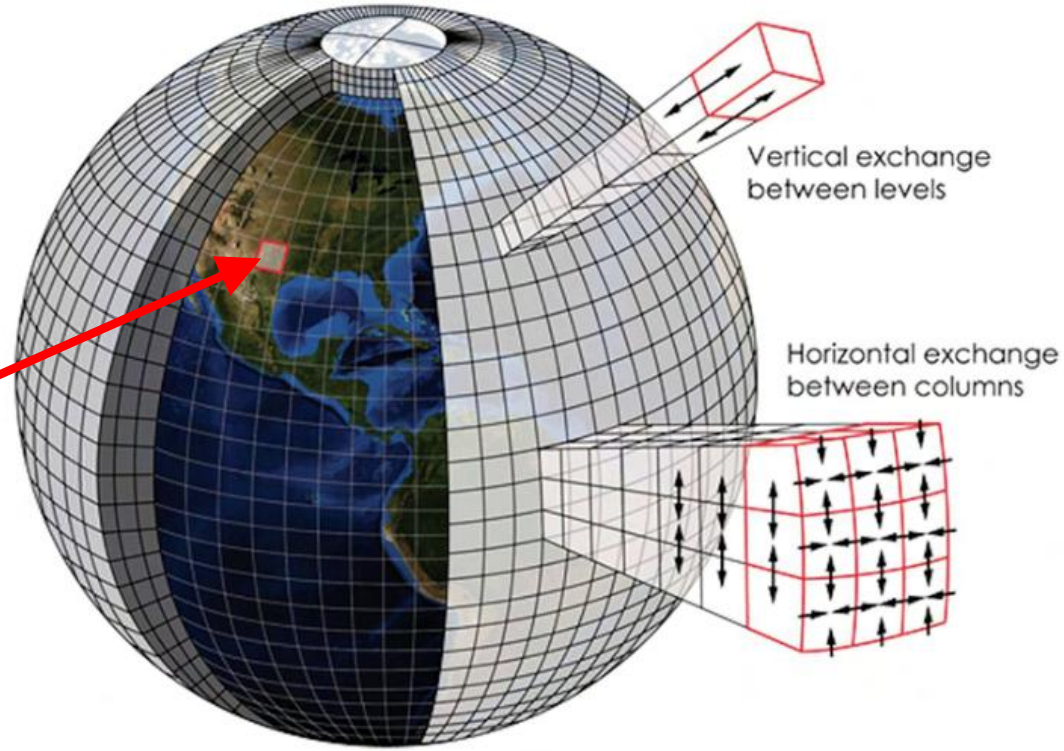
Species	Lifetime	GWP20	GWP100
Carbon dioxide (CO_2)	Multiple	1.0	1.0
Methane (CH_4)	11.8 (± 1.8)	82.5 (± 25.8)	29.8 (± 11)
Nitrous Oxide (N_2O)	109 (± 10)	273 (± 118)	273 (± 130)

IPCC AR6

Calculating a GWP for hydrogen

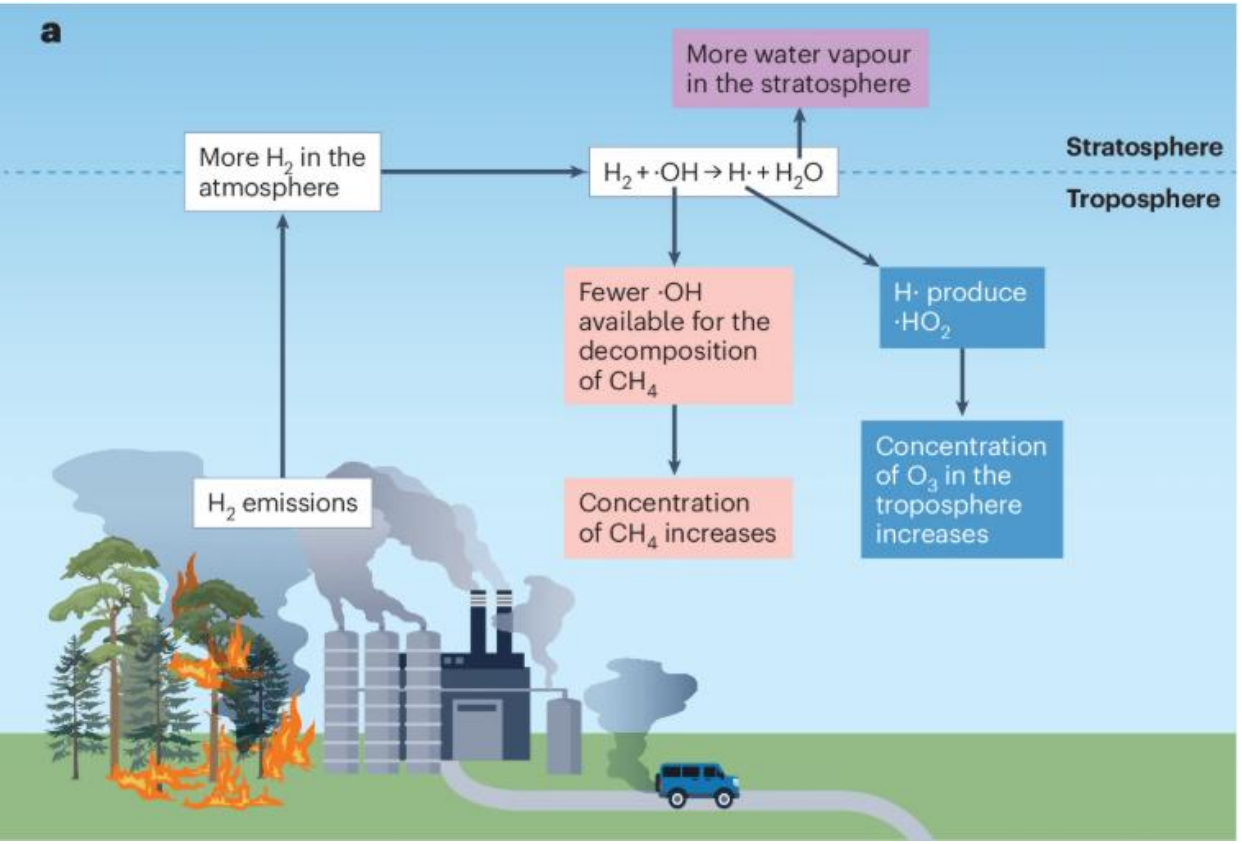


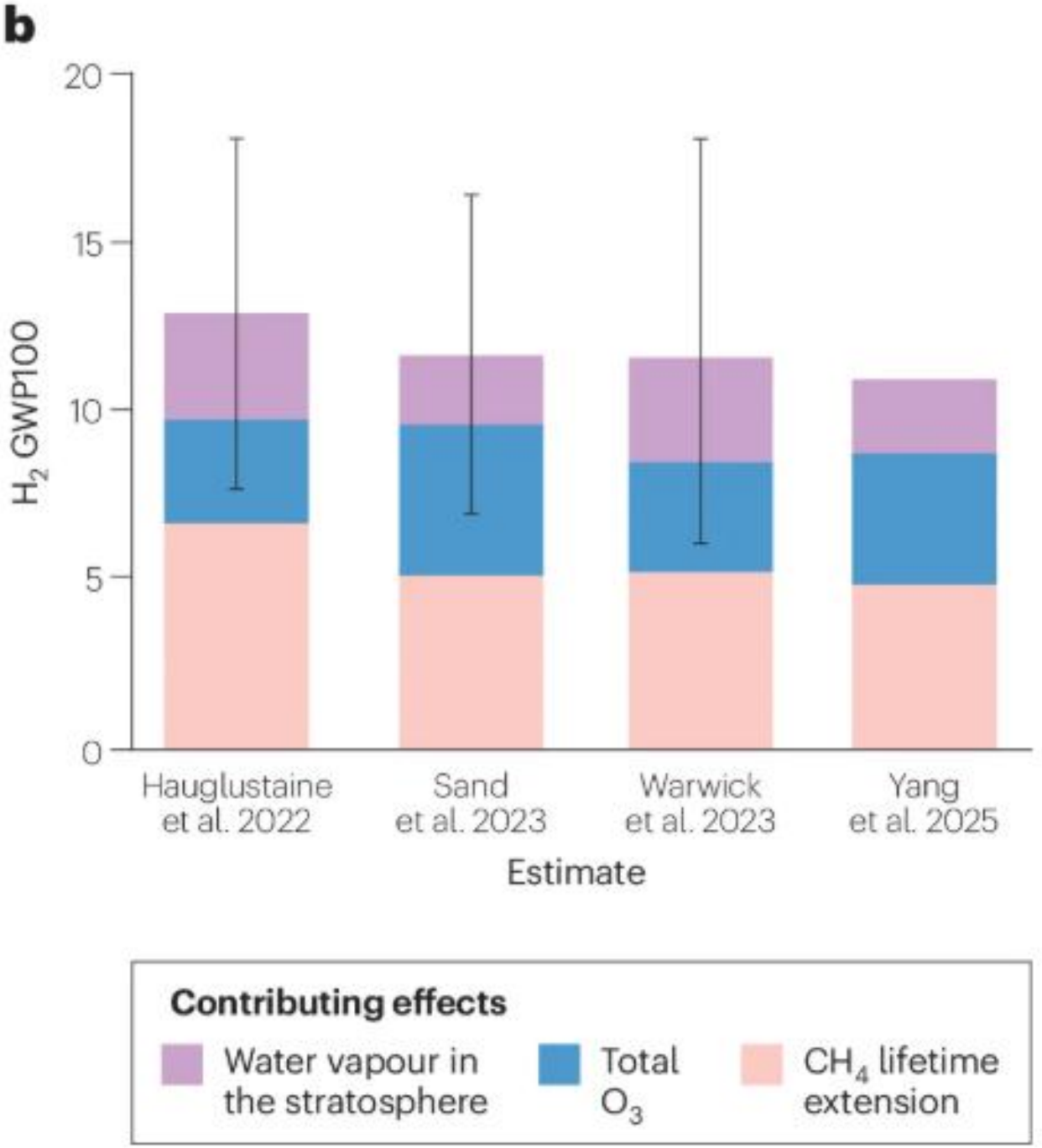
Sand et al. Nature Reviews, 2026



Global atmospheric models simulate these chemical pathways across 100,000+ grid cells to calculate the net climate impact

Models reveal a GWP_{100} for hydrogen of 12



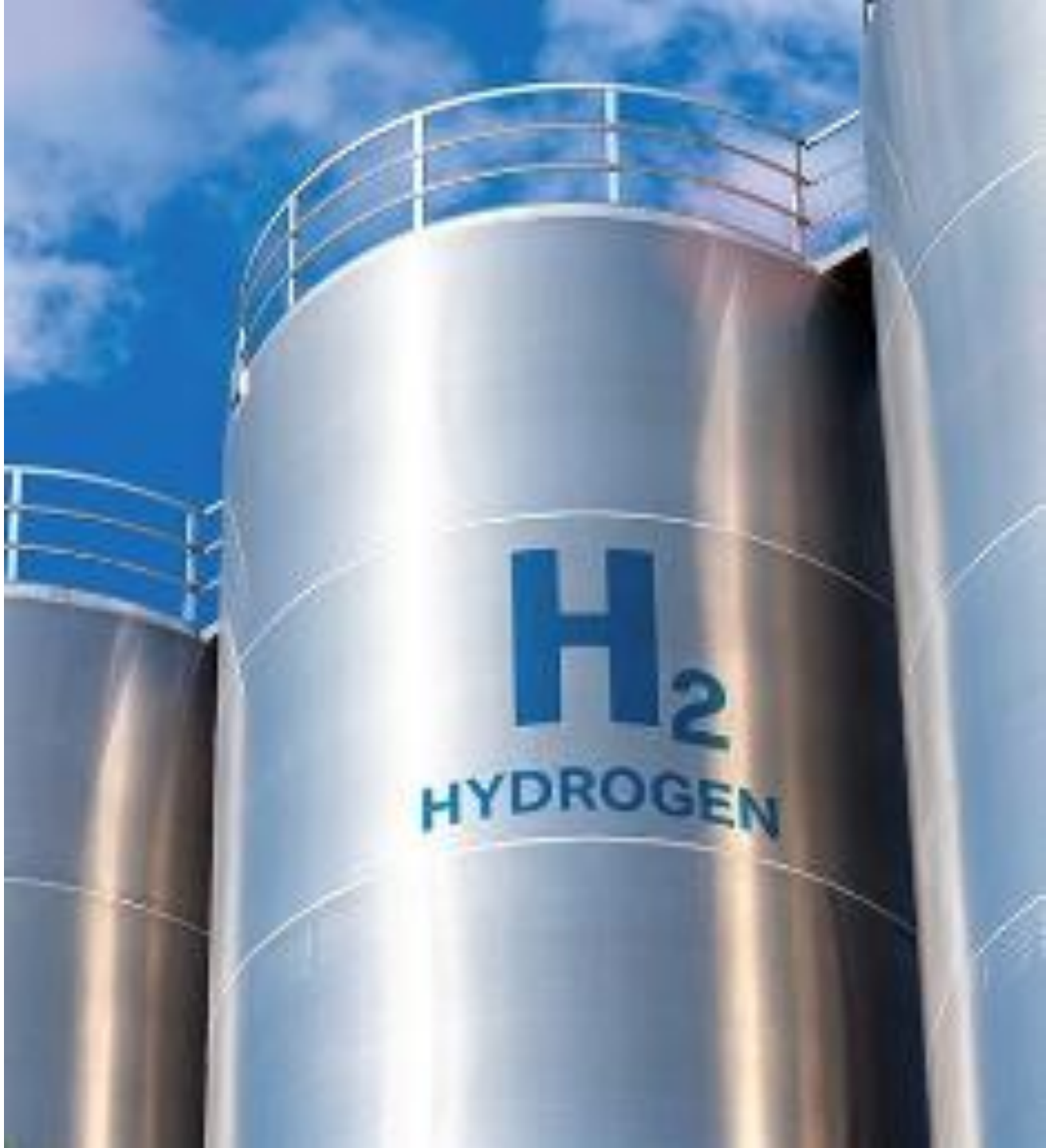


Sand et al. Nature Reviews, 2026

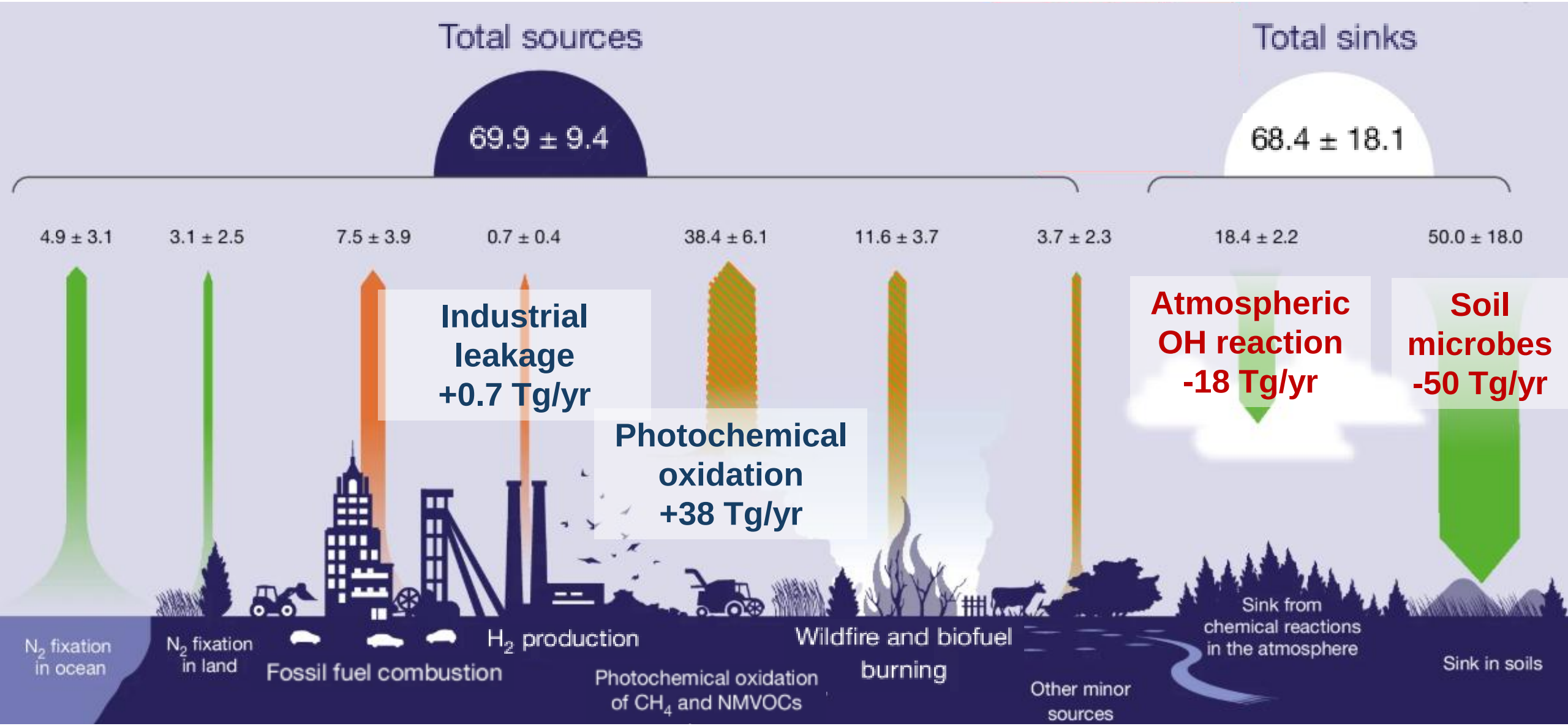
What does it mean?

- **GWP_{100} = 12:** 1 kg H_2 emissions warms the atmosphere **12x more than CO_2** over 100 years
- **GWP_{20} = 37:** H_2 warms the atmosphere **37x more than CO_2** over the first 20 years

- **H_2 is short-lived (~2 years): continuous low-level fugitive leaks cause an immediate warming penalty**

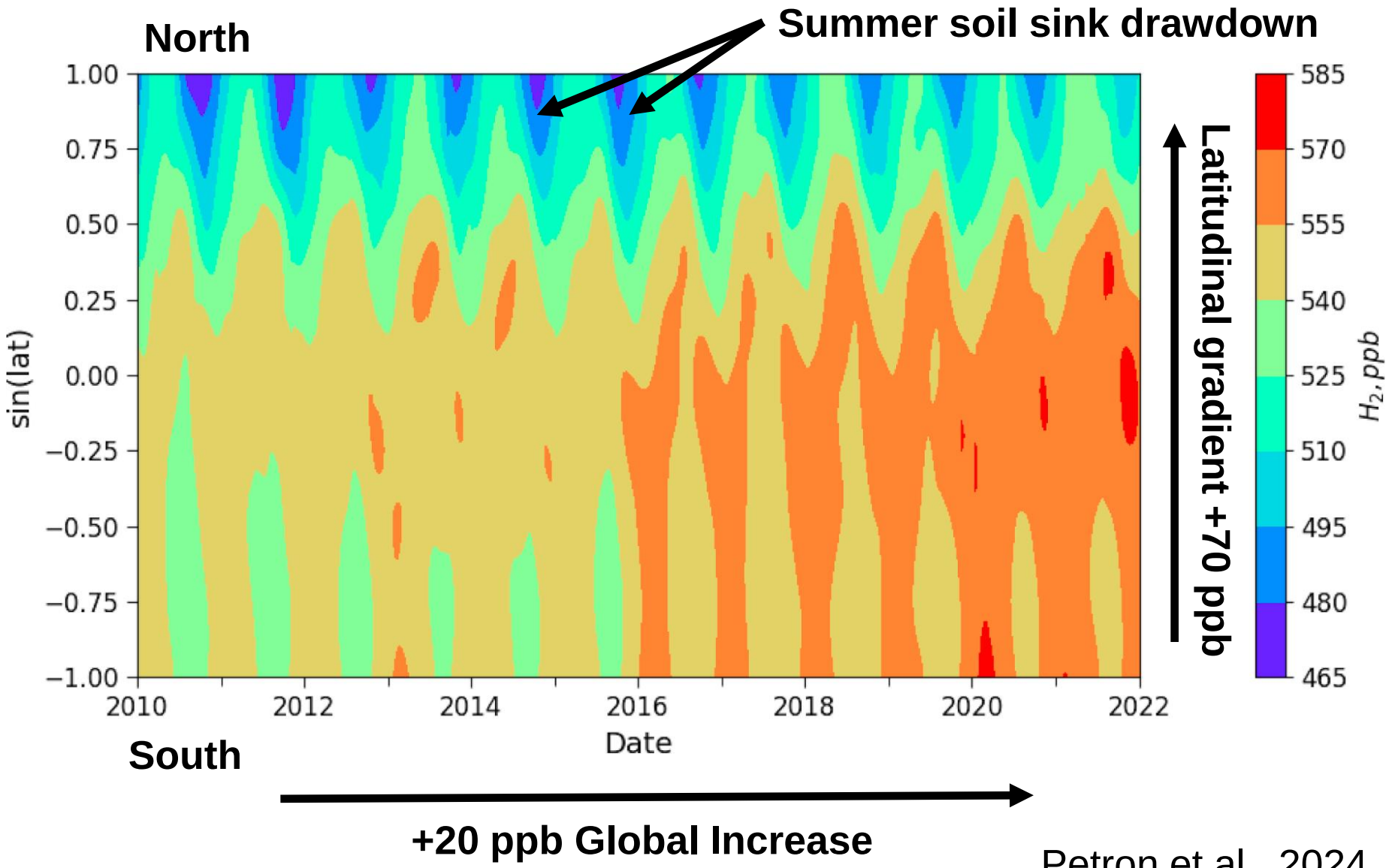


Global atmospheric H_2 budget



Ouyang et al., Nature, 2025

Atmospheric hydrogen baseline & detection limits



Petron et al., 2024

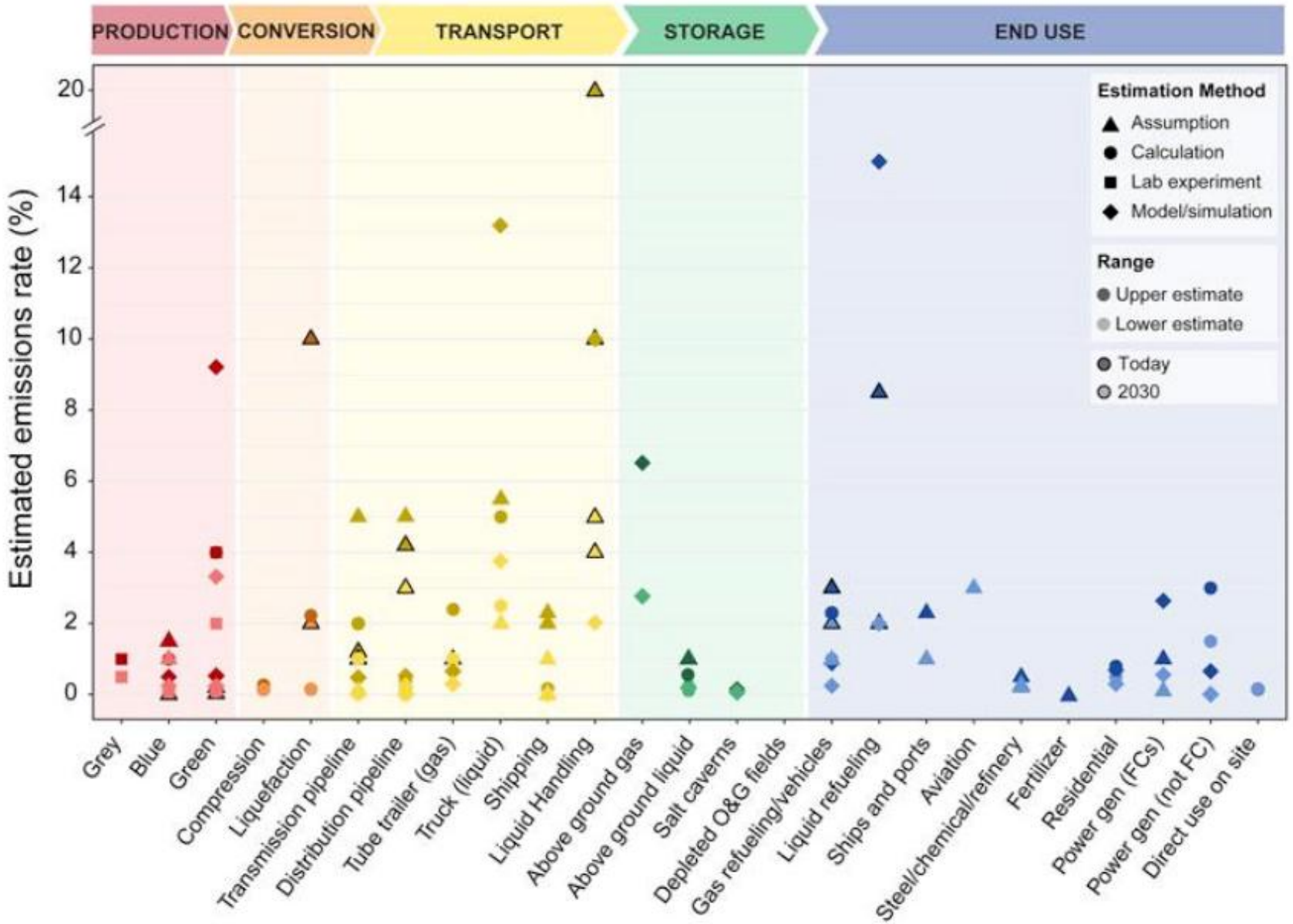
Atmospheric Baseline:

- ~ **0.5 ppm (500 ppb)**
- Fluctuates by **50-70 ppb** seasonally and annually

Sensor requirements:

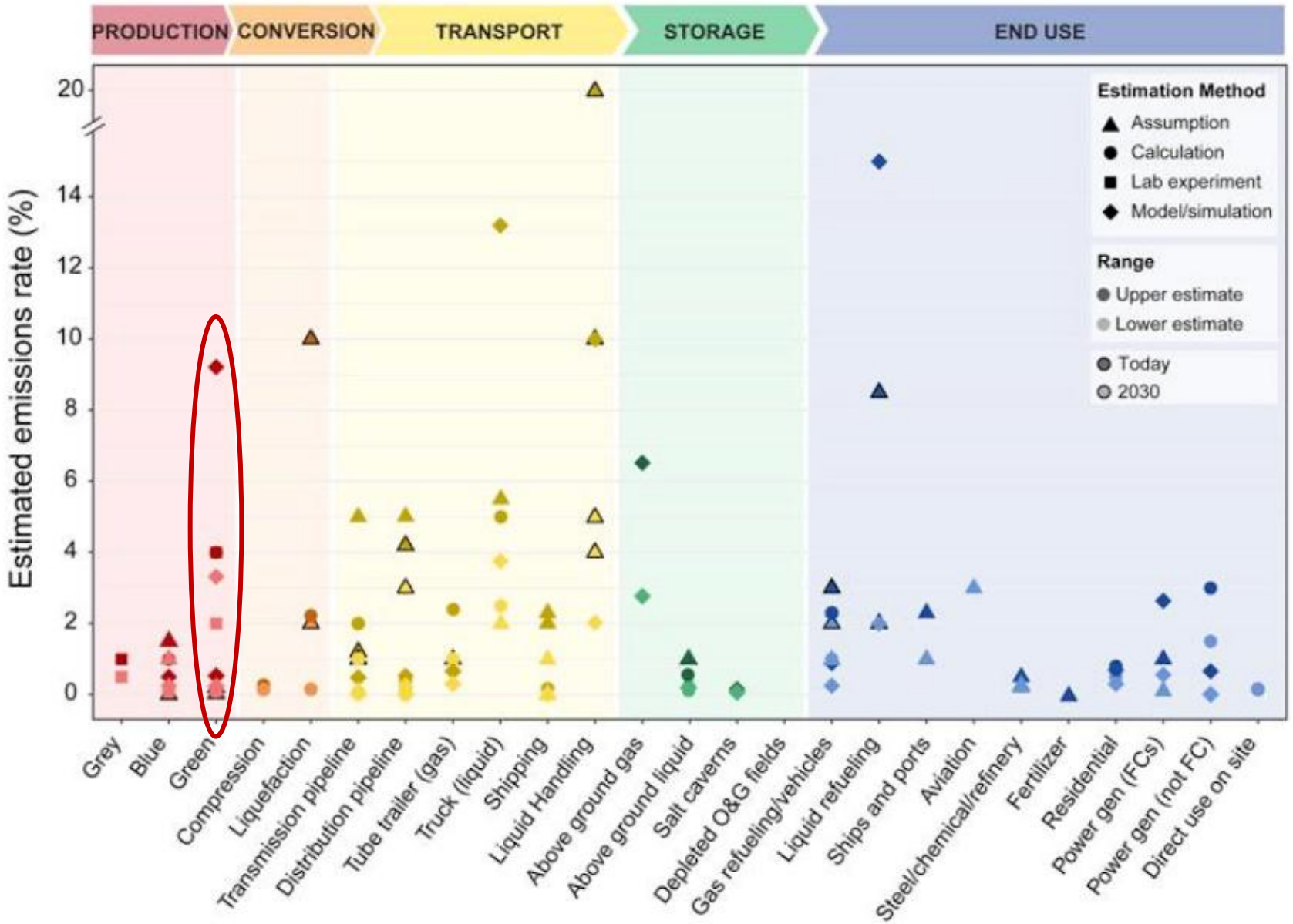
- Standard ppm-level safety sensors miss climate-relevant losses
- Ppb-level resolution required for net-zero accounting

Hydrogen leaks: where are the hotspots?



Esquivel-Elizondo et al. 2023

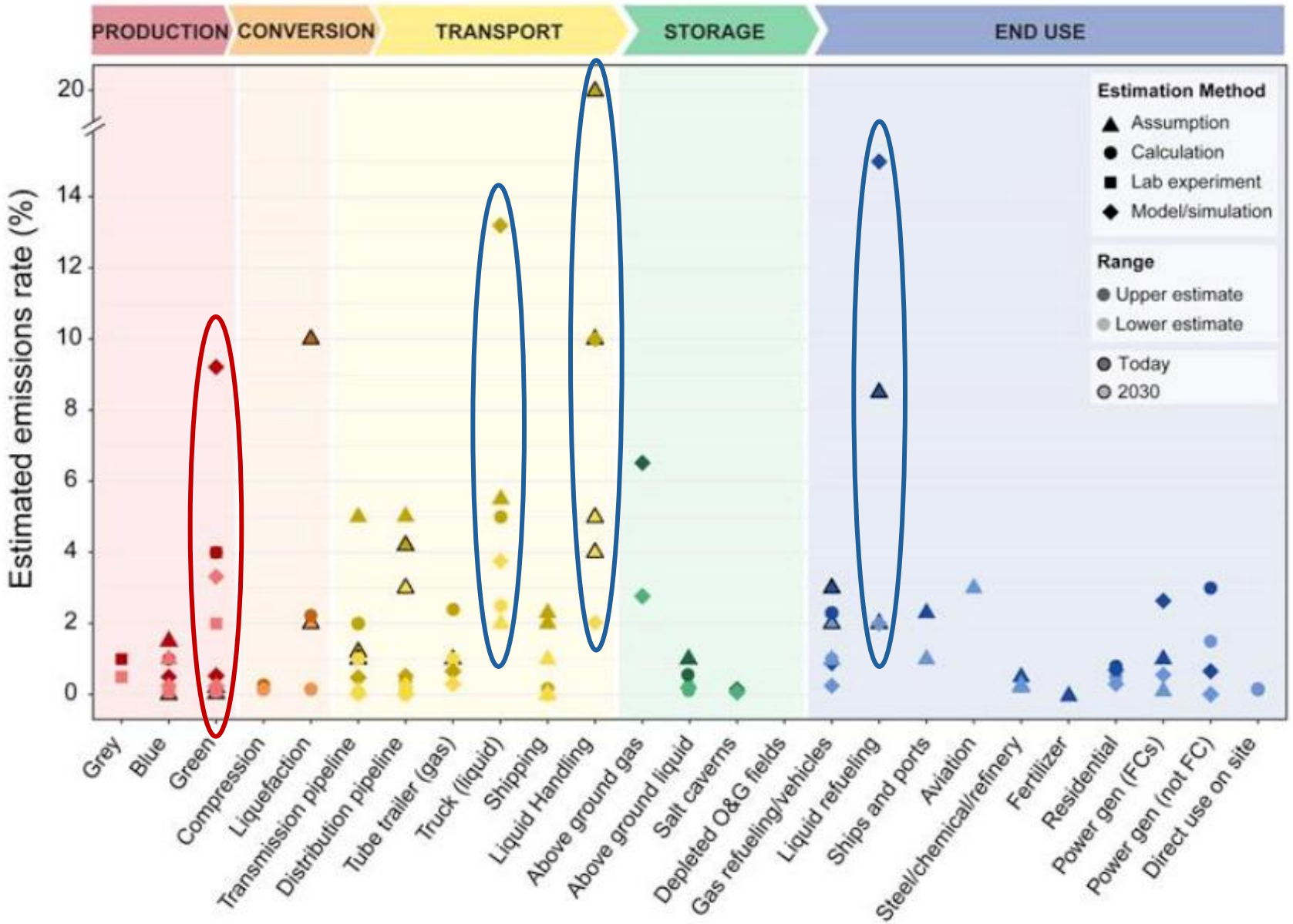
Hydrogen leaks: where are the hotspots?



- **Production (up to 9%)**: green H_2 production frequently intentionally vents H_2 during start-ups/shutdowns

Esquivel-Elizondo et al. 2023

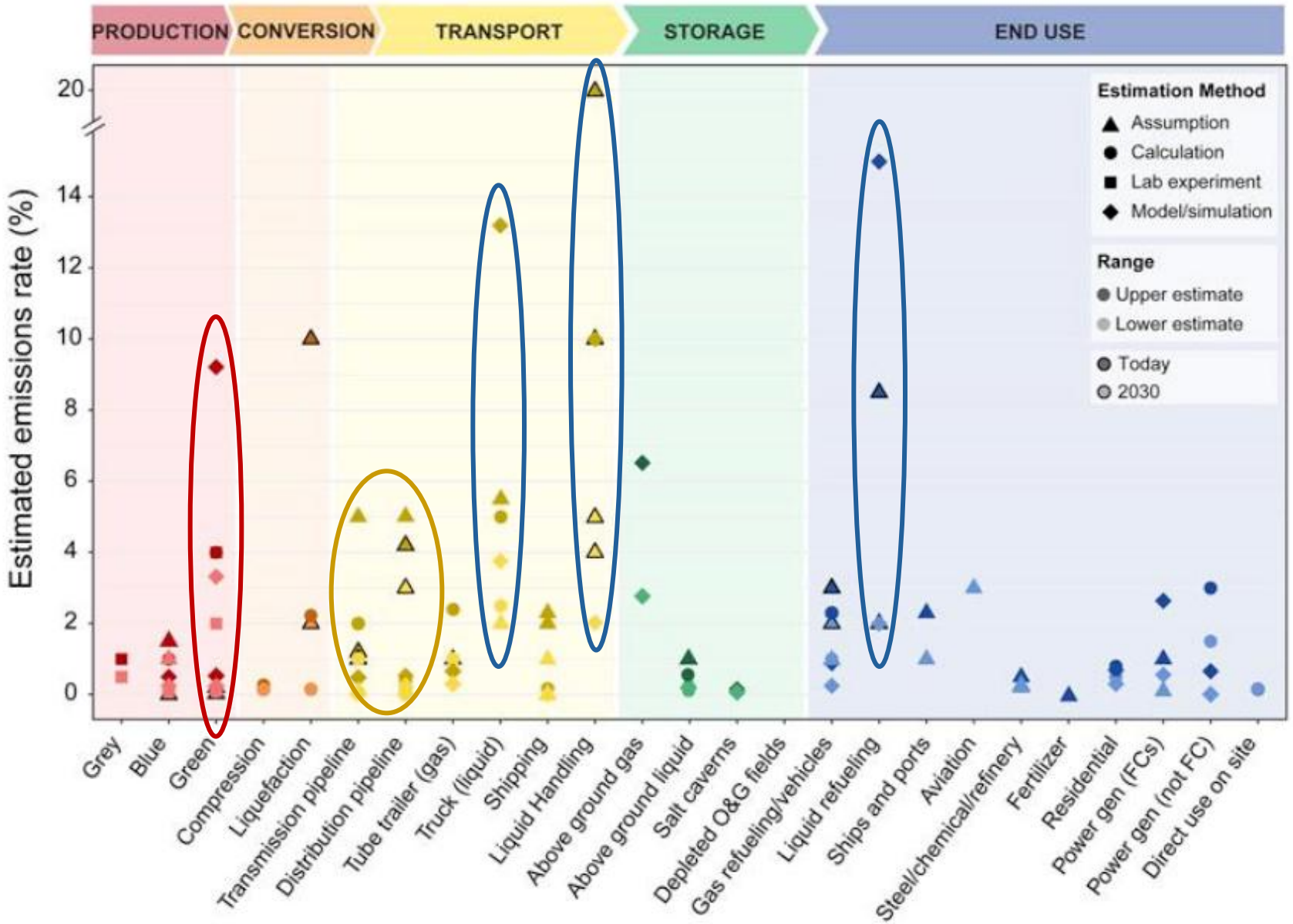
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Esquivel-Elizondo et al. 2023

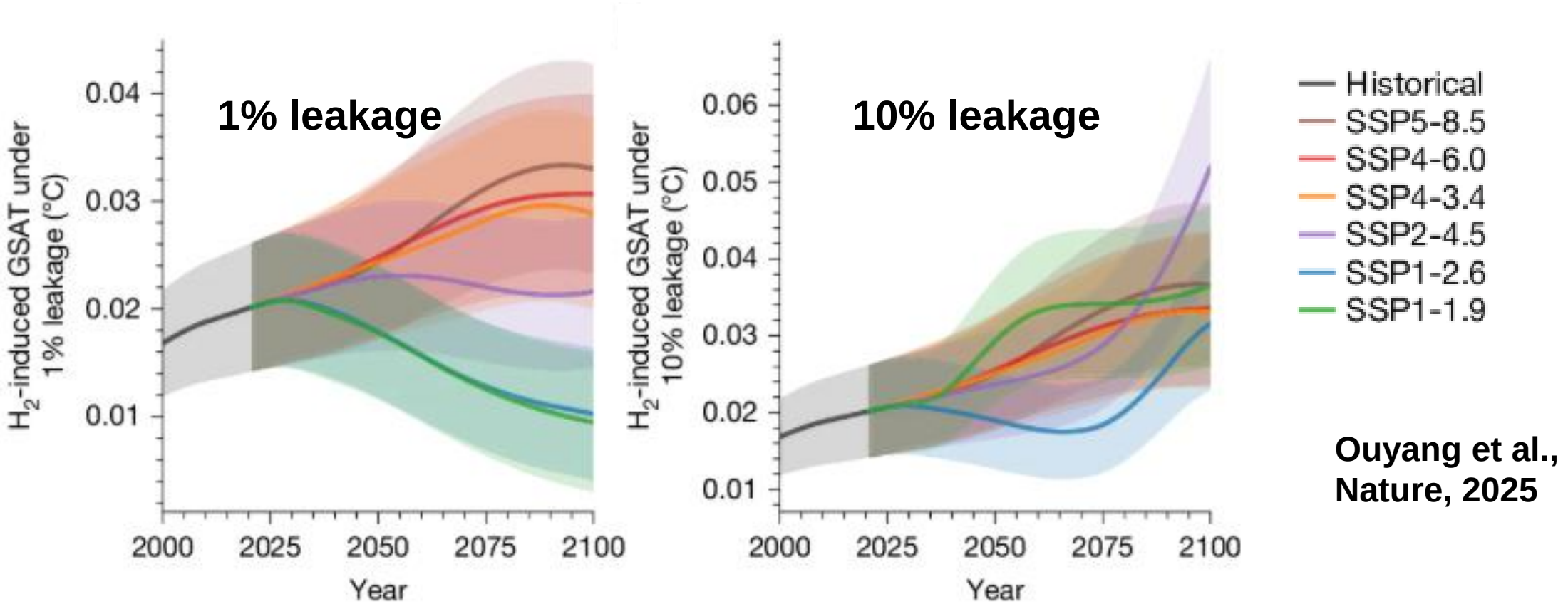
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- **Gas pipelines and distribution (1-5%)**: fugitive leaks through seals, valves and pipe joints

Esquivel-Elizondo et al. 2023

Warming impact of H_2 leakage in IPCC future scenarios



Ouyang et al., Nature, 2025

Context: How big is 0.04°C to 0.06°C?

- Consumes **15-25%** of the remaining **0.25°C** Paris budget allowance for 1.5°C
- Equivalent to adding the entire historical warming impact of global aviation

Evaluating the Net Climate Benefit of Hydrogen

+ AVOIDED EMISSIONS



CO_2 Baseline (94 g CO_2e/MJ)

Displaced carbon

Displaces fossil fuels in hard-to-abate sectors: steel, high temperature industrial heat and heavy goods vehicles

- METHANE PENALTY



Upstream CH_4 (GWP_{20} = 80)

Upstream CH_4 losses

Methane losses during extraction and reforming for blue H_2

- HYDROGEN PENALTY



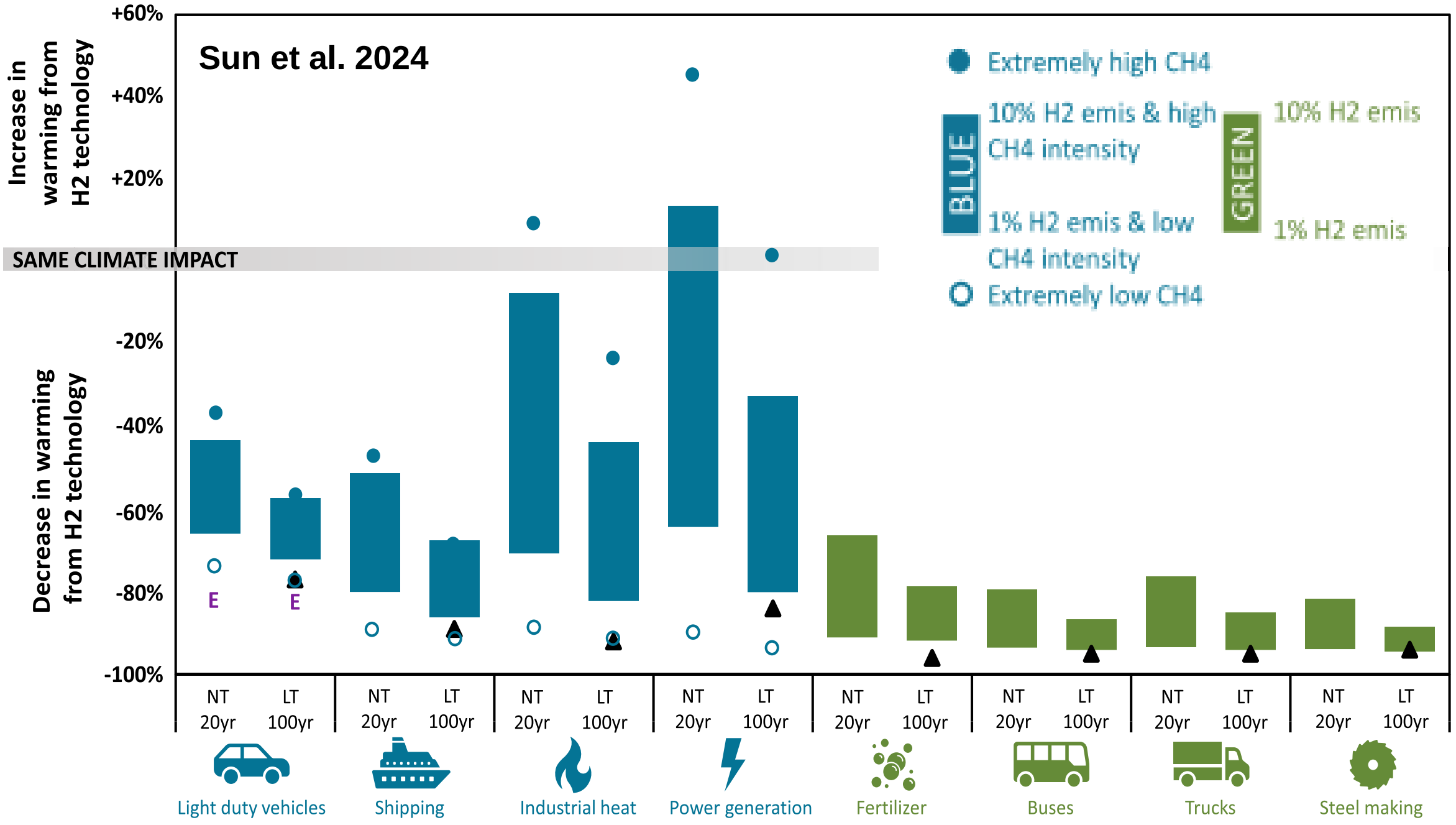
Lifecycle H_2 (GWP_{20} = 37)

Value-Chain H_2 leakage

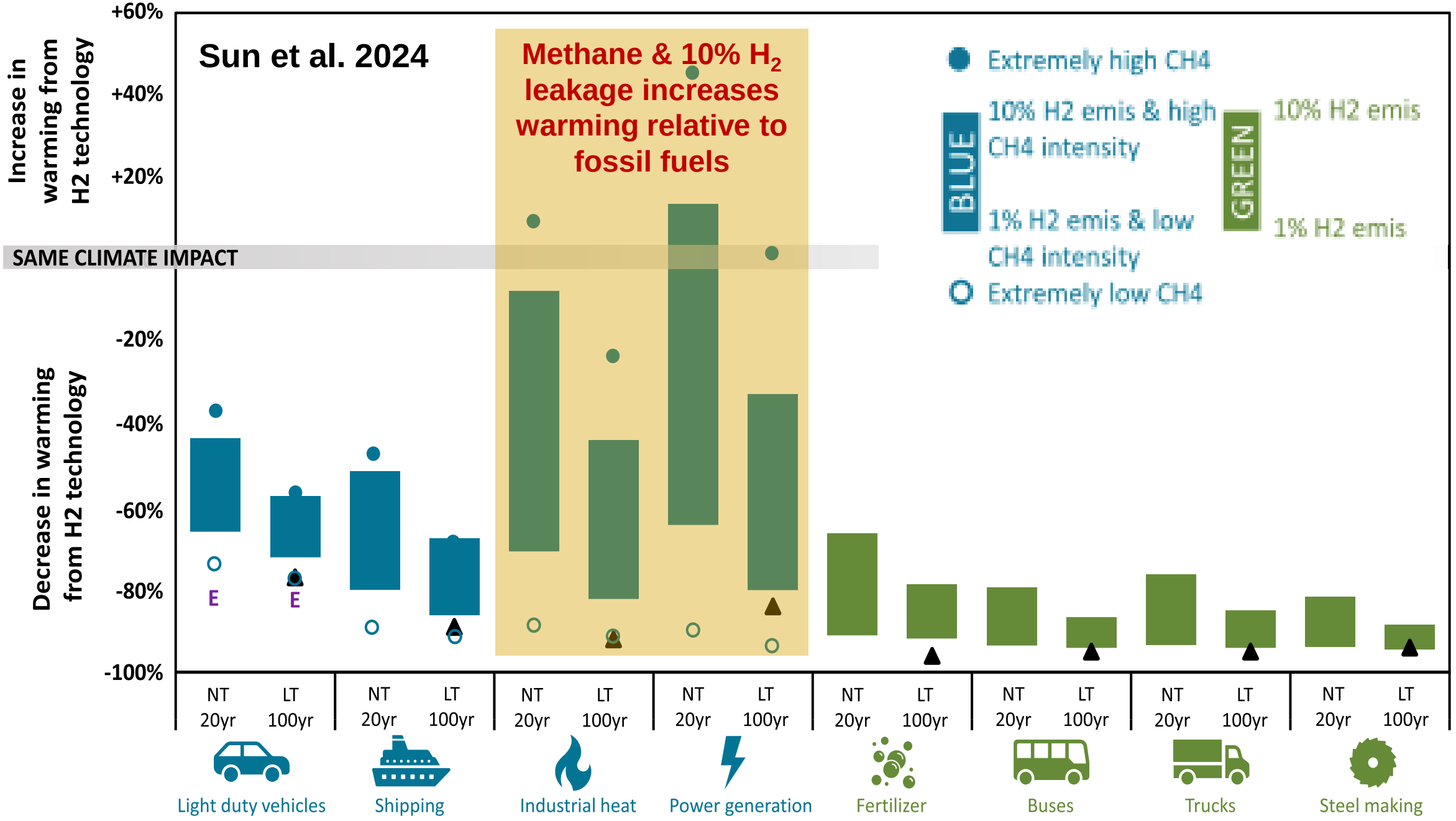
Emissions across production, transport, storage and utilisation

Net Climate Gain = Avoided CO_2 – Upstream CH_4 Losses – Fugitive H_2 Emissions

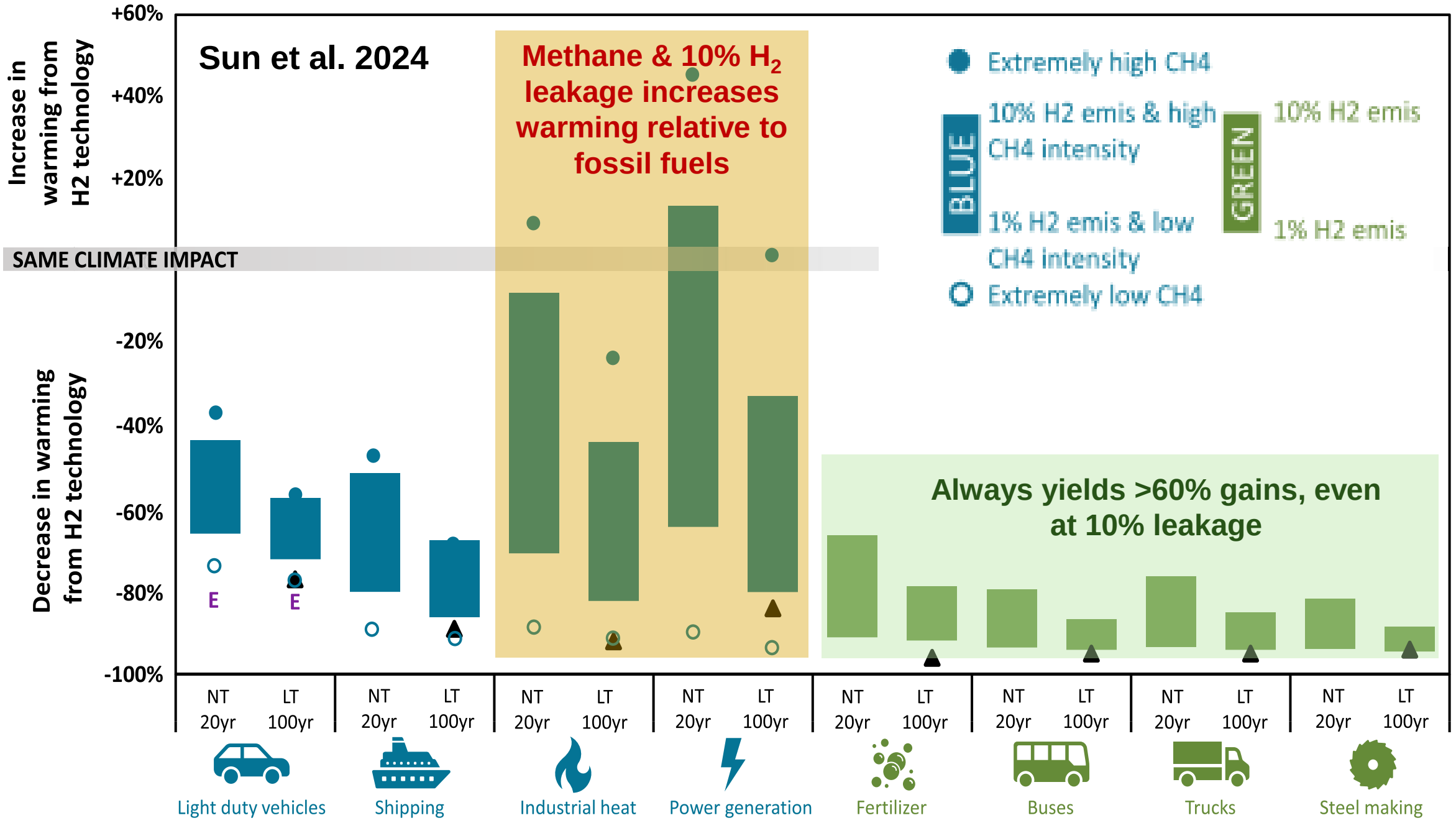
Climate impacts of eight hydrogen pathways relative to current fossil fuel use



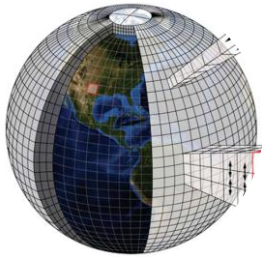
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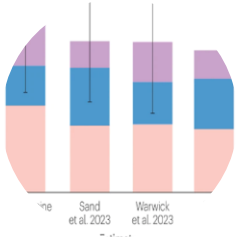
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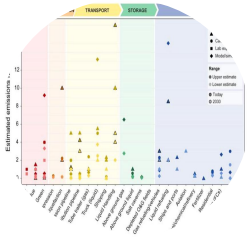
Recommendations & Key Takeaways



Indirect warming: Hydrogen leakage depletes atmospheric OH radicals, extending methane's lifetime and driving near-term warming.



High near-term potency: at GWP_{20} = 37, H_2 warming potency is nearly 50% of that due methane over the first 20 years.



Detection Upgrade: Managing fugitive loss requires ppb-level measurement precision.



Lifecycle Benefits: Depend on upstream feedstocks, low facility leakage rates and prioritised use in hard-to-abate sectors.