Maximizing climate benefits of hydrogen systems

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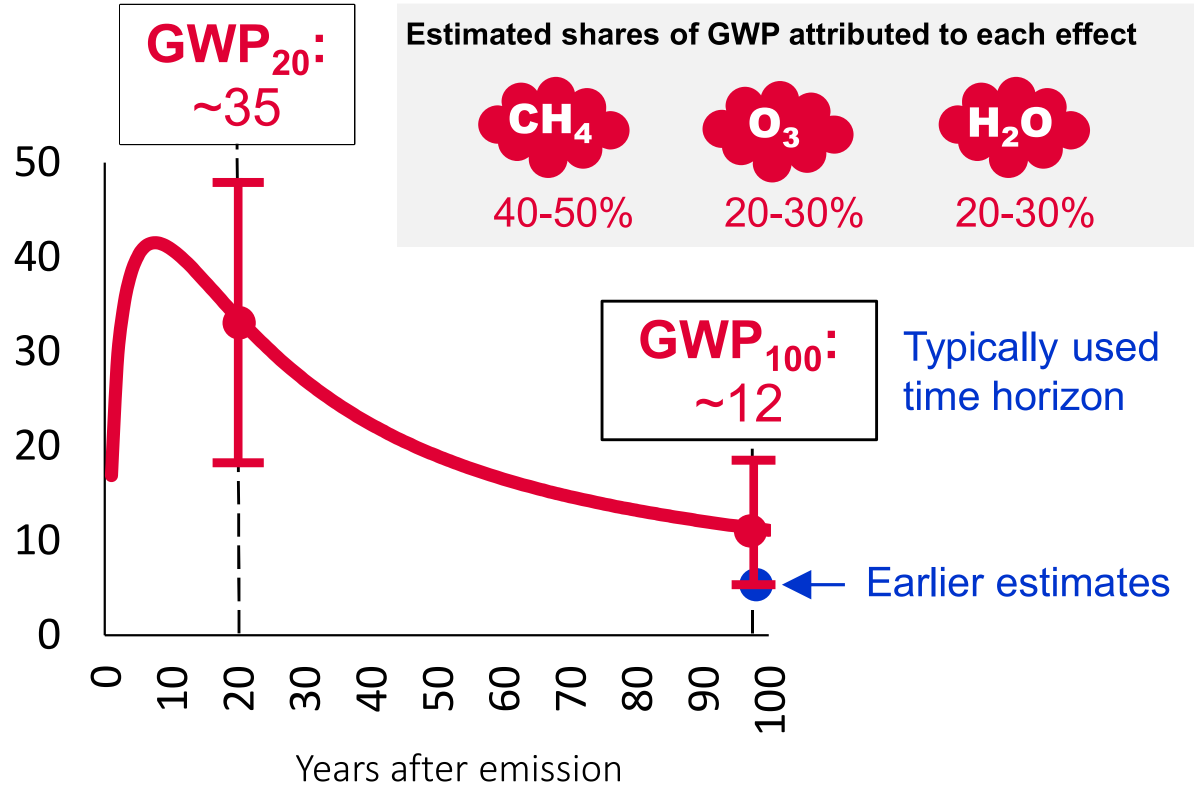
Hydrogen's warming potency

Hydrogen's warming potency is stronger than CO_2 per mass but short-lived.

Hydrogen's warming potency relative to CO_2 over time from a one-time pulse of equal emissions (Global Warming Potential)

Time series using Warwick et al. 2023 equations, GWP20&100 ranges from papers referenced below

Key sources of uncertainty: soil sink magnitude and future changes, changing future OH concentrations driven by other OH-influencing emissions



Warwick et al. (2023); Sand et al. (2023); Derwent et al. (2023); Hauglustaine et al. (2022)

History of the science

1972 — The first description of **hydrogen's atmospheric chemistry**.[Levy]

2001 — The first quantification of **hydrogen's lower-atmosphere warming potency** is published and is reported in the **IPCC's Third Assessment Report**.[Derwent et al.; IPCC TAR WGI 4.2.3 pg. 256]

2003 — Studies warn about the **climate risks of a potential hydrogen economy**.[Prather; Schultz et al.]

2007 — The **IPCC Fourth Assessment Report** indicates hydrogen's GWP_{100} (5.8).[IPCC AR4 WGI 2.10.3.6]

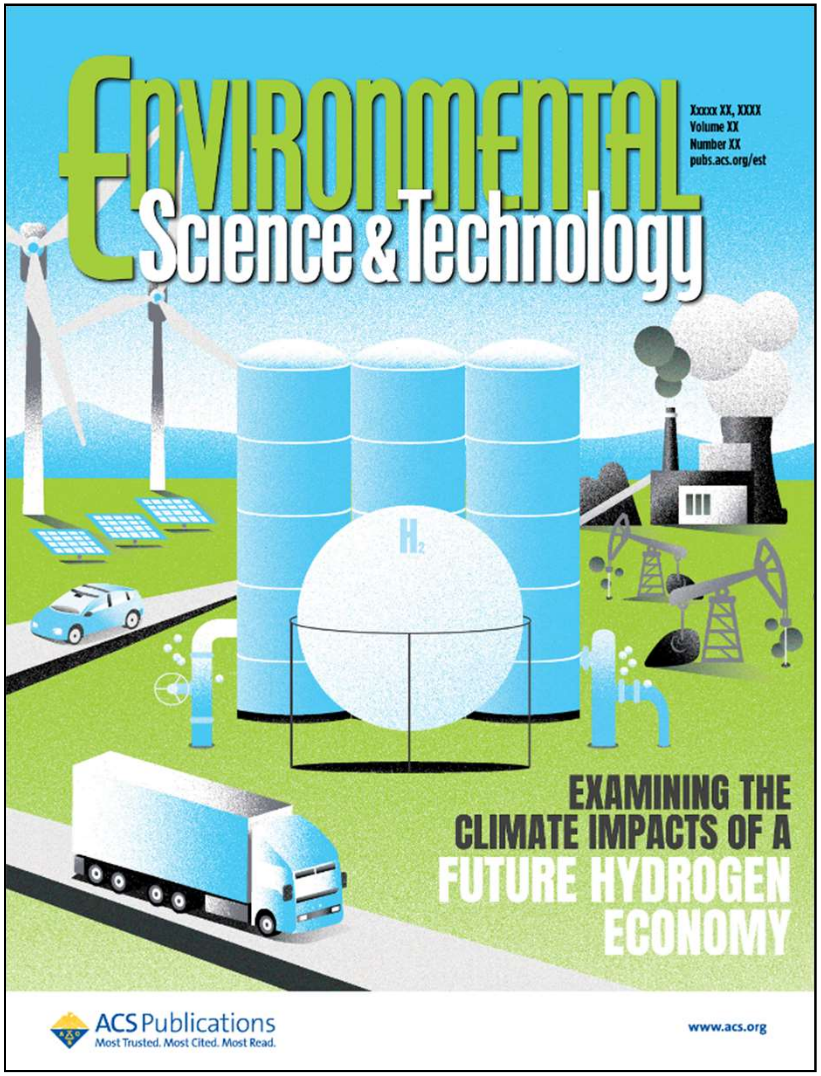
2013 — The **IPCC Fifth Assessment Report** discusses hydrogen's GWP_{100} (5.8).[IPCC AR5 WGI 8.SM.14]

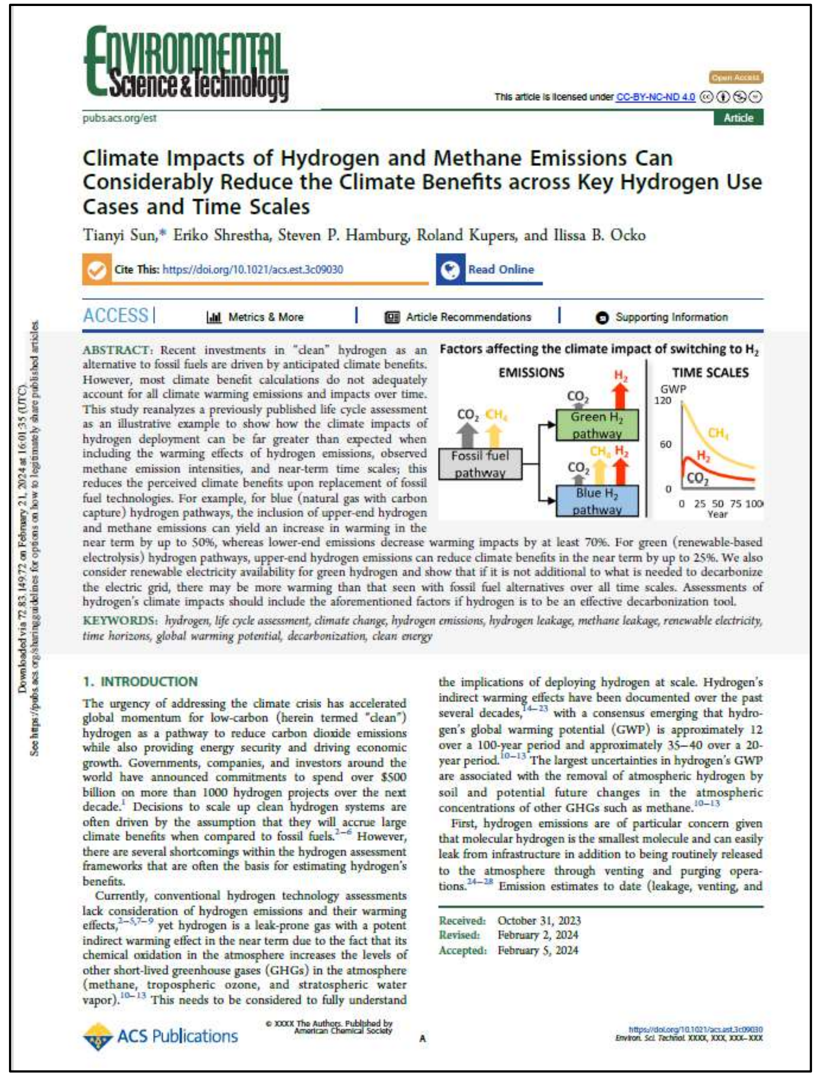
2021 — The first assessment of **hydrogen's full atmospheric warming potency** is published.[Paulot et al.]

2022 — Studies published showing the **climate risks of hydrogen emissions in the near- and long-term**. The **IPCC Sixth Assessment Report** identifies hydrogen leakage as a challenge.[Hauglustaine et al.; Bertagni et al.; Ocko and Hamburg; IPCC AR6 WGIII 6.4.5]

2023 — **Multi-model assessment of hydrogen's total warming potency** is published (GWP_{100}: 12).[Sand et al.]

Levy (1972), Derwent et al. (2001), IPCC TAR (2001), Prather (2003), Schultz et al. (2003), IPCC AR4 (2007), IPCC AR5 (2013), Paulot et al. (2021), Hauglustaine et al. (2022), Bertagni et al. (2022), Ocko and Hamburg (2022), IPCC AR6 (2022), Sand et al. (2023)





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Article

Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales

Tianyi Sun,* Eriko Shrestha, Steven P. Hamburg, Roland Kupers, and Ilissa B. Ocko

Cite This: https://doi.org/10.1021/acs.est.3c09030

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ABSTRACT: Recent investments in "clean" hydrogen as an alternative to fossil fuels are driven by anticipated climate benefits. However, most climate benefit calculations do not adequately account for all climate warming emissions and impacts over time. This study reanalyzes a previously published life cycle assessment as an illustrative example to show how the climate impacts of hydrogen deployment can be far greater than expected when including the warming effects of hydrogen emissions, observed methane emission intensities, and near-term time scales; this reduces the perceived climate benefits upon replacement of fossil fuel technologies. For example, for blue (natural gas with carbon capture) hydrogen pathways, the inclusion of upper-end hydrogen and methane emissions can yield an increase in warming in the near term by up to 50%, whereas lower-end emissions decrease warming impacts by at least 70%. For green (renewable-based electrolysis) hydrogen pathways, upper-end hydrogen emissions can reduce climate benefits in the near term by up to 25%. We also consider renewable electricity availability for green hydrogen and show that if it is not additional to what is needed to decarbonize the electric grid, there may be more warming than that seen with fossil fuel alternatives over all time scales. Assessments of hydrogen's climate impacts should include the aforementioned factors if hydrogen is to be an effective decarbonization tool.

Factors affecting the climate impact of switching to H_2

EMISSIONS

CO_2 CH_4 Fossil fuel pathway

CO_2 H_2 Green H_2 pathway

CO_2 CH_4 H_2 Blue H_2 pathway

TIME SCALES

GWP 120 60 0

CH_4 H_2 CO_2

0 25 50 75 100 Year

KEYWORDS: *hydrogen, life cycle assessment, climate change, hydrogen emissions, hydrogen leakage, methane leakage, renewable electricity, time horizons, global warming potential, decarbonization, clean energy*

1. INTRODUCTION

The urgency of addressing the climate crisis has accelerated global momentum for low-carbon (herein termed "clean") hydrogen as a pathway to reduce carbon dioxide emissions while also providing energy security and driving economic growth. Governments, companies, and investors around the world have announced commitments to spend over $500 billion on more than 1000 hydrogen projects over the next decade.[1] Decisions to scale up clean hydrogen systems are often driven by the assumption that they will accrue large climate benefits when compared to fossil fuels.[2−6] However, there are several shortcomings within the hydrogen assessment frameworks that are often the basis for estimating hydrogen's benefits.

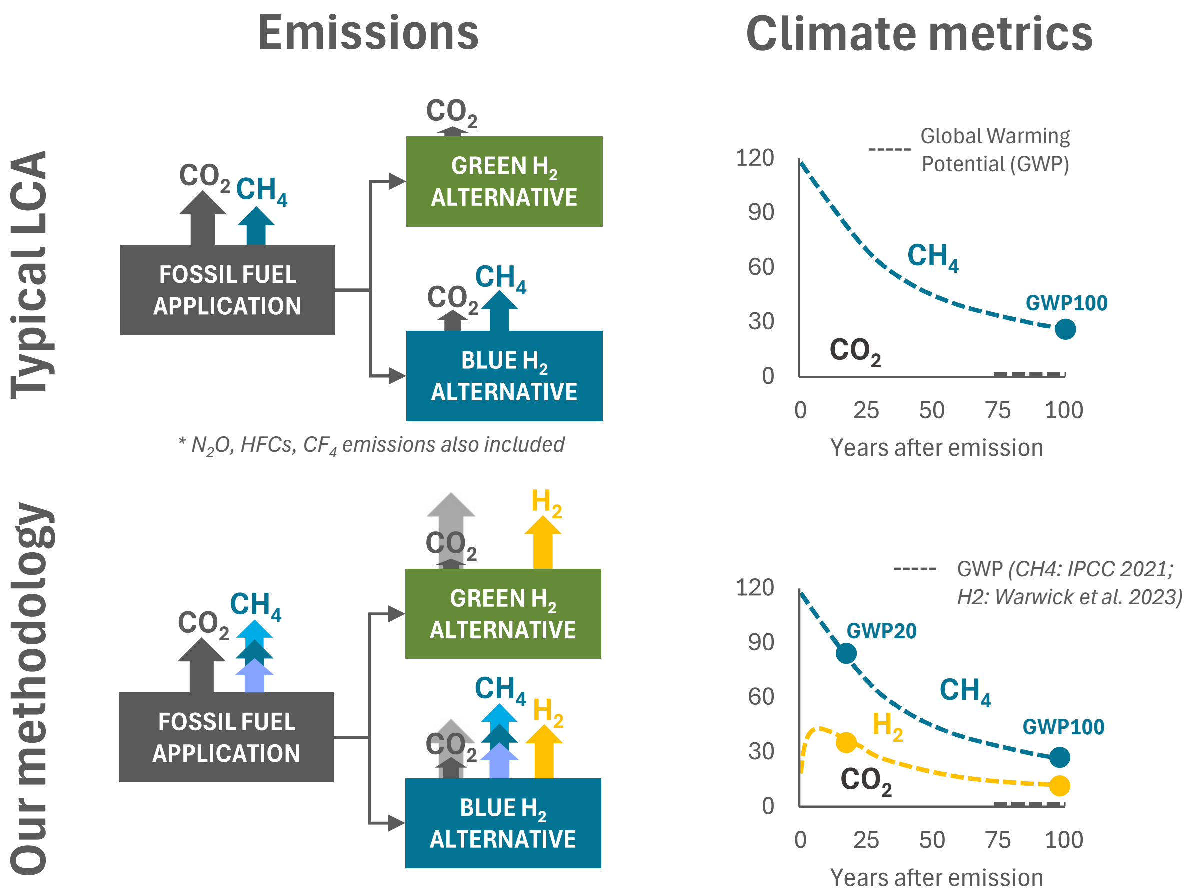
Currently, conventional hydrogen technology assessments lack consideration of hydrogen emissions and their warming effects,[2−5,7−9] yet hydrogen is a leak-prone gas with a potent indirect warming effect in the near term due to the fact that its chemical oxidation in the atmosphere increases the levels of other short-lived greenhouse gases (GHGs) in the atmosphere (methane, tropospheric ozone, and stratospheric water vapor).[10−13] This needs to be considered to fully understand the implications of deploying hydrogen at scale. Hydrogen's indirect warming effects have been documented over the past several decades,[14−23] with a consensus emerging that hydrogen's global warming potential (GWP) is approximately 12 over a 100-year period and approximately 35−40 over a 20-year period.[10−13] The largest uncertainties in hydrogen's GWP are associated with the removal of atmospheric hydrogen by soil and potential future changes in the atmospheric concentrations of other GHGs such as methane.[10−13]

First, hydrogen emissions are of particular concern given that molecular hydrogen is the smallest molecule and can easily leak from infrastructure in addition to being routinely released to the atmosphere through venting and purging operations.[24−28] Emission estimates to date (leakage, venting, and

Received: October 31, 2023
Revised: February 2, 2024
Accepted: February 5, 2024

Sun et al., *Environ. Sci. Tech.*, 58, 5299–5309 (2024)

The purpose of this study is to examine the importance of including overlooked factors in hydrogen climate impact assessments



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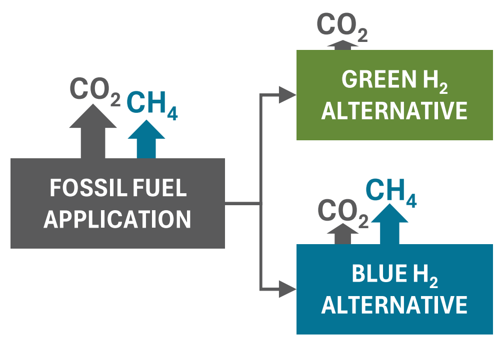
Emissions

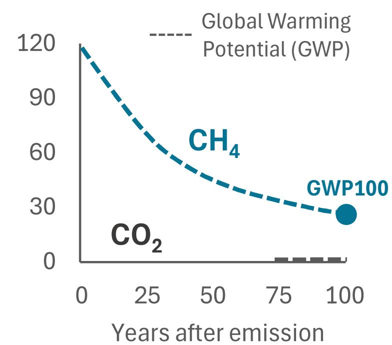
Climate metrics

Example

Typical LCA

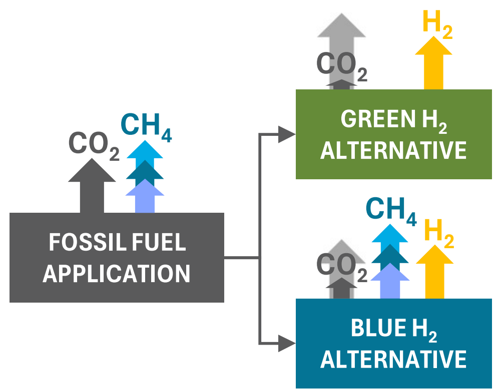


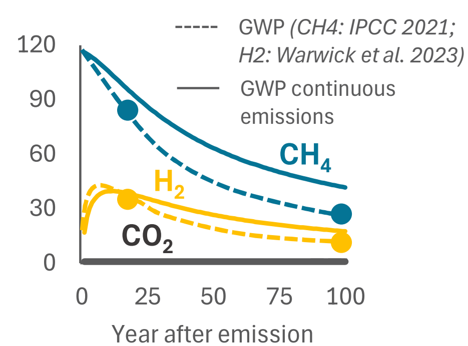
* N_2O, HFCs, CF_4 emissions also included



Hydrogen Council (2021)
Hydrogen decarbonization pathways: A life-cycle assessment
8 well-to-use hydrogen pathways in the industry, transport, and power sectors and fossil fuel technology counterparts

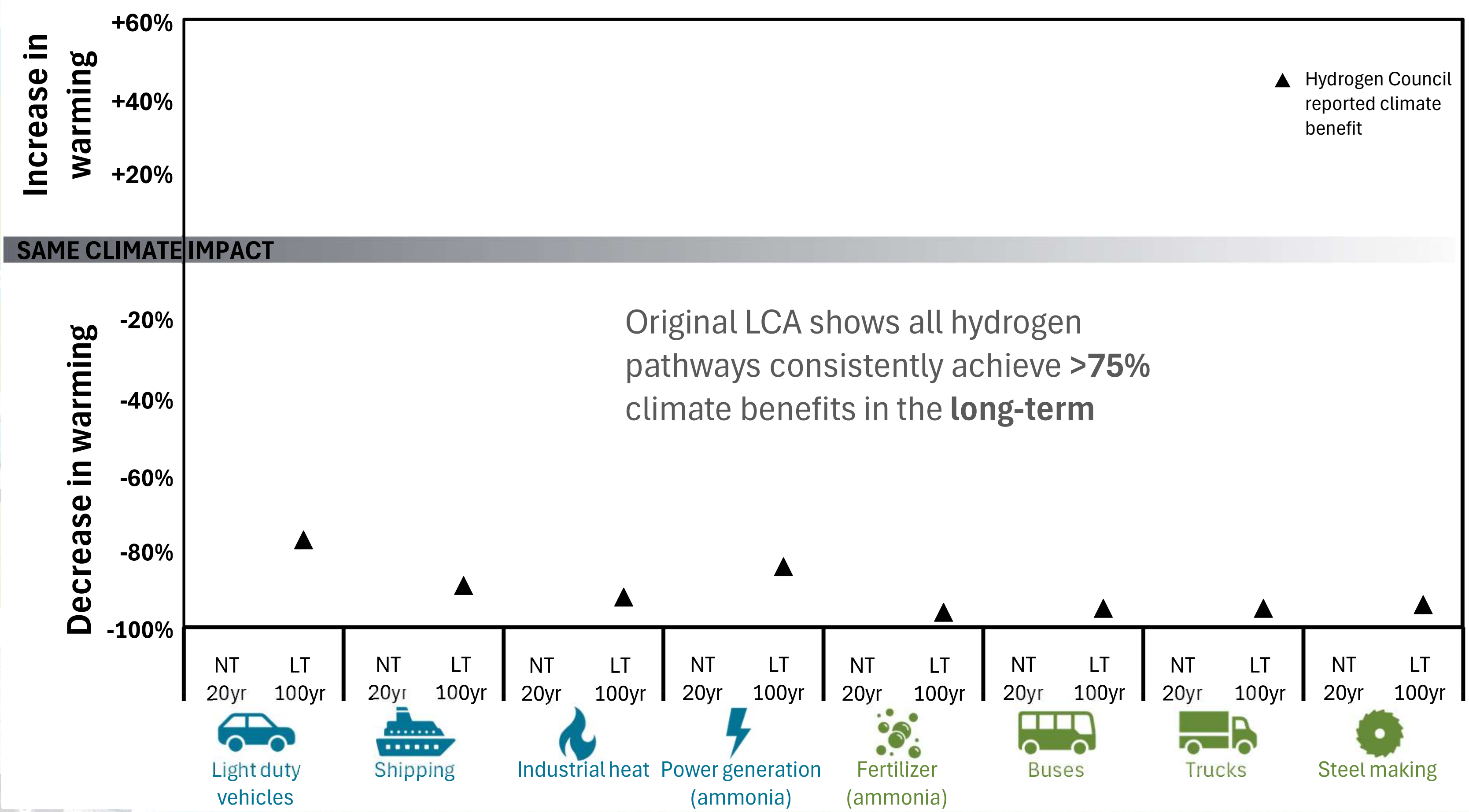
Our methodology





Our study
Reanalyze exact same pathways and fossil fuel counterparts

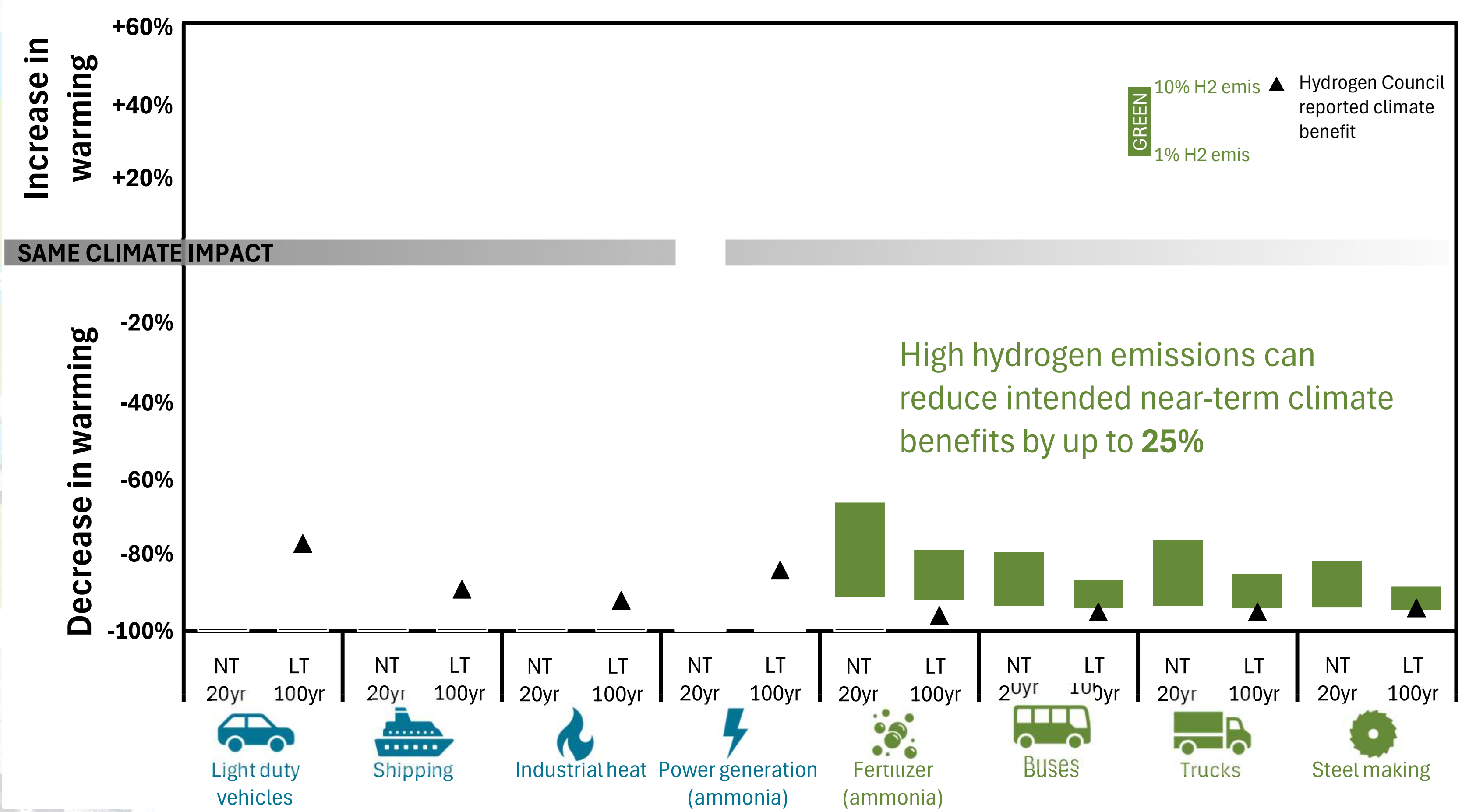
Climate impacts of switching to hydrogen technologies from fossil fuel



NOTE: climate impacts across applications and production methods ARE NOT directly comparable given the variations in pathways

Sun et al. 2024 ES&T

Climate impacts of switching to hydrogen technologies from fossil fuel



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Sun et al. 2024 ES&T

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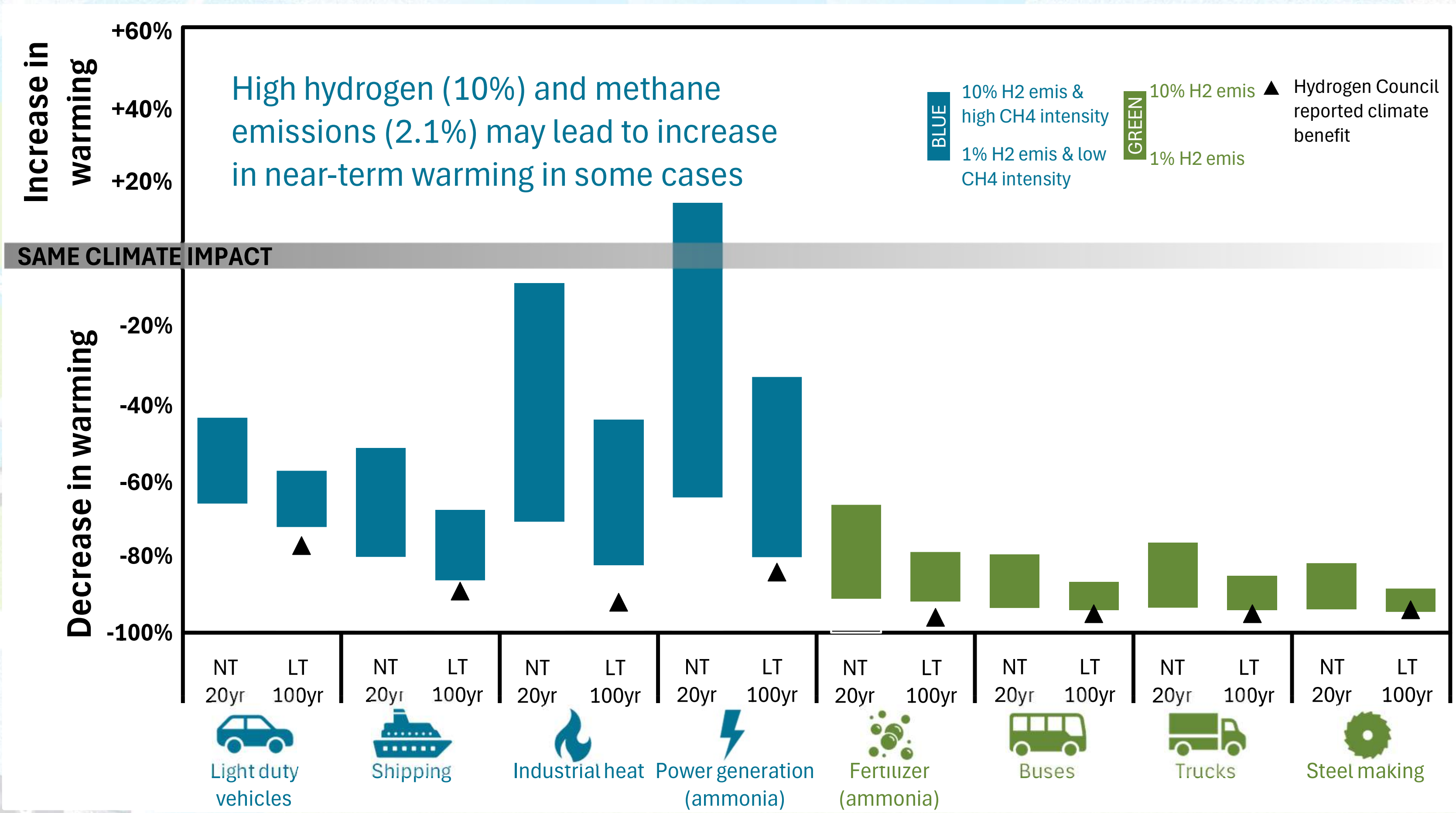

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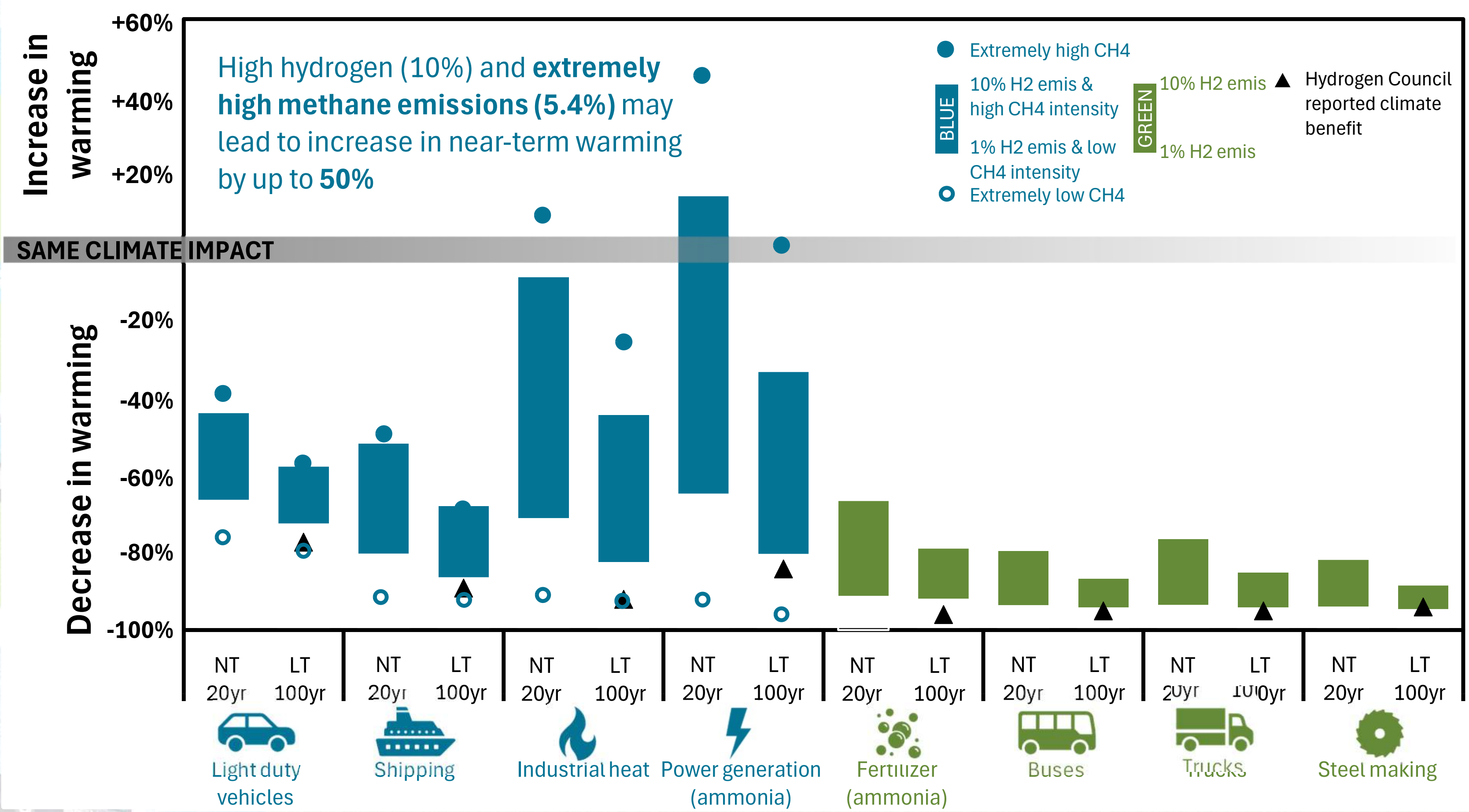

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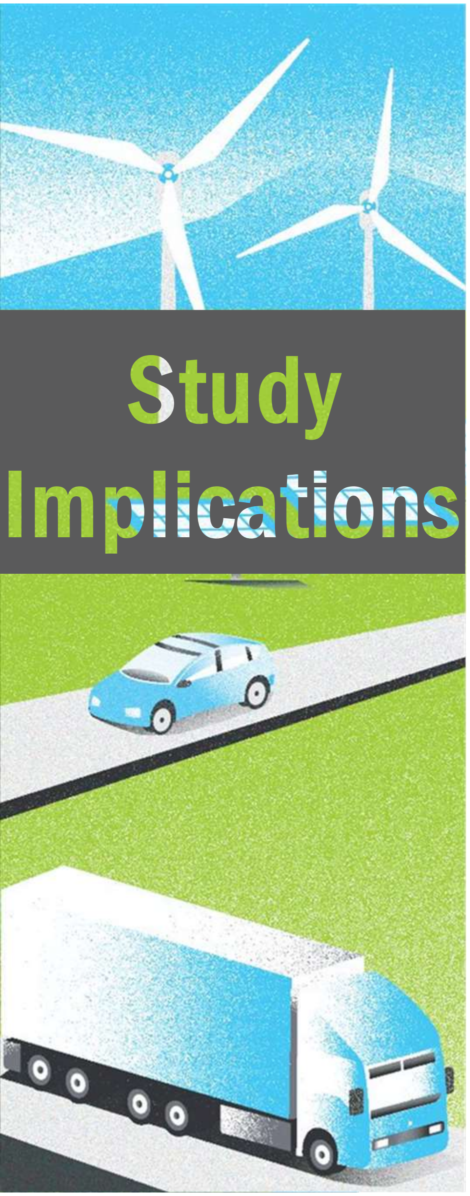
Sun et al. 2024 ES&T



Study Implications

Including the latest science in assessments of clean hydrogen's climate impacts will lead to a significantly **better climate outcomes** because we can make better decisions and determine mitigation strategies.

We have an opportunity to ensure the enormous investment in hydrogen projects worldwide yields the climate benefits being sought – and **avoids unintended climate consequences** by

- accurately accounting for hydrogen's climate impact,
- keeping **hydrogen and methane emissions** to a minimum,
- producing green hydrogen using **additional** renewable electricity, and
- deploying **high efficiency and permanence** for carbon capture.

How much hydrogen is emitted today?

Fugitive

Leakage • **Pe**rmeation • **D**iffusion

Operational

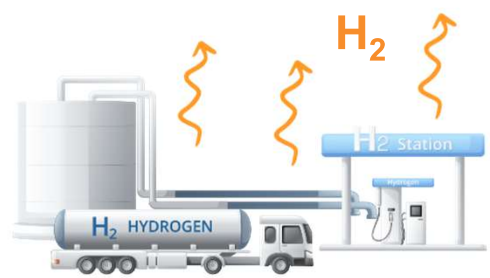
Residual • **V**enting • **Pu**rging • **B**oil-off

PRODUCTION

Electrolysis (L, R, Pu)
SMR (L, R, V, Pu)

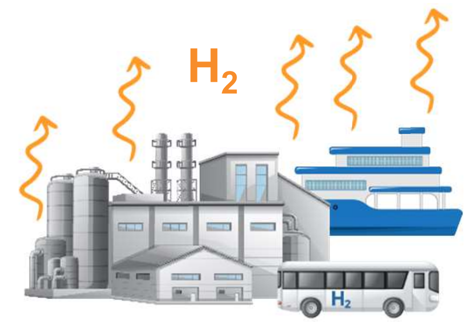
CONVERSION & STORAGE

Compression (L, V, Pe)
Liquefaction (L)
Above-ground gas (L, Pe)
Above-ground liquid (L, Pe, V, B)
Underground (L, Pe, V, Pu)



DISTRIBUTION

Pipelines (L, D, V)
Tube trailer gas (L, Pu)
Truck liquid (B)
Shipping (L, B)
Liquid handling (L, V, B)
Refueling gas (L, Pe, V, Pu)
Refueling liquid (L, B, Pu)



END USE APPLICATION

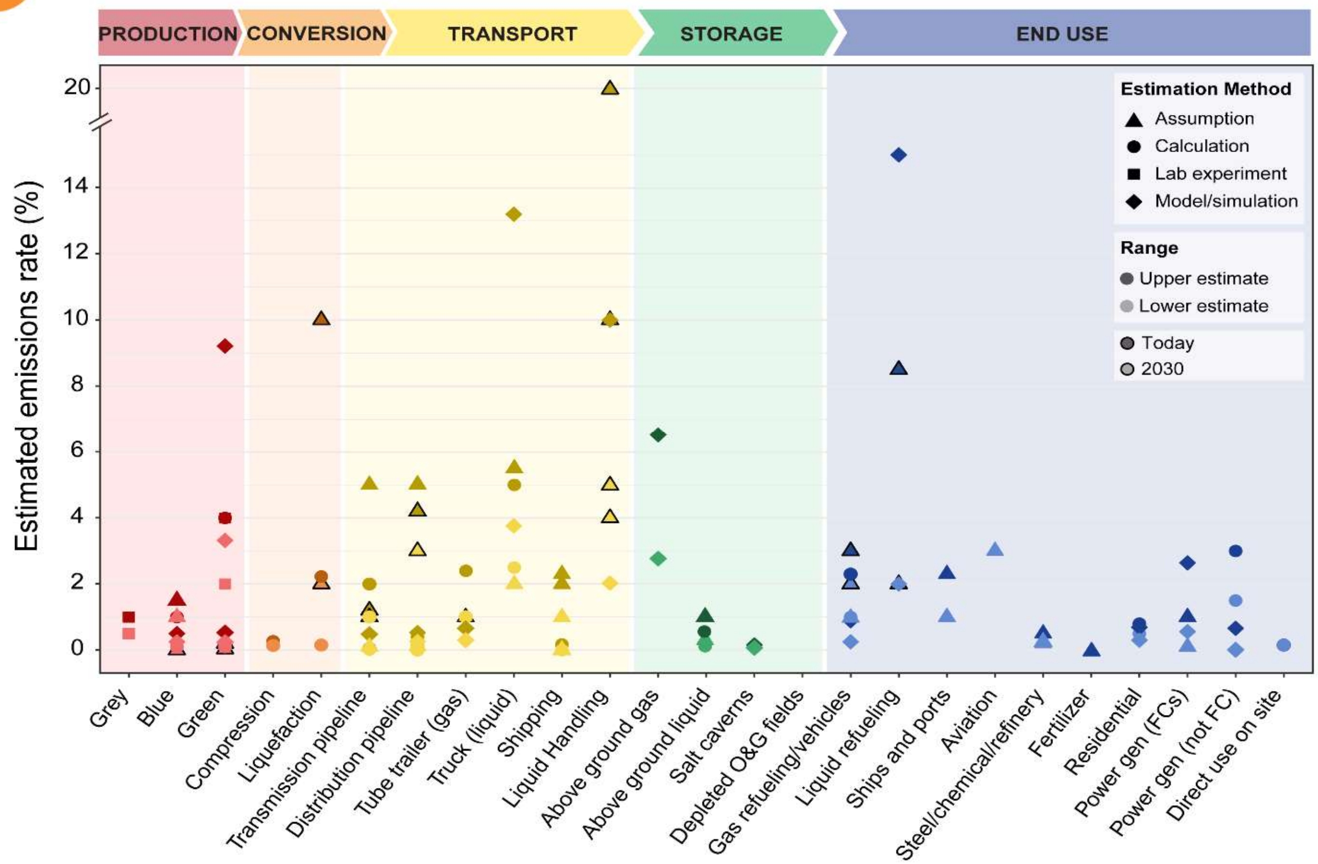
Industry (L, R)
Buildings (L, Pu)
Power gen FC (L, V, Pu)
Power gen ICE, gas turbine (L, V, Pu)

How much hydrogen is emitted today?

1 **No data**
Lack of in-field measurements from venting, purging, leakages

2 **Instrumentation**
capable of measuring small leaks and site-wide emissions (ppb level) is only now becoming available

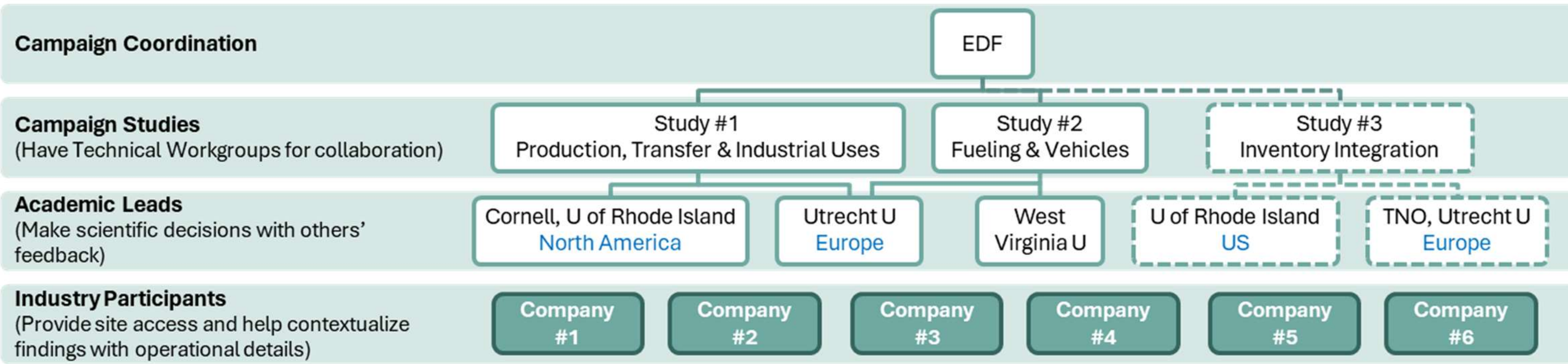
3 **Wide range in published estimates** (<1 to 20%)



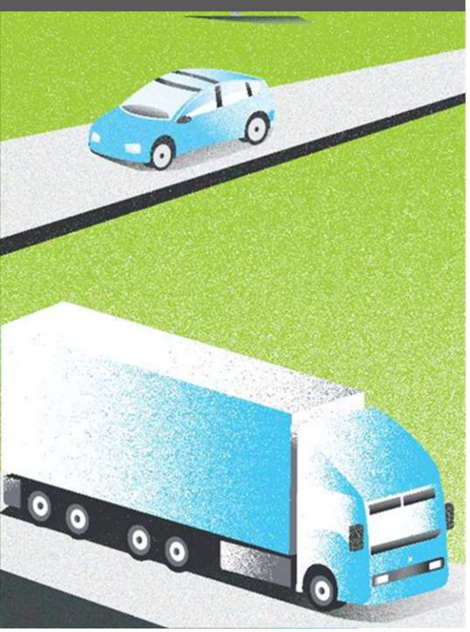
Source: Esquivel Elizondo et al. 2023

Collaborative H_2 Emissions Measurement Campaign

Campaign studies structure



What's Next



Advocating for including the latest science in assessments of clean hydrogen's climate impacts for better decision-making and determining mitigation strategies.

Working on **additional GHG assessments** comparing clean hydrogen with fossil fuels and **other clean alternatives** (e.g., electrification, carbon capture) across 11 end use applications, which can inform where to best deploy hydrogen.

Launching a collaborative initiative with academia and industry to **measure and quantify hydrogen emissions** from today's value chain, better constrain emission rates, and inform best practices and mitigation strategies to minimize hydrogen emissions as the industry scales up.

Thank you!

Environmental Defense Fund

Key references and resources

PEER-REVIEWED ARTICLES:

Warwick et al., **Atmospheric composition and climate impacts of a future hydrogen economy,** *Atmospheric Chemistry and Physics* (2023)

Sand et al., **A multi model assessment of the Global Warming Potential of hydrogen,** *Commun Earth Environ,* 4, 203 (2023) ***EDF complementary blog post***

Esquivel Elizondo et al., **Wide range in estimates of hydrogen emissions from infrastructure**, *Frontiers in Energy Research*, 11 (2023) ***EDF complementary blog post***

Ocko and Hamburg, **Climate consequences of hydrogen emissions**, *Atmos. Chem. Phys.*, 22, 9349 9368 (2022) ***EDF complementary blog post***

Sun et al., **Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales**, *Environ. Sci. Tech.*, 58, 5299 5309 (2024)

FACTSHEETS:

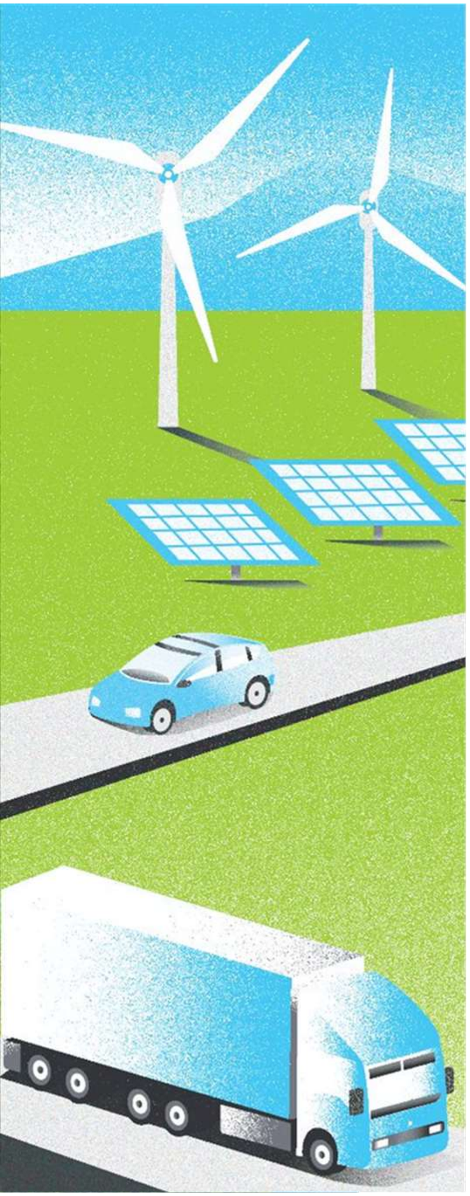
Climate impacts of hydrogen **[PDF]**

The science of hydrogen's climate warming effects **[PDF]**

Hydrogen Emissions Measurement Study **[PDF]**

Preventing and mitigating hydrogen emissions from infrastructure **[PDF]**

Environmental Defense Fund



	LCA COMPONENT	ORIGINAL[1]	OUR STUDY
BOTH	Hydrogen emissions warming impact	None	**1-10% pathway emission rate**
BLUE HYDROGEN	Observed methane emissions intensity	Gas: 0.2-0.5% Oil: 0.35 g/kWh	**Gas: 0.6-2.1%** (0.01 & 5.4%) **Oil: 0.6-2.6 g/kWh** (0.006 & 11.4 g/kWh)
	Carbon capture efficiency	98%	**98%** **60%**
GREEN HYDROGEN	Renewable electricity source	Additional	**Additional** **Non-additional, replaced by coal** **Non-additional, replaced by natural gas**

Hydrogen Council, Hydrogen decarbonization pathways: A life-cycle assessment, 2021