Climate consequences of hydrogen emissions

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5   **Abstract.** Given the urgency to decarbonize global energy systems, governments and industry are moving ahead with efforts to increase deployment of hydrogen technologies, infrastructure, and applications at an unprecedented pace, including billions in national incentives and direct investments. While zero- and low-carbon hydrogen hold great promise to help solve some of the world's most pressing energy challenges, hydrogen is also an indirect greenhouse gas whose warming impact is both widely overlooked and underestimated. This is largely because hydrogen's atmospheric warming effects are short-lived – lasting only

10   a couple decades – but standard methods for characterizing climate impacts of gases consider only the long-term effect from a one-time pulse of emissions. For gases whose impacts are short-lived, like hydrogen, this long-term framing masks a much stronger warming potency in the near- to medium-term. This is of concern because hydrogen is a small molecule known to easily leak into the atmosphere and the total amount of emissions (leakage, venting, purging) from existing hydrogen systems is unknown. Therefore, the effectiveness of hydrogen as a decarbonization strategy, especially over timescales of several

15   decades, remains unclear. This paper evaluates the climate consequences of hydrogen emissions over all timescales by employing already published data to assess its potency as a climate forcer, evaluate the net warming impacts from replacing fossil fuel technologies with their clean hydrogen alternatives, and estimate temperature responses to projected levels of hydrogen demand. We use the standard Global Warming Potential metric given its acceptance to stakeholders – incorporating newly published equations that more fully capture hydrogen's several indirect effects – but consider effects of constant rather

20   than pulse emissions over multiple time horizons. We account for a plausible range of hydrogen emission rates, and include methane emissions when the hydrogen is produced via natural gas with CCUS ('blue' hydrogen) as opposed to renewables and water ('green' hydrogen). For the first time, we show the strong dependence on timescale when evaluating the climate change mitigation potential of clean hydrogen alternatives, with the emissions rate determining the scale of climate benefits or disbenefits. For example, green hydrogen applications with upper end emissions rates (10%) may only cut climate impacts

25   from fossil fuel technologies in half over the first two decades, which is far from the common perception that green hydrogen energy systems are climate neutral. However, over a 100-year period, climate impacts could be reduced by around 80%. On the other hand, lower end emissions (1%) could yield limited impacts on the climate over all timescales. For blue hydrogen, associated methane emissions can make hydrogen applications worse for the climate than the fossil fuel technologies for several decades if emissions are high for both gases, but over 100 years yields climate benefits. While more work is needed to

30   evaluate the warming impact of hydrogen emissions for specific end-use cases and value-chain pathways, it is clear that

hydrogen emissions matter for the climate and warrant further attention by scientists, industry, and governments. This is critical to informing where and how to deploy hydrogen effectively in the emerging decarbonized global economy.

1 Introduction

Hydrogen is now considered an essential component in transitioning to a low-carbon global economy and achieving net zero greenhouse gas emissions targets. This is due to its potential to be a zero or near-zero carbon energy carrier to replace fossil fuel use, including in hard-to-abate sectors and for storage of renewable electricity (International Energy Agency, 2021). Dozens of countries have recently released plans to scale up clean hydrogen production and consumption, and $500B could be spent across the globe on hydrogen developments by 2030 (Hydrogen Council, 2021c). However, one climate concern has been largely absent in recent conversations and assessments of the role of hydrogen (International Energy Agency, 2019; International Energy Agency, 2021; BloombergNEF, 2020; Bartlett and Krupnick, 2020; van Renssen, 2020; World Energy Council, 2021; Hydrogen Council, 2021c; Ueckerdt et al., 2021; International Renewable Energy Agency, 2022): the warming effects from hydrogen emitted into the atmosphere.

Scientists have long-known and cautioned that hydrogen has indirect warming impacts (Ehhalt et al., 2001; Derwent et al., 2001, 2006, 2020; Prather, 2003; Schultz et al., 2003; Warwick et al., 2004, 2022; Colella et al., 2005; Wuebbles et al., 2010; Derwent, 2018; Paulot et al., 2021; Field and Derwent, 2021). When it escapes into the atmosphere, hydrogen has two main fates: around 70 to 80% is estimated to be removed by soils via diffusion and bacterial uptake, and the remaining 20 to 30% is oxidized by reacting with the naturally-occurring hydroxyl radical (OH), yielding an atmospheric lifetime of around a few years (Rahn et al., 2003; Derwent, 2018; Paulot et al., 2021; Warwick et al., 2022). The oxidation of hydrogen in the atmosphere leads to increasing concentrations of greenhouse gases in both the troposphere and stratosphere, as described in Fig. 1 (Derwent, 2018; Derwent et al., 2020; Paulot et al., 2021; Field and Derwent, 2021; Warwick et al., 2022).

In the troposphere, less OH is available to react with methane, and given that methane's reaction with OH is its primary sink, this leads to a longer atmospheric lifetime for methane which accounts for around half of hydrogen's total indirect warming effect (Paulot et al., 2021). Also in the troposphere, the production of atomic hydrogen from hydrogen oxidation leads to a series of reactions that ultimately form tropospheric ozone, a greenhouse gas, which accounts for about 20% of hydrogen's radiative impacts (Paulot et al., 2021). In the stratosphere, the oxidation of hydrogen increases water vapor, which in turn increases the infrared radiating capacity of the stratosphere, leading to stratospheric cooling and an overall warming effect on the climate because energy emitted out to space is now from a cooler temperature; this stratospheric effect accounts for about 30% of hydrogen's climate impacts (Paulot et al., 2021). The stratospheric cooling can also lead to an increase in stratospheric polar clouds that enable more ozone-destroying reactions to occur, but to date those effects have been deemed as minor (Tromp et al., 2003; Warwick et al., 2004, 2022; Jacobson, 2008; van Ruijven et al., 2011; Vogel et al., 2011, 2012; Wang et al., 2013; Wuebbles et al., 2010; Derwent, 2018; Paulot et al., 2021).

A growing body of research has affirmed that the warming effects from hydrogen emissions are consequential, with new work showing that hydrogen's indirect warming effects are twice as high as previously recognized (Paulot et al., 2021; Warwick et al., 2022); this is due to the inclusion of stratospheric effects that were not accounted until recently (Derwent, 2018; Derwent

65 et al., 2020). Studies that consider both tropospheric and stratospheric effects from hydrogen emissions report an indirect radiative efficiency of 0.13 and 0.18 mW m^{-2} ppbv^{-1}, respectively, whereas the studies that only account for tropospheric effects suggest an indirect radiative efficiency around 0.08 mW m^{-2} ppbv^{-1} (Derwent, 2018; Derwent et al., 2020; Paulot et al., 2021; Warwick et al., 2022). Converting hydrogen's full atmospheric radiative efficiencies to per unit mass (3.64E-13 and 5.04E-13 W m^{-2} kg^{-1}) and comparing to carbon dioxide (CO_2) and methane's radiative efficiencies (1.7 E-15 W m^{-2} kg^{-1} and 2.0 E-13 W

70 m^{-2} kg^{-1}, respectively) shows that hydrogen's indirect warming potency per unit mass is around 200 times that of carbon dioxide's and larger than methane's (Forster et al., 2021). However, like methane, hydrogen's warming effects are potent but short-lived. Most of hydrogen's effects are shorter-lived than methane's – occurring within a decade after emission – but its impacts on methane can affect the climate for roughly an additional decade (Warwick et al., 2022).
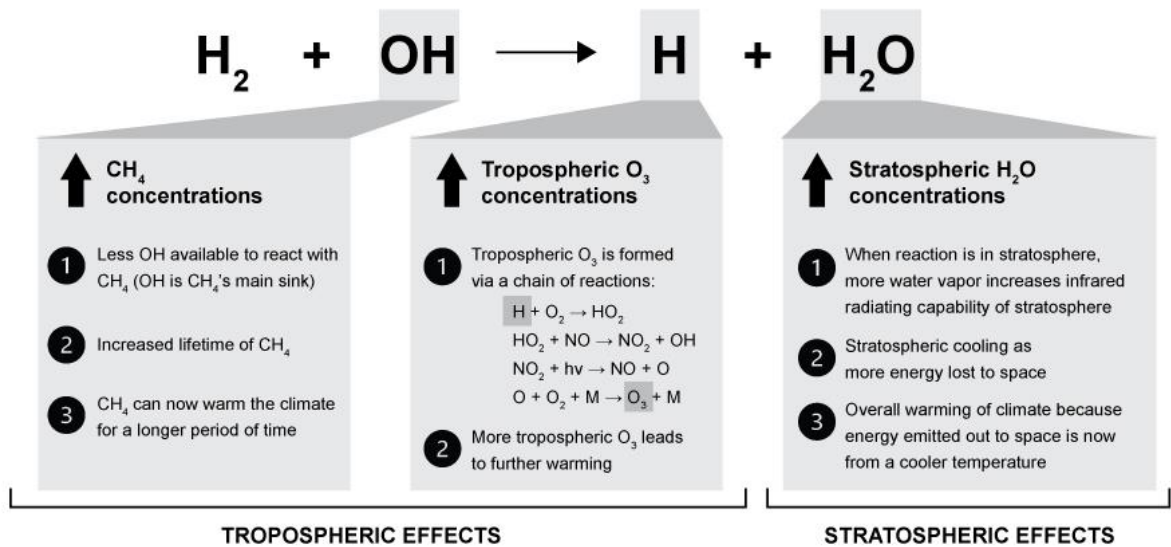

75 **Figure 1: Effects of hydrogen oxidation on atmospheric greenhouse gas concentrations and warming.**

Hydrogen's warming effects have major implications for an emerging hydrogen economy because hydrogen is a tiny molecule that is hard to contain. It can leak across the entire value chain, including from electrolysers, compressors, liquefiers, storage tanks, geologic storage, pipelines, trucks, trains, ships, and fuelling stations (Bond et al., 2011; van Ruijven et al., 2011; Melaina et al., 2013; Cooper et al., 2022; Frazer-Nash Consultancy, 2022). Further, some hydrogen is deliberately vented and

80 purged into the atmosphere from these systems (Frazer-Nash Consultancy, 2022).

While it is clear that hydrogen leakage poses a risk to decarbonization goals given its potency as an indirect greenhouse gas, there are several challenges associated with determining the overall magnitude and thus importance of its warming impacts on the effectiveness of hydrogen as a decarbonization strategy. First is the uncertainty of how much hydrogen will ultimately be emitted from hydrogen systems. The total amount of emissions (leakage, venting, purging) in current hydrogen systems remains unknown as empirical data on leakage rates from specific infrastructure (such as electrolysers, pipelines, vehicles, storage) is completely lacking. This is because measurement efforts to date have been focused on safety concerns, regulations, and risk assessment, which are focused on larger leaks. Commercially available sensing technologies able to detect smaller leaks – that would impact the climate but not safety – are unavailable (Mejia et al., 2020). Further, most of the hydrogen infrastructure needed to achieve decarbonization goals has yet to be built, with plans underway to develop more pipelines and even pump hydrogen into individual homes (United Kingdom. Secretary of State for Business, 2021).

Second is the uncertainty in how much hydrogen will be deployed in the future, how it will be produced, and what fossil fuel technologies it will replace. Currently, hydrogen is produced mostly from natural gas, and accounts for only a small fraction of the global economy with uses confined mainly to fertilizer production and refineries (International Energy Agency, 2021). However, projections suggest that demand could increase up to tenfold by mid-century, with applications ranging from industrial processes, building heating, a diversity of transportation systems, to providing clean firm power to complement long-term renewable energy intermittency (Hydrogen Council, 2017; BloombergNEF, 2020, 2021; International Energy Agency, 2021; Energy Transition Commission, 2021). While hydrogen leakage across the value chain is a concern regardless of production method and therefore applies to all hydrogen – including "green" hydrogen produced from water using renewable energy (considered "zero-carbon" or "climate neutral") and "blue" hydrogen produced from natural gas using CCUS technologies (considered "low-carbon") – blue hydrogen is subject to additional impacts on the energy balance due to residual emissions of CO_2 as well as emissions of methane from the natural gas supply value chain (see Fig. 2). The specific fossil fuel technologies that are replaced with hydrogen alternatives will also determine the net climate benefit from deploying clean hydrogen via how much carbon dioxide and methane emissions can be reduced (Fig. 2).
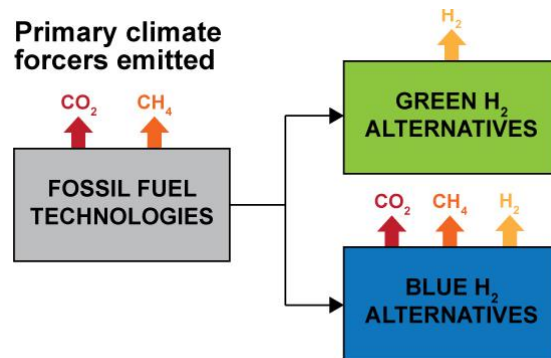
Figure 2. Primary climate forcers emitted from fossil fuel technologies and their clean hydrogen alternatives.

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The third challenge is how hydrogen's warming impacts are calculated and reported. Beyond the general uncertainties associated with estimating the direct and indirect radiative effects of any atmospheric constituent, the way in which scientists typically report the radiative potency of a climate forcer (such as via radiative efficiency or radiative forcing) can be inaccessible to and lack context for climate policy and business decision makers. Therefore, decades ago, scientists began developing simplified metrics for comparing the warming impacts among different greenhouse gases, with CO_2's potency typically as the baseline for the comparison given its status as the most concerning human-emitted climate forcer. The most well-known and widely-used metric has consistently been the Global Warming Potential (GWP) with a 100-year time horizon, and is even baked into policies, international agreements, and greenhouse gas reporting requirements. GWP calculates the relative warming effect over a specified time interval from a pulse of emissions of a climate forcer compared to an equal pulse in mass of CO_2.

However, mostly because of its pulse approach, using this method to compare the climate effects between a climate forcer whose impacts are short-lived (such as hydrogen, and most notably methane) and a climate forcer whose impacts are long-lived (such as CO_2) is complicated. For example, if a 100-year time horizon is used, it masks the true impact of hydrogen during the decades in which it is influencing the climate, providing the inaccurate perception that hydrogen's warming effects are much smaller than they are. On the other hand, it also provides the inaccurate perception that a pulse of hydrogen can influence the climate 100 years later. If a 20-year time horizon is used, it is more representative of hydrogen's impacts while it is affecting the atmosphere, but it disregards CO_2's impacts after 20 years, when it is still affecting the atmosphere.

This temporal issue of comparing warming impacts of short- and long-lived climate forcers has been extensively discussed in the literature for decades and has been a major source of confusion in the climate policy community; it has also led to the development of numerous alternative metrics designed to improve the comparisons (Shine et al., 2007; Alvarez et al., 2012; Allen et al., 2016; Cherubini and Tanaka, 2016; Ocko et al., 2017; Fesenfeld et al., 2018; Balcombe et al., 2018; Ocko and Hamburg, 2019; Cain et al., 2019; Collins et al., 2020; Severinsky and Sessoms, 2021; Lynch et al., 2021). However, stakeholders continue to rely on GWP as their way to understand the potency of any non-CO_2 climate forcer, and specifically GWP with a 100-year time horizon (GWP-100).

The implications of this challenge for hydrogen are that the majority of studies to date have assessed its climate effects either using technical indicators (such as radiative forcing) or relied on GWP-100 which did not convey hydrogen's near-term impacts (Derwent et al., 2001, 2006, 2020; Prather, 2003; Schultz et al., 2003; Wuebbles et al., 2010; Derwent, 2018; Field and Derwent, 2021, Paulot et al., 2021). Further, until recently, the only published estimates of hydrogen's warming effects were focused on tropospheric responses. These two factors have had the result of undervaluing hydrogen's warming potency and overlooking its near-term effects. For example, new estimates of hydrogen's GWP that include stratospheric effects show that hydrogen's GWP-100 is twice as high as the previous central estimate of GWP-100 = 5 ± 1 (Derwent et al., 2020; Warwick et al., 2022). In terms of its near-term potency, the first estimates of hydrogen's GWP for a 20-year time horizon (GWP-20)

yields a potency that is three times higher than its 100-year impact (GWP-20 = 33 [20 – 40]; Warwick et al., 2022). In other words, hydrogen's potency can be six times higher than commonly thought when looking at the critical next couple of decades.

140 Finally, accounting for methane emissions in climate assessments of clean hydrogen applications also suffers the same analytical challenges as hydrogen given that it is also a short-lived gas commonly assessed through a long-term lens. The climate effects of methane emissions are further underestimated given that natural gas leak rates are consistently underestimated in national emission inventories (Alvarez et al., 2018; Shen et al., 2021). Studies have shown that considering high methane emissions from upstream supply chains associated with blue hydrogen production when considered on shorter

145 time horizons reveals near-term harm to the climate that is not conveyed with standard GWP-100 assessments (Howarth and Jacobson, 2021).

Overall, the question remains: how will hydrogen's full atmospheric warming impacts diminish its effectiveness as a decarbonization strategy across all timescales? While more sophisticated modelling will be needed to fully incorporate all complexities, interactions, and uncertainties described above, a first-order analysis is possible using already published data

150 with minor improvements to the standard GWP metric to assess impacts over time and account for constant emissions. A constant emissions rate, as opposed to a one-time pulse of emissions, is important because continuous emissions more realistically represent hydrogen emissions in a hydrogen economy. In this work, we examine the net climate impacts over time for a generic case of replacing fossil fuel technologies with clean hydrogen alternatives using a plausible range of future hydrogen emission rates. We also include emissions of methane associated with blue hydrogen production for a range of

155 plausible leak rates. We use newly published GWP equations for hydrogen's indirect effects (Warwick et al. 2022) and report the outcomes of constant emissions for time horizons of 10 to 100 years.

The approach utilized is known as the Technology Warming Potential (Alvarez et al., 2012), and is similar to that of a life cycle assessment in that it compares climate impacts from two alternative technologies to help inform decision makers of the net benefits of switching from one to another. This method retains the familiar GWP formulation but conveys the climate

160 implications over time from a sustained switch to hydrogen alternatives from fossil fuel technologies. Further, we use a simple approach to estimate temperature responses to projected hydrogen demand levels, providing an indication of the absolute climate consequences of hydrogen emissions.

2 Methodology

Our analysis is comprised of three components. First, to provide context on hydrogen's warming potency as an agent of climate

165 change, we compare hydrogen's warming effects to that of carbon dioxide for equal mass using the traditional GWP methodology. Second, to provide context on the implications of this warming potency for a hydrogen economy relative to a fossil fuel one, we compare the warming impacts from deploying clean hydrogen across a range of hydrogen and methane

emission rates to that from greenhouse gas emissions (CO_2 and methane) from fossil fuel utilization. Third, to provide context on the magnitude of this warming impact, we estimate temperature responses to future hydrogen emissions based on different

170   hydrogen demand levels and leak rates.

2.1 Climate impact calculations

To calculate the warming effects of hydrogen, methane, and carbon dioxide emissions, we use the traditional GWP metric but account for constant emissions rather than a pulse of emissions. We first use the Absolute Global Warming Potential (AGWP) components, which computes the cumulative radiative forcing of a climate forcer over a specified time horizon in (W m^{-2}) /

175   (kg yr^{-1}). For carbon dioxide and methane, we use the Intergovernmental Panel on Climate Change (IPCC) formulations of AGWP, Eqns. (1) and (2), respectively (Myhre at al., 2013; Forster et al., 2021). Input parameters and their sources can be found in Table 1.

$$AGWP_{CO_2}(H) = A_{CO_2}\left\{ a_0 H + \sum_{i=1}^{3} a_i \tau_i \left(1 - exp\left(-\frac{H}{\tau_i}\right)\right)\right\} \tag{1}$$

$$AGWP_{CH_4}(H) = (1 + f_1 + f_2)A_{CH_4}\tau\left(1 - exp\left(-\frac{H}{\tau}\right)\right) \tag{2}$$

180   While these equations are appropriate for climate forcers with primarily direct radiative effects, hydrogen's radiative effects are entirely indirect. Therefore, we use the AGWP equations recently derived specifically for hydrogen based on sophisticated chemistry-climate modelling experiments, which explicitly accounts for its three main indirect effects and their varying temporal dynamics (methane, tropospheric ozone, and stratospheric water vapor) (Warwick et al., 2022). The equations are shown here (Eqns. (3) – (8)) and provide the same output information of cumulative radiative forcing per time horizon ((W m^{-2}) / (kg yr^{-1})) as in Eqns. (1) and (2). More details on their derivation are available in Warwick et al. (2022). Input parameters

185   and their sources can be found in Table 1.

$$AGWP1_{H_2,i}(H) = A_i\, a_i\, \tau_i\, \tau_{H2}\, C\left(tp - \tau_i\left(1 - exp\left(\frac{-tp}{\tau_i}\right)\right) - \left(\frac{\tau_{H2}}{(\tau_{H2} - \tau_i)}\right)\left(\tau_{H2}\left(1 - exp\left(\frac{-tp}{\tau_{H2}}\right)\right) - \tau_i\left(1 - exp\left(\frac{-tp}{\tau_i}\right)\right)\right)\right) \tag{3}$$

$$AGWP2_{H_2,i}(H) = \frac{\left(A_i\, a_i\, \tau_i\, \tau_{H2}^2 C\left(1 - exp\left(\frac{-tp}{\tau_{H2}}\right)\right)\right)}{(\tau_{H2} - \tau_i)}\left(\tau_{H2}\left(exp\left(\frac{-tp}{\tau_{H2}}\right) - exp\left(\frac{-H}{\tau_{H2}}\right)\right) - \tau_i\left(exp\left(\frac{-tp}{\tau_i}\right) - exp\left(\frac{-H}{\tau_i}\right)\right)\right) \tag{4}$$

$$AGWP3_{H_2,i}(H) = A_i\, a_i\, \tau_i^2\, \tau_{H2}\, C\left(\left(1 - exp\left(\frac{-tp}{\tau_i}\right)\right) - \left(\frac{\tau_{H2}}{(\tau_{H2} - \tau_i)}\right)\left(exp\left(\frac{-tp}{\tau_{H2}}\right) - exp\left(\frac{-tp}{\tau_i}\right)\right)\right)\left(exp\left(\frac{-tp}{\tau_i}\right) - exp\left(\frac{-H}{\tau_i}\right)\right) \tag{5}$$

$$AGWP_{H_2,i}(H) = AGWP1_{H_2,i}(H) + AGWP2_{H_2,i}(H) + AGWP3_{H_2,i}(H) \tag{6}$$

$$AGWP_{H_2,CH_4}(H) = (1 + f_1 + f_2)AGWP_{H_2,CH_4}(H) \tag{7}$$

$$AGWP_{H_2}(H) = AGWP_{H_2,CH_4}(H) + AGWP_{H_2,O_3}(H) + AGWP_{H_2,H_2O}(H) \tag{8}$$

Variable		Definition	Unit	Value	Source
H		Time horizon	Years	1 – 100	N/A
$AGWP_{CO_2}$					
A_{CO_2}		Radiative forcing scaling factor	W m^{-2} ppb^{-1}	1.33e-5	Forster et al. 2021
a_{0-3}		Coefficient for fraction of CO_2 remaining in atmosphere	unitless	α_0=0.2173; α_1=0.224; α_2=0.2824; α_3=0.2763	Myhre et al. 2013
τ_{1-3}		Timescale for fraction of CO_2 remaining in atmosphere	Years	τ_1=394.4; τ_2=36.54; τ_3=4.304	Myhre et al. 2013
$AGWP_{CH_4}$					
A_{CH_4}		Radiative forcing scaling factor	W m^{-2} ppb^{-1}	3.88e-4	Forster et al. 2021
τ		Perturbation lifetime	Years	11.8	Forster et al. 2021
f_1		Tropospheric ozone indirect effect scaling	unitless	0.37	Forster et al. 2021
f_2		Stratospheric water vapor indirect effect scaling	unitless	0.106	Forster et al. 2021
$AGWP_{H_2}$					
τ_{H2}		H_2 lifetime (combined chemical and deposition lifetime)	Years	1.9 (1.4,2.5)	Warwick et al. 2022 (Warwick et al. 2022, Paulot et al. 2021)
C		Conversion factor for converting H_2 mixing ratio (ppb) into H_2 mass (kg)	ppb kg^{-1}	3.5e-9	Warwick et al. 2022
tp		Length of step emission	Years	1	N/A
A_i	CH_4	Radiative forcing scaling factor	W m^{-2} ppb^{-1}	3.88e-4	Forster et al. 2021
	O_3		W m^{-2} DU^{-1}	0.042	Warwick et al. 2022
	H_2O		W m^{-2} ppb^{-1}	1e-4	Warwick et al. 2022
a_i	CH_4	Production rate of species resulting in the indirect forcing (mixing ratio yr^{-1}) per ppb H_2 change at steady-state	ppb(CH_4) ppb(H_2)$^{-1}$ yr^{-1}	1.46e-2	Warwick et al. 2022
	O_3		DU ppb(H_2)$^{-1}$ yr^{-1}	0.0056	Warwick et al. 2022
	H_2O		ppb(H_2O) ppb(H_2)$^{-1}$ yr^{-1}	0.042	Warwick et al. 2022
τ_i	CH_4	Perturbation lifetime of species causing the radiative forcing	Years	11.8	Forster et al. 2021
	O_3			0.07	Warwick et al. 2022
	H_2O			8	Warwick et al. 2022

Table 1: Input parameters and sources used for Absolute Global Warming Potential calculations shown in Eqns (1) – (8). For hydrogen AGWPs, we replaced IPCC Fifth Assessment Report (2013) (Myhre et al. 2013) values that were used in Warwick et al. (2022) with that from IPCC Sixth Assessment Report (2021) values (Forster et al. 2021).

To account for a constant emissions rate of each forcer as opposed to just a pulse of emissions, we consider a new pulse of emissions every year. Assuming linearity, the summation of the cumulative radiative forcing ($AGWP_i$) from past and current pulses for each year is equal to the cumulative radiative forcing from a constant emissions rate ($AGWPc_i$). To account for

200   multiple forcers emitted from each technology, we add up the individual $AGWPc_i$s for each time horizon. Finally, to compare the climate impacts from hydrogen technologies to their fossil fuel technologies counterparts, we simply divide their $AGWPc$s (comparable to how GWP is calculated). The results are then presented as a ratio of climate impacts (using cumulative radiative forcing as a proxy) as a function of time between two different technologies (i.e. hydrogen alternatives vs. fossil fuel technologies). A value of greater than 1 indicates that the alternative technology (in this case hydrogen) has larger climate

205   warming impacts at time horizon H than the original technology, and vice versa for less than 1. In our analysis, we present the results as a percent change in climate impacts (cumulative radiative forcing) from the original technology, such that 1 = 0% change (or equal), 0.5 = 50% decrease, 2 = 100% increase, etc.

This concept – an extension of AGWP and GWP that considers a constant emissions rate (as opposed to a one-time pulse) and calculates the relative climate effects over time (as opposed to one specified time horizon such as over 100 years) – is further

210   documented and discussed in Alvarez et al. (2012), where it is called the Technology Warming Potential. Several studies have used this metric to assess the climate impacts of different technologies that emit multiple greenhouse gases with varying atmospheric lifetimes, to show how the climate impacts of specific technologies change over time relative to one another (Alvarez et al., 2012; Camuzeaux et al., 2015; Ocko and Hamburg, 2019). However, given hydrogen's unique AGWP equations resulting from its varying indirect effects, we do not use the specific formulas derived in Alvarez et al. (2012), but

215   rather follow the calculation chain described above.

To account for uncertainties in our analysis, we follow the approach of Warwick et al. (2022). We first consider uncertainties in hydrogen's atmospheric lifetime, which given the uncertainty in the strength of hydrogen's soil sink is arguably the greatest source of uncertainty in hydrogen's atmospheric impacts overall (Paulot et al., 2021; Warwick et al., 2022). Compared to a central estimate of hydrogen's atmospheric lifetime of 1.9 years (Warwick et al. 2022), we use a lower end estimate of 1.4

220   years (Warwick et al. 2022) and a higher end estimate of 2.5 years (Paulot et al. 2021). Second, we apply a ±20% uncertainty to hydrogen's GWP ($AGWP_{H2}(H)/AGWP_{CO2}(H)$) due to uncertainties in radiative forcing scaling factors and CO_2's radiative effects (Warwick et al. 2022).

In order to assess the absolute warming impact from future hydrogen demand levels based on varying hydrogen emission rates, we apply the simple approach used by Paulot et al. (2021) to approximate long-term temperature responses to hydrogen

225   emissions. This method uses the best estimates of the long-term increase in global surface temperature (equilibrium climate sensitivity; ECS) and radiative forcing from a doubling of CO_2 concentrations and assumes that hydrogen would have a similar efficacy. The CMIP6 models suggest a best estimate of 3.78 ± 1.08 °C for the ECS and a 3.93 W m^{-2} effective radiative forcing for a doubling of CO_2 (Forster et al., 2021). This suggests a climate efficacy of 0.96 °C (W m^2)$^{-1}$. To estimate temperature

responses to hydrogen emissions, we multiply this efficacy with the hydrogen effective radiative efficiency estimated in Paulot et al. (2021) per unit of emission per year (0.84 mW m^{-2} (Tg yr^{-1})$^{-1}$) and the hydrogen emissions per year (emissions inputs discussed in Sect. 2.2). To account for uncertainties, we use a ±40% uncertainty in the hydrogen effective radiative efficiency which is comparable to the uncertainty arising from both soil sink impacts on hydrogen's atmospheric lifetime and the uncertainty in radiative forcing scaling factors and carbon dioxide's radiative effects (discussed above). Note that for the temperature analysis, we do not consider additional temperature impacts from methane emissions associated with the natural gas supply chain utilized in the production of blue hydrogen, as we want to focus on the absolute impacts from hydrogen emissions in particular.

2.2 Emissions from hydrogen technologies

The emissions from hydrogen applications we consider in our analysis are hydrogen emissions (leakage, venting, purging) from green hydrogen production and consumption, and both hydrogen and methane emissions (leakage, venting, purging, flaring) from blue hydrogen production and consumption. We do not consider CO_2 emissions from incomplete CCUS technologies to retain simplicity and be conservative, but this would increase the climate impacts of blue hydrogen consumption depending on the efficiency and the permanence of storage. We also do not consider greenhouse gas emissions from hydrogen infrastructure build-out.

For hydrogen emissions, there is a paucity of quantitative data addressing *in situ* hydrogen leakage along the value chain, with empirical measurements to date focused on safety concerns (i.e. large leaks) primarily in confined spaces (Kobayashi et al., 2018). While there are many methods of hydrogen gas sensing (e.g. optical, acoustic, thermal, electrochemical) and several types of sensors exist (Najjar, 2019), there are currently no commercially available sensors that can detect hydrogen emissions at levels well below the threshold for hydrogen gas flammability which is required to characterize emissions in the open.

However, it is very likely that hydrogen is emitted throughout the value chain, yet unclear—given lack of data—which components contribute most and least to emissions. Research suggests that loss rates from electrolysers could be high, and based on first principles of moving a small gas molecule, it is likely that transport of hydrogen is a major source (van Rujiven et al., 2011; Cooper et al., 2022; Frazer-Nash, 2022). Fluid dynamics theory suggests that hydrogen can leak 1.3 to 3 times faster than methane (the main component of natural gas) (Swain and Swain, 1992), although a recent study focused on low pressure distribution pipes suggests that small leaks in methane and hydrogen may occur at similar rates if the path to leakage is convoluted (Mejia et al., 2020). Previous work also suggests that liquified hydrogen could have high emission rates from boiloff (Sherif et al., 1997).

Total value chain emissions will ultimately depend on the configuration of the pathway from production through end use, and in the absence of empirical data, there can be very little confidence in any published estimates of hydrogen emissions from a future hydrogen economy. Of the previous studies that have made assumptions of total hydrogen emissions for the purpose of

assessing environmental impacts from a potential hydrogen economy, estimates range from 0.3% to 20% for minimum to maximum emissions (Schultz et al., 2003; Tromp et al., 2003; Colella et al., 2005; Wuebbles et al., 2010; van Ruijven et al., 2011; Bond et al., 2011; Cooper et al., 2022; Frazer-Nash Consultancy, 2022). All studies acknowledge major uncertainty in the estimates due to a lack of data, and several do not include all components of the value chain, e.g. production, compression, storage, and end-use applications. Some studies have made assumptions on total value chain emissions citing these previous studies, typically using a range of 1 to 10% (Prather, 2003; Derwent et al., 2001, 2020; Paulot et al., 2021; Warwick et al., 2022). Therefore, we follow the published literature and incorporate a hydrogen emission rate of 1% (best-case) to 10% (worst-case) per amount of hydrogen consumed.

For blue hydrogen production, methane is needed as both a feedstock and a heat source, and can be emitted along the supply chain (upstream and midstream) before it is used for producing hydrogen. The amount of methane needed to produce a unit mass of hydrogen will depend on the composition of the natural gas, the efficiency of the reformer, and how much is needed as feedstock and fuel combined. The amount needed is not well documented in the published literature, and based on public documents and private communications can range anywhere from 2.5 to 4.5 times the mass of hydrogen (Budsberg et al., 2015; Kearney Energy Transition Institute, 2020). In this analysis, we use a central estimate of 3 times the mass of hydrogen is needed in the form of methane. This value is on the lower end of all estimates but in the middle for published values; this makes methane emissions assumptions from blue hydrogen applications potentially conservative.

For methane emissions estimates (including venting, purging, flaring) upstream of hydrogen production, we use a range of 1% (best-case) to 3% (worst-case) per unit methane consumed. This is based on the latest understanding of upstream natural gas leakage from oil and gas production as well as distribution of natural gas (Alvarez et al., 2018).

Table 2 shows the hydrogen and methane emissions used in this study for best- and worst-case leak rates based on 1 kg of either green or blue hydrogen deployed.

Unit: kg		Best-case leaks H_2 & CH_4: 1%	Worst-case leaks H_2: 10%; CH_4: 3%
Hydrogen (Green & Blue)	Produced	1.01	1.11
	Consumed	1	1
	Emitted	0.01	0.11
Methane (Blue only)	Produced	3.06	3.44
	Consumed	3.03	3.33
	Emitted	0.031	0.103

Table 2: Hydrogen and methane emissions (kg) for deploying 1 kg of either green or blue hydrogen based on best- and worst-case leak rates. We assume 3 times the mass of hydrogen is needed in the form of methane for using methane as a feedstock for hydrogen production (Budsberg et al., 2015; Kearney Energy Transition Institute, 2020).

For estimating absolute temperature responses to future hydrogen leakage, we consider three levels of leakage (1, 5, 10%) and several levels of hydrogen demand from today's level (around 100 Tg yr^{-1}) to a theoretical maximum projected for mid-century (around 3000 Tg yr^{-1}). Depending on the scenario and source, projections for future hydrogen demand range from 100 to 210 Tg by 2030, and 130 to 1370 by 2050 (Table 3). Of 21 published estimates for hydrogen demand in 2050, the average is 590 Tg (median is 570 Tg). The theoretical maximum of using hydrogen to supply the entire final energy demand in 2050 is determined based on the estimates of hydrogen demand as a percent of final energy demand provided by Hydrogen Council (2017) and BloombergNEF (2020), 3055 Mt and 2900 Mt, respectively, that are each for scenarios of a decarbonized world.

Year	Estimate (Tg)	Source	Scenario description
2018	115	Energy Transition Commission, 2021	Hydrogen demand
2018	115	International Energy Agency, 2019	Hydrogen demand
2019	120	International Renewable Energy Agency, 2020	Hydrogen production
2020	89	International Energy Agency, 2022	Hydrogen demand
2020	90	Hydrogen Council, 2021	Hydrogen demand
2021	73	Yusaf et al. 2022	Hydrogen production
2030	102	International Energy Agency, 2021	Hydrogen projects currently under development
2030	110	International Energy Agency, 2021	Announced Pledges Scenario
2030	140	Hydrogen Council, 2021	Net zero 1.5 °C compatible scenario
2030	205	International Energy Agency, 2021	1.5 °C compatible net zero emissions by 2050
2030	211	International Energy Agency, 2022	Net zero scenario emissions by 2050
2040	385	Hydrogen Council, 2021	Net zero 1.5 °C compatible scenario
2050	130	Yusaf et al. 2022	Current growth trend of 1.8%
2050	162	Yusaf et al. 2022	Average actual growth of 2.5%
2050	187	BloombergNEFa, 2020	Weak hydrogen policy
2050	190	BloombergNEF, 2021	Blue hydrogen with little incentive to use hydrogen
2050	240	International Renewable Energy Agency, 2020	Transforming energy scenario
2050	255	International Energy Agency, 2021	Announced Pledges Scenario
2050	287	International Energy Agency, 2019	Sustainable Development Scenario
2050	520	International Energy Agency, 2021	Net zero emissions by 2050
2050	539	Hydrogen Council, 2017	2 °C compatible scenario
2050	540	Energy Transition Commission, 2021	Supply-side decarbonisation only; includes energy productivity improvements
2050	568	Yusaf et al. 2022	Annual growth rate of 6.5%
2050	590	International Renewable Energy Agency, 2020	1.5 °C compatible scenario

2050	660	Hydrogen Council, 2021	Net zero 1.5 ℃ compatible scenario
2050	696	BloombergNEFa, 2020	Strong hydrogen policy
2050	728	Energy Transition Commission, 2021	All use cases materialize combined with energy productivity improvements
2050	770	BloombergNEF, 2021	Net zero emissions by 2050 with widespread use of hydrogen mostly from nuclear
2050	801	BloombergNEFb, 2020	Well below 2 ℃ scenario
2050	813	Energy Transition Commission, 2021	Supply-side decarbonisation only
2050	1000	Energy Transition Commission, 2021	Maximum for hydrogen use by mid-century if all use cases materialize for net-zero emissions
2050	1318	BloombergNEF, 2021	Net zero emissions by 2050 and widespread use of hydrogen produced from renewables
2050	1370	BloombergNEFa, 2020	All unlikely-to-electrify sectors in economy use hydrogen

Table 3. Published estimates of hydrogen demand for various scenarios.

2.3 Emissions from fossil fuel technologies

To estimate the potential climate concern of hydrogen technologies, we compare the net climate impacts over time from green and blue hydrogen relative to their fossil fuel counterparts based on the anticipated avoided greenhouse gas emissions from the consumption of 1 kg of hydrogen continuously each year. We consider emissions of both carbon dioxide and methane. We do not include hydrogen emissions that would be avoided from the cessation of the combustion of fossil fuels, as well as other co-emitted climate pollutants such as particulates, sulphur dioxide, and nitrogen oxides that contain a mix of warming and cooling forcers.

While the carbon dioxide and methane emissions avoided from deployment of 1 kg of hydrogen will ultimately depend on the specific technology, as a first order approximation we explore the impacts from a generic case in which a variety of fossil fuel technologies are replaced. We use estimates from the Hydrogen Council (2017) that quantify avoided carbon dioxide emissions from a scenario of supplying 18% of final energy demand in 2050 with hydrogen applications. They estimate that a consumption of 550 million metric tonnes of hydrogen (roughly the same amount as the average of the 21 projections published in the literature for year 2050 – Table 3) can avoid 6 gigatons of carbon dioxide emissions annually. In their analysis, fossil fuel-powered end use applications that are decarbonized by hydrogen alternatives include segments of transport, industry energy use, building power and heating, and as an industry feedstock. For transport, their vision includes hydrogen powering hundreds of millions of cars, trucks, buses, passenger ships, and locomotives, with hydrogen-based fuels powering a share of airplanes and freight ships. For heat and power for buildings and industry, hydrogen could provide around 10% of the heat and power required for global households and industry sectors. Of the avoided 6 gigatons of CO_2 annually from this level of hydrogen deployment, around half is from hydrogen applications in the transport sector and one third is from industry energy and feedstocks. Using the Hydrogen Council's (2017) scenario and calculations provides a central estimate of 11 kg CO_2 avoided per 1 kg H_2 consumed. While this estimate is for the year 2050, in the absence of better estimates, we assume that it

can generally apply to earlier decades as well. However, to test the sensitivity of our results to different levels of avoided CO_2 (which arguably is of further importance for specific technologies as opposed to different years), we consider three different

315   levels of avoided carbon dioxide emissions (5, 10, 15 kg).

Further, given that the Hydrogen Council (2017) analysis does not provide avoided methane emissions associated with their hydrogen economy vision, additional assumptions need to be made to include their impact on the net radiative effect of fossil fuel applications vs. their hydrogen alternatives. First, the methane avoided will depend on the specific fossil fuel (coal, oil, gas) used in the displaced fossil fuel technologies. For example, a natural gas-driven technology will likely emit more methane

320   than a coal-driven technology due to emissions associated with natural gas production and distribution. However, a natural gas-driven technology will also likely emit less CO_2 than a coal-driven one because burning natural gas emits less CO_2 than coal. Therefore, for each level of avoided carbon dioxide emissions in our sensitivity analysis we also calculate the resulting radiative impact from these emissions if the CO_2 is generated from burning natural gas (i.e. considerable methane emissions). Burning 1 kg of natural gas emits 2.75 kg of CO_2 if the natural gas is almost entirely methane, and we consider methane leakage

325   rates from 1 to 3% as discussed earlier. Resulting emissions of methane are shown in Table 4.

Methane emissions (kg)		Best-case leaks 1%	Worst-case leaks 3%
Carbon dioxide emissions (kg)	5 Produced	1.84	1.87
	5 Consumed	1.8	1.8
	5 Emitted	0.02	0.06
	10 Produced	3.67	3.75
	10 Consumed	3.6	3.6
	10 Emitted	0.04	0.11
	15 Produced	5.51	5.62
	15 Consumed	5.5	5.5
	15 Emitted	0.06	0.17

Table 4: Methane emissions (kg) associated with different levels of carbon dioxide emissions (kg) from fossil fuel technologies and for best- and worst-case leak rates.

3 Results

330 ### 3.1 Hydrogen's warming potency

Global Warming Potential has become the most familiar metric for grasping the importance of a climate forcer as an agent of climate change. Hydrogen's GWP has been reported for decades, however only for its tropospheric effects and for a 100-year time horizon (thereby including numerous decades when hydrogen is not influencing the atmosphere) (Derwent et al., 2001, 2006, 2020; Derwent, 2018). This has led to an undervaluing of its impact. Recent research reports hydrogen's GWP for both

335 tropospheric and stratospheric effects and for both 20- and 100-year timeframes, revealing that hydrogen's 100-year GWP is twice as high as previous reporting and its 20-year GWP is three times higher than its 100-year GWP (Warwick et al., 2022). Fig. 3a extends this work to calculate hydrogen's GWP over time.

Hydrogen's maximum GWP occurs around seven years after the initial pulse of emissions, with a range of 25 to 60 based on uncertainties, and a central estimate of 40. This is around eight times higher than the most well-known GWP for hydrogen

340 (Derwent et al., 2020). Hydrogen's GWP initially increases before it declines again because it takes several years for methane's atmospheric lifetime to increase in response to less OH available from the reaction with hydrogen. For time horizons of 10 to 100 years, the GWP decreases as expected for when the warming effects of a pulse of emissions of a short-term forcer is compared to that of a long-term forcer; the CO_2 is still in the atmosphere 100 years later, whereas the short-term forcer's impacts are long gone – meaning that the relative potency of the short-term forcer declines. In fact, the factor of three difference

345 between hydrogen's GWP-20 (central estimate 33) and GWP-100 (central estimate 11) is similar in ratio to that from methane (80 and 30, respectively).

In Fig. 3b, we use an identical GWP calculation except consider a constant emissions rate rather than pulse emissions. The constant emissions rate approach is a more realistic representation of hydrogen leakage in a hydrogen economy, as opposed to a one-time pulse of emissions, and also more sensible in that you are calculating hydrogen's warming effects compared to

350 carbon dioxide for cases where they are both impacting the atmosphere in each time horizon.

When continuous equal emissions of both hydrogen and carbon dioxide are considered as opposed to just one pulse at time = 0, the potency of hydrogen relative to carbon dioxide can be 50% higher than that of the pulse approach. However, this is not uniform across all timescales. In fact, before 10 years, the pulse approach (GWP) yields higher potency values than the constant emissions rate approach. This is because the carbon dioxide impact is building up faster in the near-term for constant emissions

355 compared to the hydrogen impact, because the hydrogen impact takes several years to reach its full impact. However, as time goes on, the replenishing effect from constant hydrogen emissions (as opposed to decaying impacts) dominates and leads to a greater relative potency as compared to the pulse approach. For hydrogen's GWP-20, constant emissions lead to around a 15% increase in hydrogen's potency. This increases to 50% by a time horizon around 70 years, and nearly up to 60% by 100 years.
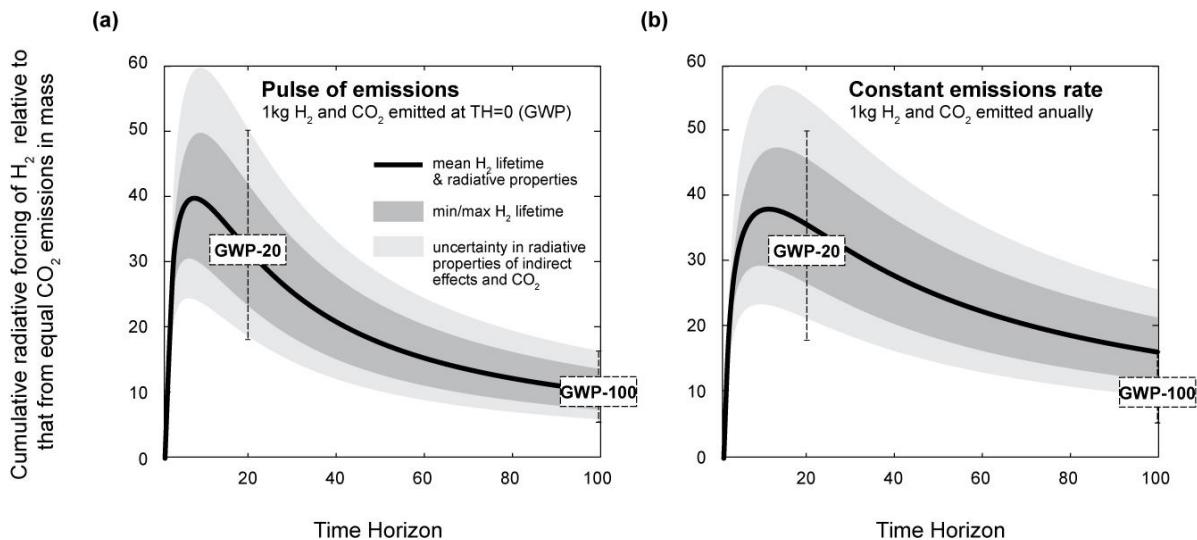
Figure 3: Warming potency of hydrogen relative to carbon dioxide using cumulative radiative forcing as a proxy for (a) a one-time pulse of equal emissions in mass (equals hydrogen's Global Warming Potential) and (b) a constant emissions rate of both hydrogen and carbon dioxide for equal emissions in mass. Solid lines are for mean hydrogen lifetime and radiative effects. The dark shaded areas correspond to a minimum and maximum hydrogen lifetime based on soil sink uncertainty, and the light shaded areas represent a 20% uncertainty in the radiative effects of hydrogen from its indirect effects and uncertainties in carbon dioxide's radiative properties. See Table 1 for all parameters used.

3.2 Warming impacts from replacing fossil fuel technologies with hydrogen alternatives

The results of our analysis of the climate impacts of hydrogen and methane emissions are shown in Fig. 4. If there were zero climate forcer emissions from the hydrogen applications, the result would be a -100% change in cumulative radiative forcing, and if there was no replacement the result would be 0%. If the climate forcer emissions from hydrogen alternatives yield more (less) warming than the fossil fuel counterparts over a particular time period, it would amount to a positive (negative) percent change in cumulative radiative forcing.

Overall, any amount of hydrogen leakage will diminish the climate benefits from avoided carbon dioxide emissions to some degree, but there are vastly different outcomes—favourable and unfavourable—depending on the production method, total emissions, and time horizon. For example, the worst-case for blue hydrogen (10% hydrogen leakage and 3% methane leakage) could be initially worse for the climate than the CO_2 emissions from the corresponding fossil fuel technologies, yielding up to 60% more warming over the first 10 years and taking around 50 years before benefits of the technology switch are realized. On the other hand, the best-case for green hydrogen (1% hydrogen leaks) could yield a near elimination of the climate impact

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as compared to fossil fuel's CO_2 emissions. Recall however that we do not include greenhouse gas emissions associated with installing infrastructure which will be needed to support the growing demand for hydrogen and its applications.

The importance of the clean hydrogen production method – i.e. green (renewable electricity with water) or blue (steam methane reforming with CCS) – in determining the magnitude of climate benefits is clear (Fig. 4). While hydrogen emissions can yield climate impacts for green hydrogen that are far from climate neutral over all timescales, the cumulative radiative impact is still less than the fossil fuels which signifies a decrease in warming from using green hydrogen alternatives. On the other hand, blue hydrogen can be better or worse for the climate depending on the leakage rate and time horizon. For example, over a ten-year time period, worst-case blue hydrogen emissions could increase the warming impact from fossil fuels by 40% (25,60), whereas worst-case green hydrogen emissions could decrease warming by 60% (43,76). For best-case leak rates for both, blue hydrogen could still only reduce the warming impact from fossil fuels by 65% over the first ten years, whereas green hydrogen could reduce the impact by more than 95%. For a 100-year time horizon, the story is similar, with worst-case leak rates yielding a doubling of the climate impact of blue hydrogen compared to green hydrogen. In fact, the worst-case green hydrogen benefits are roughly the same as the best-case blue hydrogen benefits across all timescales (such as around a 65% decrease in the warming impact from fossil fuel CO_2 emissions over a 10-year period and an 85% decrease over a 100-year period). Given that the hydrogen emissions are the same in both the blue and green cases, the difference is due entirely to the warming effects from methane emissions from the natural gas supply chain.
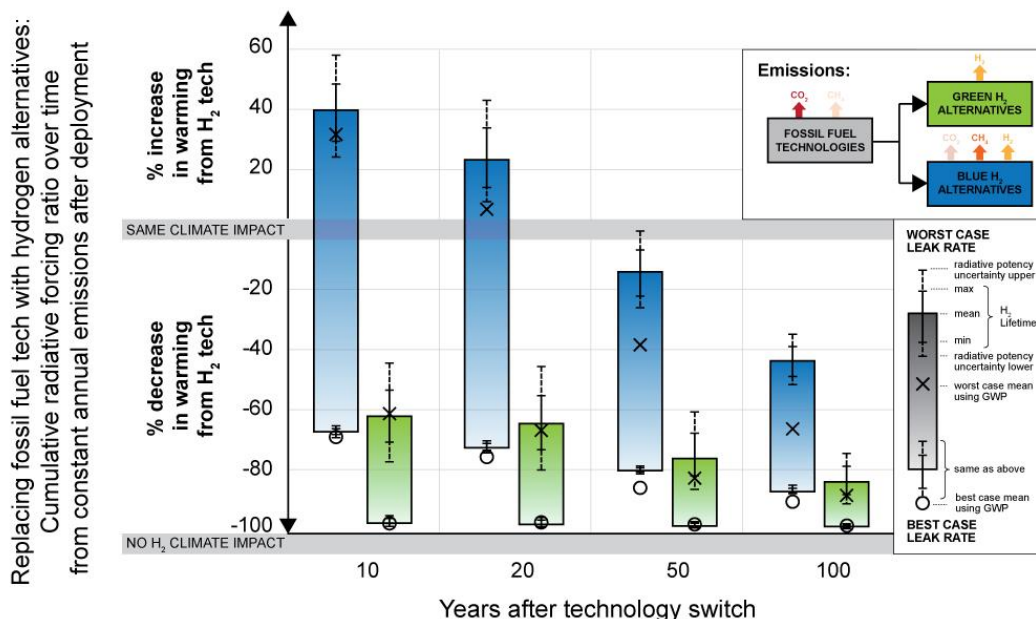
Figure 4: Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for a generic case. Ratio of cumulative radiative forcing of a constant emissions rate from deploying 1 kg of H_2 continuously is used as a proxy of relative warming impacts. Emissions from hydrogen alternatives are hydrogen for green hydrogen and hydrogen and methane from blue

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hydrogen. Emissions from fossil fuel technologies are carbon dioxide, estimated at 11 kg CO_2 avoided per 1 kg H_2 deployed based on estimates from Hydrogen Council (2017). Emissions of hydrogen and methane include a range of plausible leak rates from 1% (best-case) to 10% (worst-case) per unit H_2 deployed for hydrogen and from 1% (best-case) to 3% (worst-case) for methane. The height of each bar corresponds to the range from leakage. See Table 2 for emissions inputs for hydrogen and methane, and Table 1 and Eqns (1) – (8) for equations used in the calculation and input parameters. more details on emissions assumptions and Table 3 for radiative properties and decay functions used. Error bars represent uncertainties in both hydrogen's soil sink and therefore lifetime (solid lines) as well as uncertainties in hydrogen and carbon dioxide's radiative effects (~±20%; dashed lines). Corresponding GWP results (only difference is pulse emissions rather than constant emissions rate) are shown using the "x" and "o" markers.

While production method matters greatly, so does the level of emissions. For example, how beneficial green hydrogen is to the climate in both the near- and long-term will depend strongly on the level of leakage, with benefits ranging from more than a 95% reduction in climate impacts from fossil fuel technologies to only 65% over the first ten years for total leakage rates of 1 and 10%, respectively. Even in the long-term (100-year time horizon), green hydrogen may only reduce climate impacts by 85% if there is high leakage. The impact of leakage levels is also apparent for blue hydrogen, where high leak rates for both hydrogen and methane could lead to an increase in warming relative to the fossil fuel counterparts for decades, but the low leak rates for both could cut climate impacts by more than half within ten years. In the long-term (over 100 years), both worst- and best-case leak rates for blue hydrogen would likely yield reductions in the climate impacts, however, the magnitude of benefits ranges from a 45% to 85% reduction, respectively. These results show the importance of emission rate in determining the climate benefits (and potential disbenefits) of replacing fossil fuel technologies with hydrogen alternatives.

Whereas most assessments of climate benefits from alternative technologies inherently focus on the long-term impacts due to use of the GWP-100 metric, our analysis shows how different the picture looks when considering time horizons from 10 to 100 years. This is because unlike carbon dioxide, hydrogen's (and methane's) warming effects are short-lived and do not accumulate over time. Therefore, the benefits of hydrogen applications grow larger over time due to the prevention of the build-up of carbon dioxide in the atmosphere. If only a long-term perspective is pursued when evaluating hydrogen applications, the results will not convey the much larger relative climate impacts over shorter time horizons. For example, for the first few decades, worst-case green hydrogen may only cut in half the warming impacts of the fossil fuel applications it is replacing, but over 100 years the warming impacts could be reduced by three quarters. For blue hydrogen, the temporal significance is even more stark due to the combination of emissions of two short-term forcers. For example, worst-case blue hydrogen alternatives could increase warming relative to fossil fuel technologies for the first several decades, but over 100 years would cut the warming impact by nearly half. Therefore, depending on the time horizon that is considered in the analysis, one could receive very different insights on climate benefits of the decarbonization potential of hydrogen.

This is even more acute if the GWP metric with a pulse approach is used as opposed to a constant emissions rate. While in our analysis we consider constant emissions, Fig. 4 shows the corresponding result if a pulse approach was used (see X and O markers). While the pulse approach reasonably captures the near-term impacts of hydrogen applications relative to that of fossil fuels, over time it diverges and ultimately undervalues the cumulative radiative forcing. For example, worst-case blue hydrogen could yield a decrease in warming of only 45% even after 100 years of replacing fossil fuel technologies, but GWP-

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100 suggests a decrease in warming of 65%. And if GWP-100 is used exclusively and taken to represent hydrogen's impacts over any timescale (as it often is), then the near- and mid-term impacts of hydrogen (and methane) leakage will be overlooked entirely – which in some cases means assuming a benefit to the climate when it is actually a disbenefit for decades.

In the above, we considered a generic case for avoiding carbon dioxide emissions from fossil fuel technologies. However, the perceived climate benefits of hydrogen alternatives will depend on the amount of CO_2 avoided, which will vary depending on the technology that is replaced. Therefore, to test the sensitivity of our results to the amount of CO_2 avoided, we consider avoided emissions of 5, 10, and 15 kg per 1 kg of hydrogen deployed (compared to our central estimate of 11 kg) and compare the relative climate impacts of the hydrogen applications over a 20-year time horizon (solid bars in Fig. 5). We find that if avoided emissions of CO_2 are on the lower end, blue hydrogen could yield more than a 150% increase in warming over the first 20 years if leak rates are at the upper end, and green hydrogen may only reduce warming by 20%. However, if avoided emissions of CO_2 are on the higher end, both worst-case blue and green hydrogen would yield climate benefits, reducing warming by 10 and 75%, respectively.
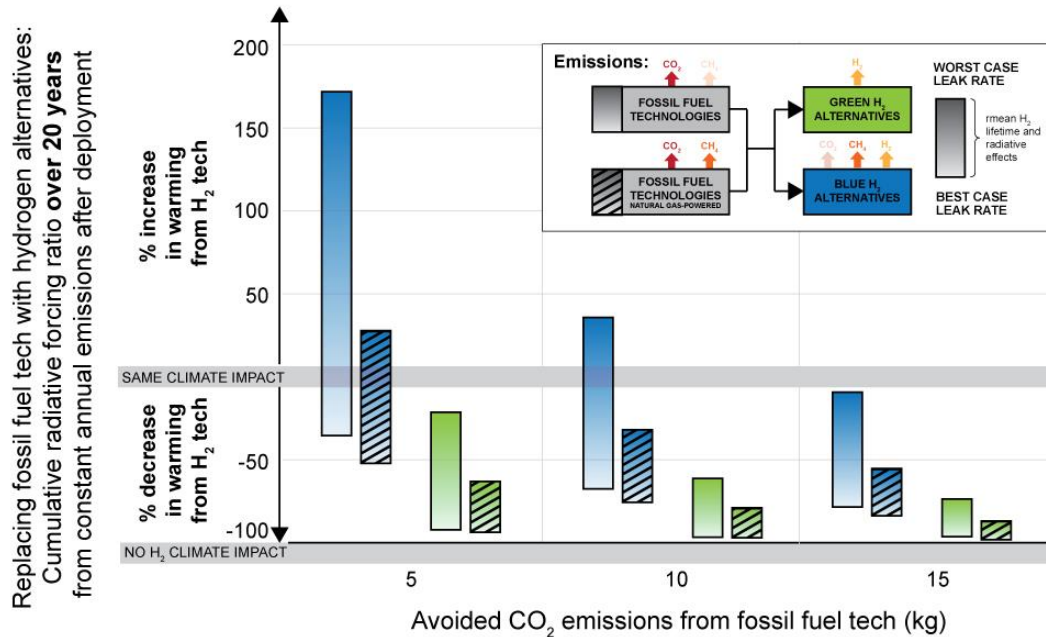
Figure 5: Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for different levels of avoided carbon dioxide and methane emissions. Ratio of cumulative radiative forcing of a constant emissions rate from deploying 1 kg of H_2 continuously is used as a proxy of relative warming impacts. Emissions from hydrogen alternatives are hydrogen for green hydrogen and hydrogen and methane from blue hydrogen. Emissions from fossil fuel technologies are carbon dioxide and methane. Emissions of hydrogen and methane include a range of plausible leak rates from 1% (best-case) to 10% (worst-case) per unit H_2 deployed for hydrogen and from 1% (best-case) to 3% (worst-case) for methane. The height of each bar corresponds to the range from leakage. See Table 2 for emissions inputs for hydrogen and methane from hydrogen applications, Table 4 for emissions of methane from fossil fuel technologies, and Table 1 and Eqns (1) – (8) for equations used in the calculation and input parameters.

455   Given that methane emissions may also be avoided from replaced fossil fuel technologies, we extend the analysis in Fig. 5 to consider a case where the fossil fuel that was burned to produce the CO_2 was natural gas (diagonal line bars), using the same best- and worst-case methane leak rates as in the hydrogen applications. We find that the avoided methane emissions may play a significant role in increasing the near-term benefits of hydrogen applications, but there is a strong dependence on the corresponding CO_2 emissions that are avoided. For example, while worst-case blue hydrogen with the lower end avoided CO_2

460   would still be worse for the climate over the first 20 years even with including avoided methane, the central estimate avoided CO_2 case would switch from worse for the climate to better for the climate. For worst-case green hydrogen, climate benefits would double for all levels of avoided CO_2 when including avoided methane emissions. However, given that natural gas emits less CO_2 when burned than coal, it is likely that when methane emissions are higher, CO_2 emissions are lower, as opposed to both being on the higher end. Therefore, a case-by-case study with reported data on both carbon dioxide and methane emissions

465   from fossil fuel technologies is warranted to fully understand the impact of avoided methane emissions.

3.3 Absolute warming impacts due to hydrogen emissions

    We find that for all levels of hydrogen emissions, today's hydrogen demand (around 100 Tg) may cause at most 0.01 ℃. For 2030 projections, five estimates based on different scenarios and sources suggest an average hydrogen demand of 150 Tg (see Table 3), which could double the 100 Tg impact for upper end leak rates (10%) and uncertainties (0.02 ℃). For 2050

470   projections, 21 different estimates suggest a range in demand from 130 to 1370 Tg (Table 3), with an average of 590 Tg. For worst-case hydrogen leak rates (10%), these levels of demand could yield anywhere from 0.01 ℃ to 0.1 ± 0.05 ℃. On the other hand, if total hydrogen emissions are kept minimal (1%), temperature responses could be less than 0.02 ℃ including uncertainties. For context, 590 Tg of hydrogen demand could supply around 20% of final global energy demand in 2050 under a 2 ℃ scenario (Hydrogen Council, 2017; BloombergNEF, 2020).

475   Fig. 6 shows the long-term temperature responses to various hydrogen demand levels, up to a theoretical maximum estimated for 2050 of 3000 Tg (this would correspond to using hydrogen for total final energy demand in a 2 ℃ decarbonization scenario). Using hydrogen for all final energy demand in 2050 could lead to greater than 0.1 ℃ of warming with a 5% leak rate, and up to 0.4 ℃ of warming with 10% leak rates and uncertainties in hydrogen's radiative effects.

    However, this level of hydrogen demand is not realistic. Of the available projections in the literature for hydrogen demand in

480   2050, four suggest demands between 100 and 199 Tg, three suggest demands between 200 and 499 Tg, 11 suggest demands between 500 and 999 Tg, and three suggest demands between 1000 and 1999 Tg (Table 3). None project hydrogen demands below 100 and above 2000. Sustained hydrogen demands around 800 Tg or greater (could account for around a quarter of final energy demand in 2050) could contribute at least 0.1 ℃ of warming if leak rates and uncertainties are at the upper end. For context, this amount of warming could offset the avoided warming in 2050 from deploying all cost-effective options to mitigate

485   methane emissions globally over the next decade – which otherwise could have slowed down global-mean warming rates by

up to 15% (Ocko et al., 2021), or the avoided warming anticipated from the phasing out of hydrofluorocarbons (HFCs) (Xu et al., 2013). This amount of warming (~0.1 °C) is also equal to the amount of warming projected in 2100 from carbon dioxide emissions from international shipping and aviation combined in the absence of climate action (Ivanovich et al., 2019). However, if leakage does not exceed 1% the temperature response could be an order of magnitude smaller.
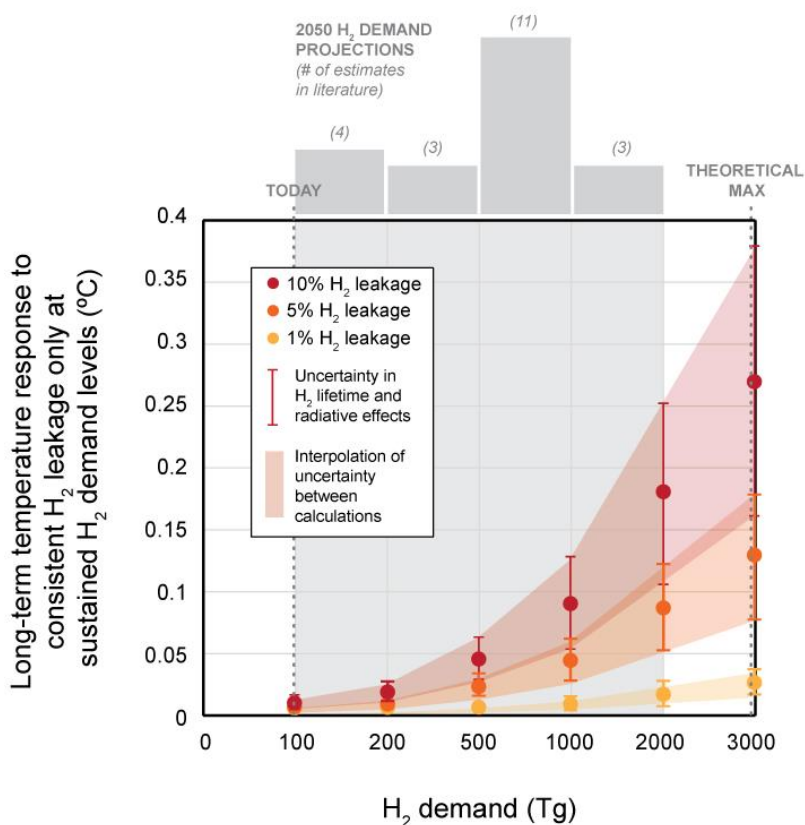
Figure 6: Long-term temperature responses (°C) to different levels of hydrogen leakage based on sustained hydrogen demand levels (Tg). Red/orange/yellow markers and shading represent leakage levels of 10/5/1%. Uncertainty is based on uncertainties in both hydrogen's soil sink and therefore lifetime (~±20%) as well as uncertainties in hydrogen's radiative effects (~±20%). Markers indicate calculations and shaded regions represent interpolation. Histogram and shaded grey area characterize projections of hydrogen demand for the year 2050 in the published literature (see Table 3). The theoretical max is an estimate based on using hydrogen to supply total final energy demand globally in 2050 based on decarbonization scenarios.

4 Discussion

The purpose of our study is to improve understanding of the role of hydrogen leakage in undermining the climate benefits from deployment of clean hydrogen alternatives to replace fossil fuel technologies. We evaluated hydrogen's climate consequences in three ways: its warming potency relative to carbon dioxide, the warming impact of its leakage compared to that from the avoided emissions from fossil fuel technologies, and the absolute warming impacts from future levels of demand and leakage.

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We found that hydrogen's warming potency strongly depends on time horizon, and, similar to methane, can be at least three times more potent in the near-term than in the long-term relative to carbon dioxide when using the traditional GWP framework with pulses of equal emissions. If a constant emissions rate is used in the calculations instead, hydrogen's warming potency may be 50% higher for time horizons of several decades and longer. When assessing the relative climate impacts from replacing fossil fuel technologies with their hydrogen alternatives (based on a unit of clean H_2 deployed relative to the avoided CO_2 emissions for a generic case), we found that there are vastly different climate outcomes depending on emission rates, time horizons, and production method. For example, blue hydrogen with high hydrogen and methane emissions (10 and 3% emission rate, respectively) can be worse for the climate than the fossil fuel technologies for decades, but green hydrogen with low hydrogen emissions (1%) can nearly eliminate climate impacts from fossil fuel counterparts over all timescales. On the other hand, best-case blue hydrogen (1% for both hydrogen and methane) can have roughly the same climate benefits as the worst-case green hydrogen (10% emissions) – far from climate neutral but still cutting in half the impacts from the fossil fuels within a decade. However, the perceived benefits from clean hydrogen alternatives to fossil fuel technologies will depend on how much carbon dioxide and methane are avoided, which needs to be assessed on a case-by-case basis with reliable emissions data. Finally, we found that levels of hydrogen demand around 800 Tg or above (which could account for around a quarter of final energy demand in 2050) could contribute at least 0.1 °C in warming with high hydrogen leakage (10%) and upper bound uncertainties in hydrogen's radiative properties.

Our findings add to recent research that has revealed that the warming impacts of hydrogen emissions are higher than previously recognized (Paulot et al., 2021; Warwick et al., 2022) by exploring the implications this has for the potential of hydrogen as a decarbonization strategy in the near- and long-term. For example, we show for the first time the strong dependence of timescale when evaluating the climate change mitigation potential of clean hydrogen alternatives. This is because hydrogen's warming effects are most powerful in the decade or two after hydrogen is released. While short-term climate warming impacts – followed by long-term climate change mitigation impacts – may lead to an eventual beneficial outcome, the short-term warming may lead to climate impacts that cause more socioeconomic and environmental damages in the near-term that are not necessarily reversible (Fischer et al., 2021). This could strongly affect the choice of whether or not to deploy hydrogen in applications that have multiple "clean" options. But if GWP-100 is relied on exclusively, the near- and mid-term warming power of hydrogen is masked, and therefore the anticipated climate benefits from deploying hydrogen are perceived to be much higher over the next few decades than in reality. However, we find that a dual approach of using both GWP-20 and GWP-100 adequately captures the climate impacts of hydrogen over all timescales, and therefore is a straightforward way to effectively understand temporal trade-offs across hydrogen deployment opportunities.

Taken together, our findings and the findings of previous studies make it clear that hydrogen emissions (leakage, venting, and purging) matter for the climate. And given that hydrogen is a very small molecule that is hard to contain, it can easily escape from infrastructure. A new network of production facilities, pipes, storage tanks, and hydrogen-powered homes and vehicles,

can create a vast potential for hydrogen to leak. Further, moving hydrogen through existing natural gas systems that are already

535   shown to leak significant amounts of methane is even more problematic. However, the total amount of leakage in current hydrogen systems remains unknown, with the analytical capacity to accurately measure small levels of leakage *in situ* largely unavailable. And lessons learned from extensive measurements of natural gas value chain leaks over the last decade (similar infrastructure, larger molecule) have shown that leakage rates were far higher than expected (Alvarez et al., 2018). While hydrogen is an arguably more valuable product than natural gas given the current cost of producing it, the lack of empirical

540   measurements cannot confirm any assumptions regarding the influence of the cost of lost product on leakage rates, especially if there is no regulatory enforcement. Without measurements of hydrogen leakage and in turn knowledge of strategies to mitigate leakage and deploy best practices, we risk developing leaky systems that could significantly contribute to climate change in the near to medium-term. More attention is therefore needed to measure and minimize hydrogen leakage as hydrogen efforts are ramped up.

545   Beyond needing accurate measurements of hydrogen emissions, more work is needed to improve understanding of hydrogen's atmospheric impacts. This is because far less work has gone into refining hydrogen's radiative effects compared to gases such as methane and carbon dioxide. There is a need for more integrated chemistry-climate modelling to build confidence in and refine the tropospheric and stratospheric radiative effects of hydrogen emissions. This is especially true regarding gaining a better understanding of the climate impacts in the first couple of decades after hydrogen is emitted to the atmosphere, given

550   the complex temporal dynamics of hydrogen's indirect effects; to date there is only one study that explores these near-term issues (Warwick et al., 2022). Chemistry-climate modelling is further required to: (1) understand the net effects when including co-emissions from hydrogen and fossil fuel technologies (such as sulphur dioxide, black and organic carbon, nitrogen oxides, and carbon monoxide); (2) estimate climate responses to hydrogen emissions beyond forcings (such as global surface air temperature); and (3) assess how changing concentrations of other atmospheric constituents may affect hydrogen's potency

555   (such as changing concentrations of methane resulting from reduced emissions in response to aggressive policies to address climate goals). For example, all else equal, hydrogen emissions will lead to an increase in other greenhouse gases. However, a new study shows that reductions in emissions of carbon monoxide, nitrogen oxides, and volatile organic carbon can lead to a smaller increase in methane's lifetime from hydrogen (because more OH is available), and a net decrease in tropospheric ozone (Warwick et al., 2022). These complexities and interactions will need to be explored in assessing the climate effects of

560   decarbonization strategies.

Climate benefits of clean hydrogen alternatives to fossil fuel technologies also need to be assessed on a case-by-case basis, given (1) the dependency of the leak rate on the production method, value chain pathway (i.e. compression, storage, distribution), and end-use application; and (2) the dependency of the benefits on the avoided greenhouse gas emissions which in turn depends on pathway, application, fuel, and also location. While analysis of a generic hydrogen deployment case is

565   valuable for first-order insights, decisions will ultimately need to be made based on implications for specific technological

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shifts. For example, if the hydrogen is burned in the stratosphere (for example from aircrafts), the direct combustion of hydrogen could also increase stratospheric water vapor.

Further, there are additional climate and other environmental concerns associated with deployment of hydrogen that need to be better understood quantitatively. These include the diversion of renewably-produced electricity to produce green hydrogen
570 when a potentially more effective decarbonization pathway would be to use the renewable electricity directly to offset fossil fuel use (Ueckerdt et al., 2021); emissions of nitrogen oxides from combusting hydrogen, which is a health concern for local communities (Lewis, 2021); local water availability for green hydrogen production (Beswick et al., 2021; Simoes et al., 2021); and CCUS efficiency and permanence for blue hydrogen (Saadat and Gersen, 2021).

5 Conclusions

575 Around the world, industry and policymakers are enthusiastic about clean hydrogen's potential as an alternative to conventional fossil fuels that can greatly reduce greenhouse gas emissions. Billions in new investments and financial subsidies are being proposed to speed its adoption. But hydrogen itself has significant climate impacts that are both widely overlooked and underestimated, and it is a very small molecule that can easily leak into the atmosphere from infrastructure.

In this study, we evaluate the climate consequences across all timescales of deploying clean hydrogen given a range of plausible
580 leak rates. Our results indicate that hydrogen emissions can considerably undermine the climate benefits of decarbonization strategies that involve clean hydrogen – especially in the decades immediately following deployment. This issue therefore deserves more attention, both on advancing the science of hydrogen's indirect climate effects and improving estimates of hydrogen emissions throughout the value chain. Minimizing leakage will be essential to the effectiveness of hydrogen as a climate change mitigation strategy. Further, given that it may be possible to prevent leakage in some applications and it is
585 easier to address and minimize hydrogen leakage when designing a system versus retrofitting one, we have the rare opportunity to get ahead of this issue before the infrastructure and systems are widely deployed.

Our results suggest that five key actions can help minimize hydrogen's warming effects and therefore maximize climate benefits in a future hydrogen economy:

(1) advance research of hydrogen's indirect radiative effects and temperature responses to hydrogen emissions by
590 incorporating interactive emissions, chemistry, and radiation parametrizations in further coupled chemistry-climate models as well as reduced-complexity climate models;

(2) employ climate metrics and/or models that effectively reflect the role that hydrogen could play in meeting net zero goals in the desired time frames – this means not exclusively relying on GWP-100 and potentially adopting a dual GWP-20/GWP-100 approach (Ocko et al., 2017);

595   (3)   improve quantification of hydrogen leakage rates by developing technologies that can be taken into the field to accurately measure hydrogen emissions at low-detection thresholds (i.e. ppb level);

    (4)   include the likelihood of hydrogen leakage and its impacts in decision-making about where and how to effectively deploy hydrogen – such as collocated production and end use applications; and

    (5)   identify leakage mitigation measures and best practices before building out infrastructure.

600 If we are to meet the climate challenge before us, it is imperative that we carefully examine each alternative decarbonization pathway using robust and appropriate metrics and data. The near- and mid-term warming impacts of hydrogen emissions are higher than widely perceived. These impacts should be explicitly and quantitatively accounted for in order to maximize the climate benefits of replacing fossil fuel systems with hydrogen. Taking a proactive and scientific approach to understand the implications of and address hydrogen leakage can help ensure that the global rush to hydrogen delivers on its promise to benefit
605 the climate over all timescales.

Code and data availability

All code and data are available upon request.

Author contribution

IBO and SPH conceptualized the study. IBO conducted the analysis and data visualization. IBO and SPH wrote and edited the
610 manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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