RESPONSE TO THE REFEREES' COMMENTS

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Climate consequences of hydrogen leakage

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We sincerely appreciate the time and effort of the two anonymous referees and the Editor in carefully reviewing our manuscript. We were happy to hear that Referee #1 considers the overall quality of the paper great; agrees that the paper addresses an important emerging issue; and finds the discussion and recommendation for practice sound. Referee #2 also agrees that the topic is timely and important, finds the authors knowledgeable of previous work, and thinks the introduction is well-written.

Both referees and the Editor provided excellent suggestions that have greatly improved the manuscript and analysis. In the following pages, we explain how we have improved the manuscript based on the helpful feedback (reviewer comments in black, responses in blue). Further, given the recent publication of a relevant study since we submitted the paper, we have also improved our analysis based on new scientific insights to ensure that our study is based on the best available science. The combination of incorporating the latest science as well as the referees' suggestions has considerably strengthened the paper and we are extremely pleased with the outcome.

In particular, major revisions include:

- Restructuring and streamlining the manuscript to a more traditional Intro, Methods, Results, Discussion, and Conclusion format. This includes:
    - More information in the introduction about hydrogen's warming effects in response to Referee #1
    - Less detail and discussion of the problem with hydrogen leakage in response to the Editor
    - More clarity and information about our methods in response to both referees and the Editor, including all relevant equations and input parameters
    - More detail on what is shown in the figures in response to the Editor
    - A new discussion section that interprets the results, shows the broader implications of our findings, and discusses limitations, in response to the Editor
- Improving our methodology to include newly published GWP equations that more accurately account for hydrogen's several indirect effects
- Greatly clarifying the metrics approach used in our analysis and its relationship to GWP, in response to Referee #2
- Removing a lot of the text about metrics issues with a more objective, balanced, and concise discussion and tone, in response to Referee #2
- A new approach for the simple temperature analysis and a revised figure to better capture the physical meaning of the results, in response to both referees
- Addition of 19 new references

Referee #1

The overall quality of the preprint is great. The paper addresses an important emerging issue of hydrogen use in the decarbonation process of the coming decades. The quantification of the climatic consequences in terms of offsetting the benefit of decarb is accounted for in various scenarios and assumption space. The discussion and recommendation for practice is sound.
We are sincerely grateful to Referee #1 for all the time and attention spent on carefully reviewing our paper. Below we respond point-by-point to both major and minor comments, with revised text *italicized* in quotes.

Major Comments:

Framing:

Line 46. "how much hydrogen is ultimately deployed to replace fossil fuel systems". There are many places where similar statements are made. e.g., Line 240. "replacing fossil fuel systems with hydrogen applications"

My comment here is that fossil fuel as the primary energy sources are not *replaced* by hydrogen which is secondary sources. Fossil fuel can be replaced by wind, solar and nuclear etc. Hydrogen is more like electricity in the battery as the energy carriers. In that sense, the analysis presented is more akin to the climatic and environmental assessment of future battery use. Maybe some rewording for the context is needed.
We see the point the referee is making, and agree that hydrogen is not purely a 1:1 replacement for fossil fuels. To that end, we had tried to be careful by using qualifying language when discussing "replacements," such as inserting words like fossil fuel "technologies" and hydrogen "alternatives." What we were and are ultimately trying to characterize is the shift from fossil fuel driven technologies to hydrogen driven alternatives, and to that extent we are "relacing" fossil fuel tech with hydrogen tech, but we understand how the text can make it seem like we are saying you can swap out one for the other and that they are "equal" in terms of their role in the energy transition. We have therefore gone through the text to try to be as careful as possible in terms of expressing a technology switch for the end use applications, either a fossil fuel technology or its hydrogen alternative/counterpart. We hope this clarifies our intent.

Line 67. " The impact of energy transitions". Similar to my comments on Line 46, again in terms of framing of the question, I think the issue here is not energy transition (from fossil fuel to clean energy), but the use of hydrogen as the energy carrier, due to its high energy density, to fulfill the energy demand of some applications that are hard to be electrified. In plain language, there are intense ongoing debate between battery powered EV vs. fuel cell cars. The study here essentially addresses the underreported negative climate effects of the latter.
We fully agree with the referee's assessment. Due to other revisions of the manuscript and a complete rewrite, reformulating, and reframing of our methods, this phrase and its accompanying sentence have been removed.

The authors need to clarify that in the TWP calculation, by “continuous emission” they had assumed constant emission rate after deployment. This is important because if the short-lived compound emission is backloaded toward the end of time horizon (i.e., with increased emission, a more likely case for hydrogen economy scaling up), the cumulative forcing (and the associated warming) at these longer time scale would be even higher than what TWP implies.

Yes, great point. “Constant emission rate after deployment” is much clearer than our original phrasing, and we have therefore adopted this throughout the text and in the figures.

Line 440. “Fig. 5 shows the anticipated temperature increase in 2050 based”. Since the temperature response calculation here is simply a conversation from the instantaneous radiative forcing at a given year, it’s assuming temperature equilibrium very quickly which is not the case in the real world (and even in simple climate models). The forcing*climate sensitivity is best known as (geophysical, not socioeconomically) committed warming, which is always larger than the “expected/anticipated” warming at certain point due to the response time of climate system (check e.g., https://www.researchsquare.com/article/rs-969513/v1 or http://www.pnas.org/content/early/2017/09/13/1618481114.abstract)

Fully agree that our simple temperature derivation does not apply to instantaneous responses in any given year, and this is confusing in both original figures 4 and 5. In response to this comment and comments by Referee #2, we have decided to remove original Fig. 4 and revise original Fig. 5. We also modified and reframed our comparison for original Fig. 5 (looking at sustained hydrogen demand levels and their long-term temperature responses) and further revised the figure based on this referee’s feedback in the minor comments section (markers and colors). Below is the new figure:

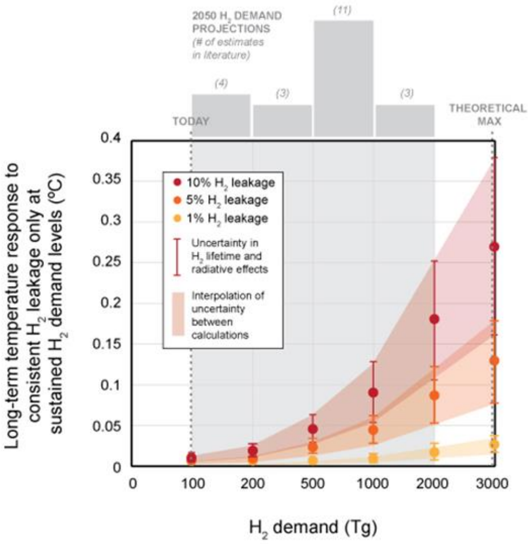

Figure 6: Long-term temperature responses (ºC) to different levels of hydrogen leakage based on sustained hydrogen demand levels (Tg). *Red/orange/yellow markers and shading represent leakage levels of 10/5/1%. Uncertainty is based on uncertainties in both hydrogen’s soil sink and therefore lifetime (~±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.*

Line 269. Why is the 50% estimate here a “conservative” one?

We considered this estimate to be conservative because not all the fossil fuel technologies that are replaced with hydrogen alternatives are natural gas-driven and thus associated with potentially high methane emissions. For example, many technologies are fueled by gasoline, diesel, and coal. So it is quite possible that we were overestimating the avoided methane emissions (as also demonstrated by the referee in the following comment) which would overestimate the benefits of hydrogen applications, and thus be “conservative” in the context of consequences of hydrogen. However, given that (1) the results highly depend on the level of avoided carbon dioxide and methane; (2) we have no data for our generic case on how much methane would be avoided; and (3) avoided carbon dioxide and methane are functions of one another, we have decided to take a different approach and consider a sensitivity analysis to explore this further. This has the added benefit of clarity in how we handle methane emissions from blue hydrogen, which are now not offset; we completely agree with the referee in that it was confusing and have struggled with communicating our explanation of that decision.

The new analysis is as follows: We first test the sensitivity of our results to different levels of avoided CO2, where we consider three different levels of avoided carbon dioxide emissions (5, 10, 15 kg per 1 kg H2 deployed). Then for each level of avoided carbon dioxide emissions we also calculate the resulting radiative impact from these emissions if the CO2 is generated from burning natural gas. Burning 1 kg of natural gas emits 2.75 kg of CO2 if the natural gas is almost entirely methane, and we consider methane leakage rates from 1 to 3% as in the blue hydrogen production. Resulting emissions of methane are shown in the new Table 4, and the results of the analysis for a time horizon of 20 years are shown in new Fig. 5:

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

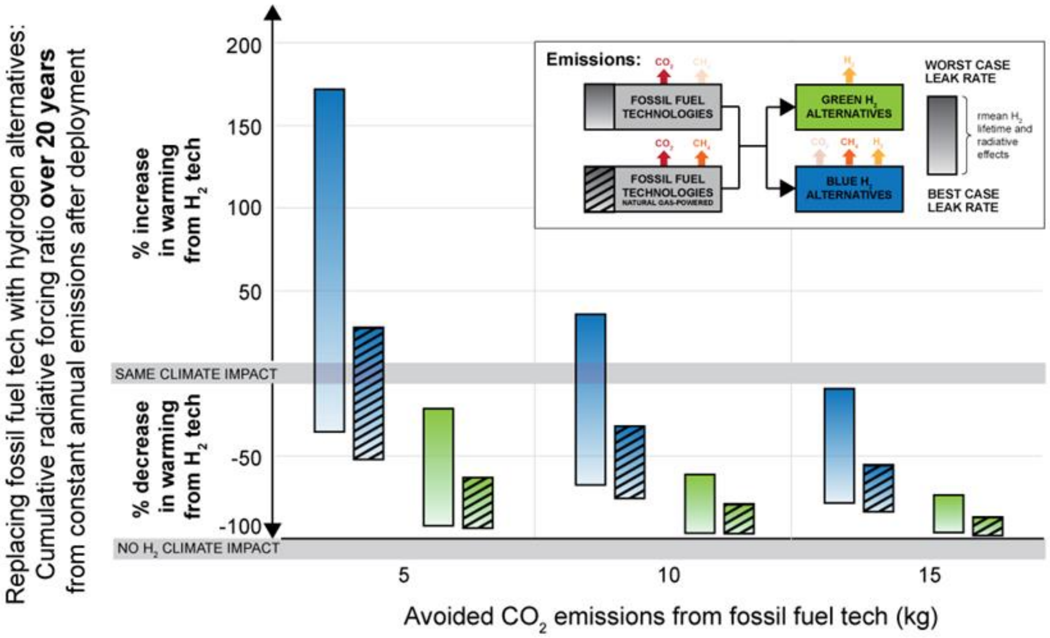

Figure 5: Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for different levels of avoided carbon dioxide and methane emissions. *Ratio of cumulative radiative forcing of a constant emissions rate from deploying 1 kg of* H_2 *continuously 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 (solid bars) and carbon dioxide and methane (lined bars). 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.*

This assumption of “additional” CH4 fugitive leakage need some more justification. One can argue that nearly all CH4 usage here for generating H2 would otherwise be used as gas fuel. I think the author can quantify how much energy supply from 1kg of H2 (~120 MJ) and calculate how much that can be from CH4 equivalent (roughly 120/55=2.2 kg). Therefore, there is an additional demand of 3.3-2.2=1.1 kg of CH4 if the purpose of CH4 here is to generate H2 (while losing some energy to the byproduct of CO2) as opposed to use it as direct fuel.

If the derivation I worked out above make sense, the ratio is more likely to be 1.1/3.3=33%, as opposed to 50%. Of course, I only have spent 10 minutes thinking about this. But I encourage the authors to check my argument and make improvement in the assumption of fugitive CH4 leakage in the blue hydrogen case.

We think we overcomplicated the previous analysis by lumping together the net impact on methane emissions from switching technologies. Therefore, as described in the response to the previous comment, we have completely recrafted how we represent methane emissions for both blue hydrogen and fossil fuel technologies, and keep the emissions separate. We hope our new approach is an improvement and much clearer, though we note it is a large source of uncertainty because of the lack of data and how dependent it will be on the specific fossil fuel technology and value chain pathway. Therefore, we have added discussion about this in the paper and made it clear that this analysis needs to be repeated on a case-by-case basis to truly understand the net effects. Our analysis therefore provides a first-order approximation of potential diminished climate benefits and a framework for further assessments. Case by case assessments are certainly needed as a follow up in order to guide decision making and bring clarity to the magnitude of climate benefits from each hydrogen application.

The text now reads (Line 565): *"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 valuable for first-order insights, decisions will ultimately need to be made based on implications for specific technological shifts."*

The authors accounts for the impact of H2 leakage on stratospheric water vapor " when this reaction (in Figure 1) occurs in the stratosphere", which has a warming effect. Had the authors or previous studies considered the emission of water vapor due to direct combustion of H2 fuel (e.g., aviation in the stratosphere)? Would that (>90% H2 not leaked) be more important than the "climate consequences of hydrogen leakage"?

Good question. We have not considered the impact of the emission of water vapor in the stratosphere due to direct combustion of H2 fuel such as via aviation. At this point we think it is more likely that aviation will use synthetic fuels based on hydrogen as a feedstock, but there is one report that we are aware of that does explore this (prepared by McKinsey & Company for the Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU, 2020). They conclude: "initial simulations of H2 direct combustion show that the formed ice crystals of contrails are heavier (i.e., they precipitate faster), and contrails are optically thinner (i.e., they are more "transparent") [as compared to contrails from traditional fuels]. As such, these water molecules lead to a lesser, briefer global warming effect – resulting in a 30 to 50 percent reduction in impacts from contrail and cirrus formation compared to kerosene aircraft." However, more work is needed on this issue to determine the climate impacts relative to leakage, and we have added mention of this effect in our paper as an example of how important case-by-case analyses will be (Line 567): *"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."*

Specific Comments:

I also have some specific comments, in the order of occurrence in the paper, for the authors to consider during the revision phase.

Abstract:

On the first reading, I'm a bit confused by what are the worst-case and best-case rates? Better to specify the numbers (worst is the 10% leakage rate later in Line 25?)

Great point – we have revised the text to reference the leakage rate value and do not use “best” and “worst” in the abstract anymore.

Line 36. Can you add some details of how H2 can perturb the atm chem and lead to increase in other GHGs? Is it true that H2 always leads to increase in other GHGs or are there any second-order compensation effects?
Absolutely. We had initially included the details of H2’s impact on atmospheric chemistry in Section 2 in order to tighten the intro before we went into further details. However, based on this feedback and that of the Editor, we have moved that text into the intro, and also revised Fig. 1 to be clearer about how H2 perturbs atmospheric chemistry.

The intro now reads (Line 51): *“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).”*

The new Fig. 1 is:

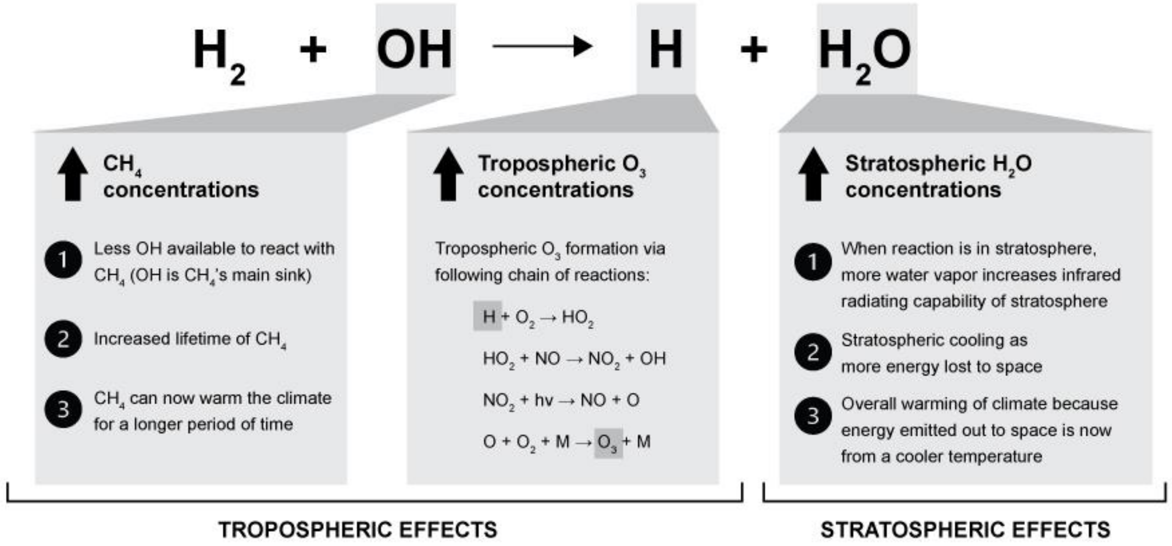

Figure 1: Effects of hydrogen oxidation on atmospheric greenhouse gas concentrations and warming.

We have also added text in the new discussion section to address the second question, which is looked at in a new study by Warwick et al. (2022) that was published since we submitted our paper. Essentially, all else equal, H2 emissions will lead to an increase in other GHGs, however if emissions of other species change, there can be compensation effects. For example, reductions in emissions of CO, NOx, and VOCs can lead to a smaller increase in methane from H2. The tropospheric ozone responses is also dependent on changes in emissions of other species, and reductions in CO, NOx, and VOCs can lead to a decrease in tropospheric ozone even with increased H2 emissions.

The paper now reads (Line 557): *"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 decarbonization strategies."*

Line 64. I suggest delete "in hydrogen assessments" here.
Done!

Line 86. "has a positive forcing on the climate due to stratospheric cooling from water vapor's absorption of heat". This is a bit confusing. Can be reworded to explain why it's a positive forcing (for the surface) f it leads to local cooling in the stratosphere?
Definitely. We have reworded in the text as well as in Fig. 1 (Line 55): *"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)."*

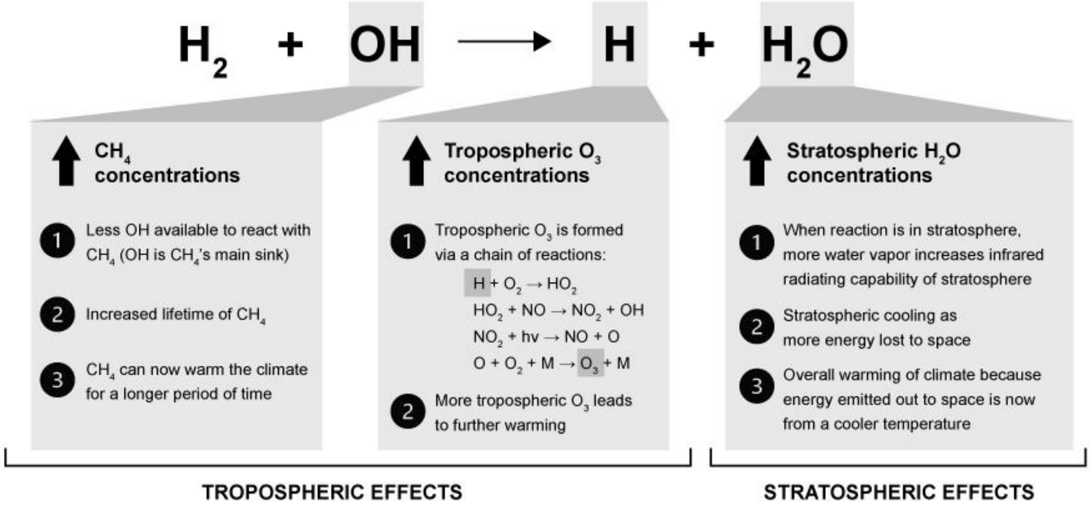

Figure 2: Effects of hydrogen oxidation on atmospheric greenhouse gas concentrations and warming.

The lower-right of Fig 1 says stratospheric warming which contradicts the message here. Please adjust. I think you meant surface warming due to stratospheric effects (Paulot 2021), not stratospheric warming.
Yes we definitely see how this is confusing and we have rephrased to “stratospheric effects” (see above figure).

Line 134. “Using the GWP formulas”. Can you document the formula for it (and also the TWP) since you used it multiple time for conversation of GWP and radiative efficiency?
Absolutely. We have added all GWP formulas to the paper (Eqns (1) – (8)) and the input parameters and sources in Table 1 (see below). Given that (1) TWP is just GWP with a constant emissions rate and reporting of the results as a function of time horizon; (2) we use new hydrogen GWP equations that would require new formal derivations of TWP; and (3) it was clear from Referee #2’s feedback that our use of TWP and how it relates to GWP was confusing and misunderstood, we decided to reframe our methodology through the GWP lens with minor improvements, and not focus on the TWP metric except to mention that this approach has a formal name and documentation. We therefore explain in the text how we use the GWP equations but just adopt a constant emissions rate and report results for various time horizons. Hopefully this is clearer.

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

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

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

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

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

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

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

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

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).*

Line 198: *“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 (AGWPi) from past and current pulses for each year is equal to the cumulative radiative forcing from a constant emissions rate (AGWPci). To account for multiple forcers emitted from each technology, we add up the individual AGWPcis for each time horizon. Finally, to compare the climate impacts from hydrogen technologies to their fossil fuel technologies counterparts,* *we simply divide their AGWPcs (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 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 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 rather follow the calculation chain described above."

Fig 2. How exactly is the solid line of cumulative radiative forcing (Alvarez et al., 2012) defined and calculated? Is that the same as GWP except for the assumption of emission profile (continuous vs. instaneous)? What's its unit? Is that the same as Tech Warming Potential mentioned in the end of Introduction section.
The calculation (what we call TWP) *is* GWP, but includes constant emissions (as opposed to a pulse) and presents the results as a function of time horizon rather than for just one time horizon. As in GWP, it is a ratio of two cumulative radiative forcings, so it is unitless. We have rewritten the methods section to be clearer (Sect. 2.1), added text when we discuss the figure, and reformatted original Fig. 2 based on the new hydrogen GWP equations provided by Warwick et al. (2022). We now only look at combined tropospheric and stratospheric effects, and panel (a) is for the pulse approach (GWP), and panel (b) is for the constant emissions rate approach.

The supporting figure text reads (Line 348): *"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 carbon dioxide for cases where they are both impacting the atmosphere in each time horizon."*

The new figure is:

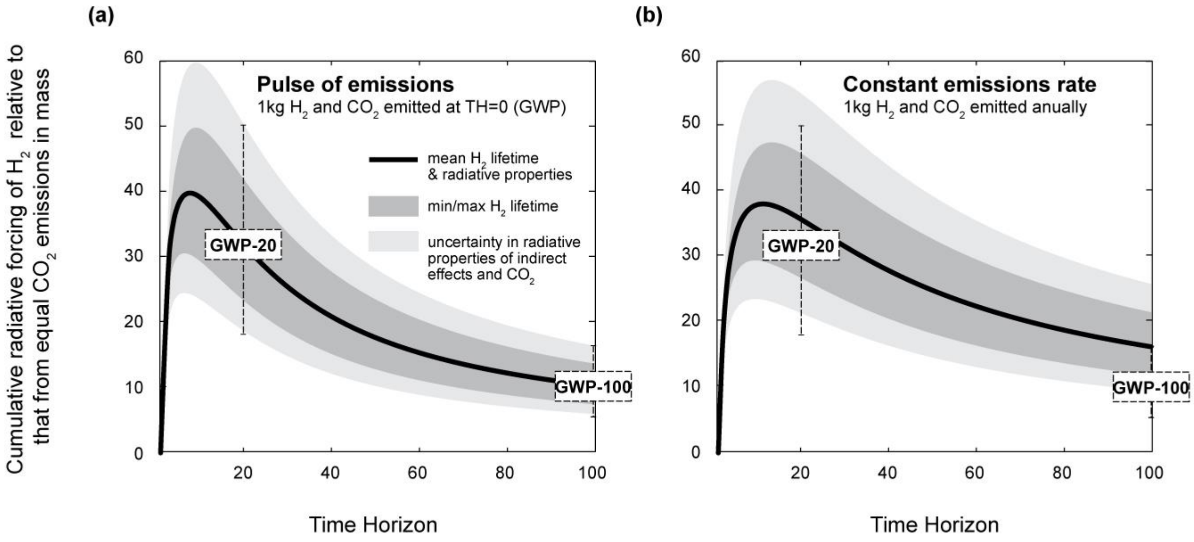

Figure 3: Warming potency of hydrogen relative to carbon dioxide using cumulative radiative forcing as a proxy for (a) a one-time pulse of equal emissions in mass (equals hydrogen's Global Warming Potential) and (b) a constant emissions rate of both hydrogen and carbon dioxide for equal emissions in 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.*

The paragraphs immediately after Fig 2 seems to be out of place. My understanding is that discuss the caveats of the simple metric approaches (constant radiative efficiency and H2 lifetime etc.). If so, maybe move it to a later place of discussion. (On a second read, maybe move it to be around Line 340).
Thanks for bringing this to our attention – we fully agree. We also note that with the recent publication of Warwick et al. (2022), this aspect of our analysis has been greatly improved with more confidence in the results in the near-term. Therefore, this discussion text has changed accordingly. We have also moved the discussion of uncertainties to the new discussion section, and it now reads (Line 546): *"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 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)."*

Line 150. Why 20 times? I thought it's more than that just eyeballing from solid line of Fig 2b.
We had conservatively said "more than" 20 times because of the uncertainty in the indirect effects in the years following emission. Now that this part of our analysis has been greatly improved, the new value is "more than 10 times" and the math aligns with the figure. We also note that the figure has also been modified to look at pulse emissions on the left and continuous emissions on the right, both for radiative effects derived from new equations from Warwick et al. (2022) that clarify temporal dynamics of H2's

indirect effects. The new figure is as follows:

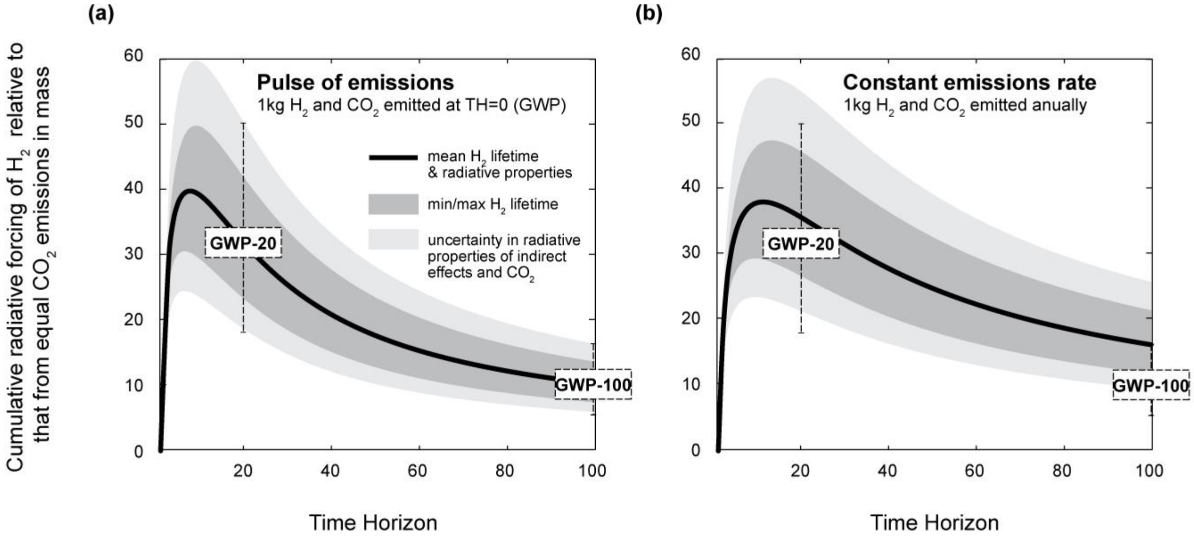

Figure 3: ***Warming potency of hydrogen relative to carbon dioxide using cumulative radiative forcing as a proxy for (a) a one-time pulse of equal emissions in mass (equals hydrogen's Global Warming Potential) and (b) a constant emissions rate of both hydrogen and carbon dioxide for equal emissions 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.*

Line 153. Reword a bit. I guess you cannot call it GWP anymore.
This section has been rewritten to reflect the new results and figure, and we break up the results into several paragraphs.

Section 4 title is “Climate implications of hydrogen leakage” which is actually the paper title. Thus, I suggest move 4.1 and 4.2 to be Section 4 (Method) and 5 (Results) instead, and avoid sub-sub-title.
Yes, this Section title was close to the title of the paper. Based on this feedback and that of the Editor, we have restructured the paper to sections of Intro, Methods, Results, Discussion, and Conclusion, with only one subsection level for each.

Line 244. I think here Section 4.1.3 should be Section 4.1.1.
We rearranged the sections so that we discuss climate impact calculations first, and emissions assumptions second.

Where does the factor of 3 come from in generating H2 from CH4? I thought it's more like (12+4)/4=4. It is because of the addition of H2O in the process to provide more H atoms?
Natural gas is used as both a feedstock for H2 production and as a fuel source for the required heat. There is a two-step process for H2 production that involves water in both parts, which contributes additional H atoms:

$CH_4 + H_2O \rightarrow 3H_2 + CO$ (1)

$CO + H_2O \rightarrow H_2 + CO_2$ (2)

The amount of CH_4 needed will depend on the composition of the natural gas, the efficiency of the reformer, and how much is needed as feedstock and fuel combined. It is difficult to find published values, and based on public documents and private communications we've found it can range anywhere from 2.5 to 4.5 times the mass of hydrogen. Therefore, we use a central estimate of 3 times the mass of hydrogen because it is in the middle for the published values, but it is on the lower end of all estimates we've come across. This makes methane emissions assumptions from blue hydrogen applications potentially on the conservative end.

We've expanded discussion of this in the text to clarify (Line 269): *"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."*

0.111 kg for 3*1.1*3%=0.099 kg?

3*1.1=3.33 kg is needed to produce 1.1 kg of hydrogen. But this 3.33 kg of methane is the result *after* methane leakage, and is what is consumed. So, 3.44 kg is needed in methane production to end up with 3.33 kg for hydrogen production if there is a 3% leakage before the point of H_2 production. 3.44*3% = 0.103 kg methane leaked.

Line 265. With CO_2 leakage, it's falling into the realm of grey hydrogen.

Grey hydrogen is using SMR without CCUS. Blue hydrogen incorporates CCUS. However, CCUS efficiency can be 65% or 90% depending on the CC technology. Therefore, there are still residual emissions of CO_2 that will contribute to blue hydrogen's climate impacts.

Table 1. The row for CO_2 should be 11 for all cases.

Correct, but now we have redone the Table and do not include this value in the table, only in the text.

The row of CH_4 produced does not seem to agree with the add-up of Consumed and Emitted. Please double check if this affects the main results presented later.

Yes you are right. There was an error in the table for worst-case CH_4 but it was correct in the analysis. Also, we had halved the leaks of methane to account for avoided methane emissions from displacing the fossil fuel systems so that made the table more complicated. However, as noted earlier, we have completely revised the way we address avoided methane emissions – via a separate sensitivity analysis and new figure. As a result, this table is now clearer, and the values add up in the way they are expected to:

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).*

Table 2. foot note b seems to duplicate the text right below Table 2.

Yes, they were similar. Given that we have revised our analysis of the temperature impacts given feedback and the confusion of using an equilibrium climate sensitivity for transient climate responses, this table is no longer in the paper.

Here you also need to verify the assumption of energy composition in 2050. Does the 2017 study assume the same fraction of coal/oil/gas as of now or (a more likely) switch from coal to gas? Since coal emits more CO2 than gas (per unit of energy supply), assuming a constant offset of 11 kg of CO2 can underestimate the benefits of H2 because in the near-term the CO2 offset could be larger than 11.

Given that the Hydrogen Council (2017) analysis is based on specific fossil fuel technologies replaced with hydrogen alternatives (such as hydrogen powering certain vehicles and supplying the heat needed for industry), we are not as concerned about the energy composition changing over time (because that is not how the avoided CO2 emissions are calculated). However, it's true that over time these fossil fuel technologies could become more efficient, and therefore less CO2 would be avoided in the future from hydrogen applications relative to now. This is further motivation for our new sensitivity analysis where we look at different levels of avoided CO2 (and methane) to see how it affects the perceived benefits of hydrogen.

Line 286. What's "avoided hydrogen emissions from displaced fossil fuel combustion"??

There are some hydrogen emissions from fossil fuel combustion. What we meant here was avoided H2 emissions from fossil fuel technologies no longer used. We have clarified this in the text (Line 296): *"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."*

Line 310? What' the assumption of relative magnitude of green vs blue hydrogen evolving from 2020 to 2050.

Given our revision of the temperature analysis, we no longer use demand scenarios that change over time. However, the assumption of the relative magnitude for green vs blue hydrogen was estimated from a figure in a Hydrogen Council (2021) report and is as follows. However, we only calculated absolute temperature impacts for hydrogen emissions, and therefore it didn’t matter what the type of hydrogen production method was.

Global hydrogen production (Mtpa)							
Hydrogen type	2020	2025	2030	2035	2040	2045	2050
Blue	0	30	40	60	90	150	220
Green	0	10	40	60	100	180	330

Source: Hydrogen decarbonization pathways Potential supply scenarios, Hydrogen Council, 2021.

Line 313. “When considering climate impacts, we only account for emissions from hydrogen leakage for total hydrogen demand ”
I’m confused. I thought you also include CH4 leakage from blue hydrogen?
This sentence was specifically referring to the temperature impacts analysis, where CH4 leakage from blue hydrogen was not included. We have clarified this in the text (Line 234): *“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.”*

Line 355 . 0.84 mW m-2 (Tg yr-1)-1) Why is this a different number than the 3.64E-13 in Table 3?
This number refers to an emissions-based radiative efficiency, whereas the number in the original Table 3 was the burden-based radiative efficiency. However, we now use the GWP equations and inputs derived in Warwick et al. (2022) for hydrogen’s impacts, and thus are no longer using a burden-based radiative efficiency for calculating hydrogen’s effects over time.

Line 370. Again, is the cumulative radiative forcing the same as the technology warming potential (TWP)? Maybe it’s worth showing the equation set.
Yes, and we apologize for the confusion. We have greatly clarified our methods and included equations, and moved away from referring to TWP as it confused the readers more than it helped describe our method, and GWP with constant emissions rate is a more accessible explanation of our approach.

Line 400. Again, need to justify the 50% assumption.
Based on the referee’s helpful comments, we have revised our analysis to include a sensitivity test of different levels of avoided carbon dioxide and methane emissions from fossil fuel technologies. Therefore, this text has changed and the main “TWP” figure is simpler and only includes avoided carbon dioxide emissions as to not confuse the reader on the net methane impacts. We then added a new figure to illustrate the impact of avoided methane emissions on our results.

Line 424. “continuing to use GWP-100 to calculate climate effects will not only overlook near- and mid-term impacts on the climate,” How about using GWP20 as the authors had previous argued in 2017?
Yes, we had mentioned this strategy in original Line 132: “One strategy for indicating the potency of short-lived climate pollutants is to report GWPs for two time horizons – one that conveys near-term

impacts (most commonly 20-year time horizon) and one that conveys long-term impacts (100 years) (Ocko et al., 2017)."

However, at the time of submitting the article it was unclear how useful GWP20 would be given the short lifetime of H2 of only a few years, and therefore we did not emphasize this approach further. However, now that there has been more research on the temporal dynamics of the indirect effects, we feel confident that GWP20 is a useful indication of impacts in the near-term. Therefore, we are recommending our dual GWP approach (Ocko et al. 2017) for evaluating H2's climate impacts. The text now reads (Line 527): *"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."* And (Line 593): *"(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)…"*

Fig 5. Would you make it a colored graph?   Also did you really run the calculation for various levels of assumption of final energy demand (y-axis), or it's really an extrapolation based on the 20%, 50%, 100% cases shown in Fig 4? If it's the later, it's best show those actual data points in markers.
We have completely revised this figure based on feedback of the temperature calculation as well as this comment. We did run the calculation for various levels of assumptions of final energy demand (every 10% starting at 10%). Regardless, we agree that it's best to show the actual data points in markers rather than a line. Further, because the final energy demand also depends on the energy pathway scenario (1.5C world, 2C world, no further action world, etc), we have decided to reframe as temperature response to levels of H2 consumption, with indications of what each level may be associated with in terms of previously published projections. The new figure is:

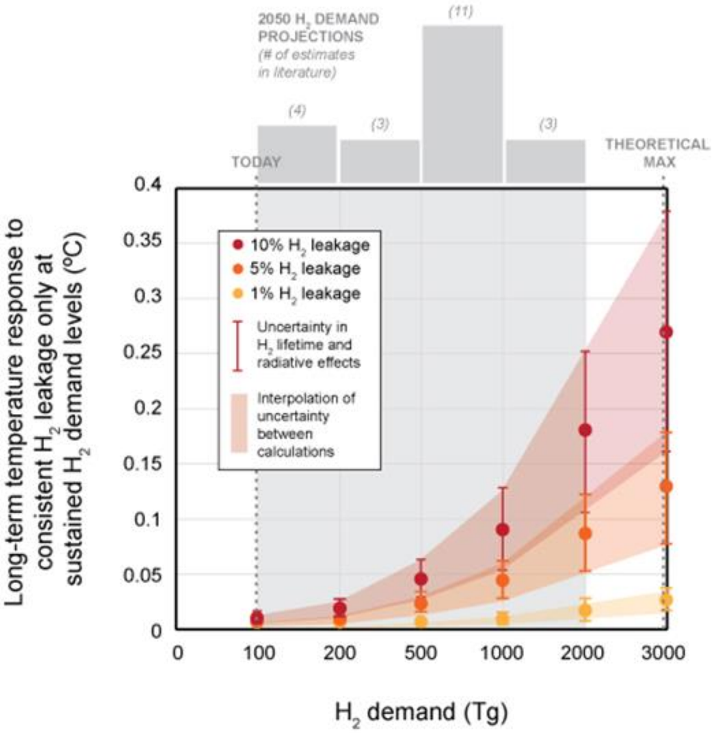

Figure 6: Long-term temperature responses (ºC) to different levels of hydrogen leakage based on sustained hydrogen demand levels (Tg). *Red/orange/yellow markers and shading represent leakage levels of 10/5/1%. Uncertainty is based on uncertainties in both hydrogen's soil sink and therefore lifetime (~±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.*

Also, the extrapolation to 0% is problematic; why would the warming be more than zero if there is no hydrogen use after all?

This was an error, as the starting point in the x-axis was supposed to say 10%. Regardless, bad form to start at 10% and so it would have been confusing even with the label included.

Line 565. "Derwent, R. G.: Hydrogen for Heating: Atmospheric Impacts, Ph.D., Department for Business, Energy & Industrial Strategy, 2018." Can you specify the citation source?

Yes, we have revised the citation and provided a link to the report.

Derwent, R. G.: Hydrogen for Heating: Atmospheric Impacts, Department for Business, Energy & Industrial Strategy, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760538/Hydrogen_atmospheric_impact_report.pdf, 2018.

Referee #2

The paper is about climate impacts of hydrogen leakages, a timely and important topic. Even though the authors have good knowledge about previous studies and the introduction is well-written, unfortunately, I cannot recommend publication of this paper in ACP. I do not think this paper substantially contribute with new knowledge in the field and I do not think the results are discussed in an appropriate and balanced way. To me, this paper is a bit misleading, and it looks more like an opinion piece about their metric being much better than GWP100. The figures are a bit confusing, and I would argue, sometimes wrong. Figure 4 and 5 shows ECS (equilibrium, and not transient!) for each year, do the authors assume the climate reach equilibrium in an instant? Also, the paper only interprets already published data and the authors do not state this very clearly. I am also confused about how the authors compare the impacts of hydrogen emissions and CO2 emissions.

We greatly appreciate Referee #2's time in reviewing our manuscript, and responding to their feedback has made the paper substantially stronger. In addition, we think that there were several misunderstandings that we hope we have clarified in the responses below and also in the manuscript. Overall, we have:

- Emphasized and made clearer how our study contributes to new knowledge in the field
    - For example, in the abstract: *"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."*
- Separated our discussion of the results so that the interpretation and implications of the results are now included in a new Discussion section, and the Results section just focuses purely on the results of the analyses
- Considerably revised our discussion of metrics and our methodology as to not imply that this paper is about metrics and especially one metric being better than another, also toned down any discussion about GWPs, removing language like "misleading" and "limited value"
- Revised the calculations of hydrogen's warming effects based on newly published scientific insights that greatly improve the temporal dynamics of its indirect effects; this had the result of greatly improving estimates of hydrogen's "GWP" in the following years after its emission, and made the original Fig. 2 much more robust
- Removed original Fig. 4 and redid the analysis for Fig. 5 as to not imply that temperature impacts occur instantaneously
- Clearly stated in the abstract and elsewhere that our study uses already published data
    - *"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."*
- Rewrote the methods section and included all relevant equations and input parameters to better explain how we compare impacts of hydrogen, methane, and carbon dioxide emissions

Below we respond point-by-point to both major and minor comments, with revised text *italicized* in quotes.

1. Not a balanced discussion on GWP100:

The authors state many, many places in the manuscript that using GWP100 is wrong (e.g. L10: "To date, hydrogen's warming effects have been primarily characterized using the GWP-100 metric—which is misleading for short-lived gases, such as hydrogen, as it obscures impacts on shorter timescales."), even though this is the standard and official metric by UNFCCC. No metric is perfect, but this is not unique to hydrogen, and I don't think the authors address this in a well-balanced way, for instance see Boucher and Reddy, 2008 for a description on how to use GWP100 for SLCFs. Since the authors want to bring this discussion to the manuscript, I find it problematic that there is a lack of discussion of other more widely used alternative metrics such as GWP*, GTP or cGTP, the latter two of which are both suggested as suitable metrics for short-lived climate forcers by the IPCC (Forster et. al 2021). GWP100 has an advantage of being comparable to published literature and provides a measure for a time well after the effects of hydrogen have reached steady state. GWP20 will underestimate the long-term effects of CO2 but this is not mentioned at all. Shine et al. (2005) and Allen et al. (2016) also stress that short time horizon lead to overestimates of short lived climate forcers. This is because GWP is an integrated metric in contrast to end-point metrics such as GTP.
We thank the referee for bringing to our attention that the paper could be interpreted in this way. We never meant to imply that GWP-100 is "wrong" (and never used the word "wrong"), but rather that when it is relied on exclusively for understanding the impacts of short-term forcers, it misses the impacts in the near-term – which could lead to suboptimal outcomes from climate policies and decarbonization strategies. However, while the GWP-100 issue with hydrogen partially motivated this study, it does not need to be a focus of the paper – and the analysis and results stand on their own. Rereading the paper through the lens of the referee made it clear that the majority of the GWP conversation in our paper is a distraction and largely unnecessary. We do not want this to be a "metrics" paper" – rather, we want it to be a paper improving the understanding of the climate significance of hydrogen leakage. Therefore, we have removed the majority of text that implied GWP-100 is "wrong," and taken a more objective and balanced approach. For example, we completely agree that GWP-20 has its own shortcomings (which is why we suggest using both GWP-20 and GWP-100 as an inseparable pair as neither on its own is sufficient but combined can adequately convey impacts across all relevant timescales). And we also agree that GWP-100 can falsely imply that short-lived forcers have a big impact on the climate in the long-term). We are now more explicit about the pros and cons of GWP in our paper.

For example: (Line 106): *"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 CO2'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 CO2.*

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 CO2) 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 CO2's impacts after 20 years, when it is still affecting the atmosphere."

Further, we think there is a misunderstanding of our metrics approach, which we take full responsibility for and have greatly clarified in the text. This is because we do primarily use the GWP metric in our analysis, we just incorporate constant emissions of forcers (as opposed to a one-time pulse) and present our results as a function of time horizon (instead of for one time horizon). A motivation for using the GWP equations (as opposed to other metrics) is that they are easily understood by non-scientists stakeholders, and we want our results to be as accessible as possible. However, presenting the results for all timescales is key to adequately conveying the climate consequences of hydrogen alternatives relative to fossil fuel technologies, given the differences in timescales of their effects. Further, using constant emissions is also important because it is a more realistic representation of hydrogen leakage in a hydrogen economy, as opposed to a one-time leak, and also makes more sense in that you are calculating hydrogen's warming effects compared to carbon dioxide for cases where they are both impacting the atmosphere in each time horizon. Technology Warming Potential (TWP) is just the formal published title for this approach – GWP for constant emissions and for all time horizons. It seems that there was a lot of confusion regarding our discussion and use of TWP (also noted in Referee #1's comments), and therefore we have moved away from calling our methodology throughout by its formal name because it will likely be better understood as simply using GWP for constant emissions and all time horizons. We do keep a few mentions of it, however, to acknowledge its formal publication in the literature, and to direct readers to more information on it.

The text now reads (Line 148): "*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 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 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 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."

Finally, given that we have toned down the discussion of metrics, do in fact use GWP, and have moved away from referring to TWP, we do not think it is necessary to go into a discussion of other widely used alternative metrics such as GWP*, GTP or cGTP. We do not want to distract readers from the focus of our study, which is improving general understanding of the climate consequences of hydrogen leakage. Further, we note that GWP* and cGTP metrics were designed to improve comparisons of short-lived climate forcers to long-lived forcers specifically regarding climate stability, long-term temperature goals, and CO2 removals, and therefore are not necessarily appropriate for our paper where we specifically want to improve understanding of near-term impacts. And, as the referee pointed out, no metric is perfect and GWP is the official metric of the UNFCCC, further justifying our use of GWP. Overall, we have decided to provide a brief acknowledgment of the complex history of metrics.

The text now reads (Line 123): "*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-CO2 climate forcer, and specifically GWP with a 100-year time horizon (GWP-100)."*

L66: "Given hydrogen's known indirect greenhouse gas properties and unknown leak rates, we use a metric for looking at the impacts of energy transitions on net radiative forcing over time called Technology Warming Potential (Alvarez et al., 2012) that considers continuous emissions, providing a more realistic understanding of the climate impacts of fuel switching." I read this as the only possible metric for estimating climate impact of continuous emissions – GWP100 can also be estimated for continuous emissions.

We have removed this sentence from the paper. As mentioned above, we do in fact use GWP for continuous emissions, and we certainly don't mean to imply that TWP is the only metric that can do this.

The text in the introduction now reads (Line 149): *"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 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 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 implications over time from a sustained switch to hydrogen alternatives from fossil fuel technologies."

L112: As several previous studies have shown, relying on GWP-100 for understanding the importance of short-lived greenhouse gases relative to carbon dioxide is misleading (Alvarez et al., 2012; Ocko et al., 2017; Ocko and Hamburg, 2019)". These 'several' papers only refers to papers from the authors themselves and I am not particularly blown away by this list of self-citations on the topic.
We have removed this statement from the text, and no longer refer to GWP-100 as "misleading."

L131: "Given hydrogen's short atmospheric lifetime of only a few years, reporting hydrogen's potency in GWP-100 has limited value. One strategy for indicating the potency of short-lived climate pollutants is to report GWPs for two time horizons – one that conveys near-term impacts (most commonly 20-year time horizon) and one that conveys long-term impacts (100 years) (Ocko et al., 2017) " GWPs always have a time horizon where integration stops, GWP20 will not then consider long-term effects of CO2. GWP20 will underestimate the long-term effects of CO2, but the authors do not mention this at all, I find this problematic.
We agree completely that this point should be mentioned, and have added it to the text (Line 121): *"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 CO2's impacts after 20 years, when it is still affecting the atmosphere."*

L142: "However, assessing the impact of hydrogen through a pulse of emissions is also problematic. This is because continuous emissions are a better representation of actual hydrogen deployment. To better understand the climate effects of hydrogen over all timescales, one would need to consider the radiative effects of continuous emissions over time (Alvarez et al., 2012)." But the authors have already converted the radiative effects calculated by Paulot et al 2021 and here they also use continuous emissions.
Yes, we see how this is confusing. We had used Paulot et al. 2021's radiative efficiency based on H2's burden, which was derived from continuous emissions of hydrogen. However, the radiative efficiency can be applied to pulse emissions as well as continuous when using the GWP equations, and in this sentence we were justifying our use of continuous rather than pulse emissions in our analysis. Based on the referee's comment, we have completely rewritten this text, and also note that our calculations of H2's GWP have changed given a new publication that derives new GWP equations for resolving the temporal dynamics of hydrogen's indirect effects in the near-term (Warwick et al. 2022; see response to Comment 2 for more information). Therefore, we no longer use Paulot et al.'s efficiency. We do note however that the resulting radiative efficiency per unit burden of H2 from Warwick et al. 2022 is similar to that from Paulot et al. 2021.

The text now reads (Line 149): *“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 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 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 implications over time from a sustained switch to hydrogen alternatives from fossil fuel technologies.”

Line 376: “The benefit of the Technology Warming Potential method is that we can analyse climate impacts over multiple time periods of interest—in the near-, medium-, and long-term—insights that are not available with the use of the GWP-100 metric. This is important when short-lived climate pollutants are emitted as they are often reported and assessed based on the long-term impact of a pulse emission, which overlooks their true impacts during the time they are active in the atmosphere.”

We’re not sure what the comment here is, but based on previous comments, we can surmise that the referee is pointing out how our text makes it seem like TWP and GWP100 are the only options and GWP100 is wrong and TWP is right. This was not our intention, and we have rewritten the text to tone down the language discussing GWP100 and the better explain our methodology in that it is based on GWP (Line 149): *“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 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 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 implications over time from a sustained switch to hydrogen alternatives from fossil fuel technologies."*

And (Line 173): *"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."*

L418: "However, even the standard GWP-100 approach undervalues the cumulative radiative forcing over a 100-year time period given its reliance on pulse, instead of continuous, emissions (Fig. 3)."
Again we surmise that the comment is on the negativity of GWP-100 and that GWP can be used for continuous emissions whereas we imply that it can't. We have removed this sentence, but what we meant here is that accounting for a constant emissions rate means that you are comparing the 100-year integrated warming impact for H2 and CO2 when they are both still affecting the atmosphere. Overall, we have toned down references to GWP-100's shortcomings and discuss the pulse vs constant emissions rate implications independently. For example, (Line 149): *"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 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 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."*

2. Figures are misleading

Figure 2: – do the authors suggests that GWP_0 can be used? How did you estimate the numbers in Fig. 2? Do you assume the same lifetime for the indirect effects of hydrogen here? If that is the case, this figure is not correct.
No, we do not suggest that GWP_0 can be used, and we had stated in the original text (original Line 164): *"However, given that hydrogen's radiative effects are entirely indirect, any time horizon shorter than the lifetime of hydrogen (in which the required reactions have not yet taken place) will not provide a meaningful GWP result."*

The numbers in original Fig. 2 were calculated by using the standard equations for Global Warming Potential (simple exponential decay for H2 and the more complex decay function for CO2 as in IPCC AR5 and AR6), for either a pulse of emissions or for constant emissions. We did assume one lifetime for H2 that applied to its indirect effects, which we agree was not optimal for early time horizons when the indirect effects are playing out over different timescales. However, at the time of submission there was a lack of quantification on how these indirect effects evolve. One way we approached this limitation was by averaging climate impacts over the first fives years in our original Fig. 3 that showed the relative climate impact from replacing fossil fuel technologies with hydrogen alternatives (original Line 336): *"Further, given that the effects of hydrogen emissions are entirely indirect, we average the climate impacts over the* *first five years after initial emission to account for the individual timelines in chemical responses and to remain conservative during the first few years where hydrogen potency would strongly outweigh that of carbon dioxide if considered an instantaneous effect (recall that the radiative efficiency of hydrogen is around 200 times that of carbon dioxide for equal mass). For example, Field and Derwent (2021) suggest that the tropospheric ozone response is immediate, but that the methane response takes a few years to reach its full potential."*

In addition, we had highlighted the need for chemistry-climate models to further evaluate this aspect to improve understanding of hydrogen's warming effects during short time horizons (original Line 164): *"Further, while Field and Derwent (2021) suggest that the tropospheric ozone effects are nearly immediate, the methane effects may take a few years to build up. This highlights the need for a more integrated chemistry-climate modelling approach to accurately determine the tropospheric and stratospheric radiative effects of hydrogen leakage in the first several years after emission."*

Not only do we see how our handling and discussion of this limitation could have been stronger, but new published research since we submitted the paper (Warwick et al. 2022) provides, for the first time, explicit quantitative insights into the temporal dynamics of hydrogen's indirect effects. This is what we had mentioned was needed by the scientific community to improve the GWP over time assessment. This new study derives Absolute Global Warming Potential equations specifically for hydrogen emissions based on the different indirect effects (methane, tropospheric ozone, and stratospheric water vapor; see Eqns (3) – (8) in our revised manuscript and Table 1 for input parameters). Therefore, we now use these equations in our analysis which has greatly resolved the estimation of hydrogen's GWP in time horizons "0" to around 20. The figure (below) now makes much more intuitive sense in the early years, although we note that time horizons from 20-100 still have similar results as the first version.

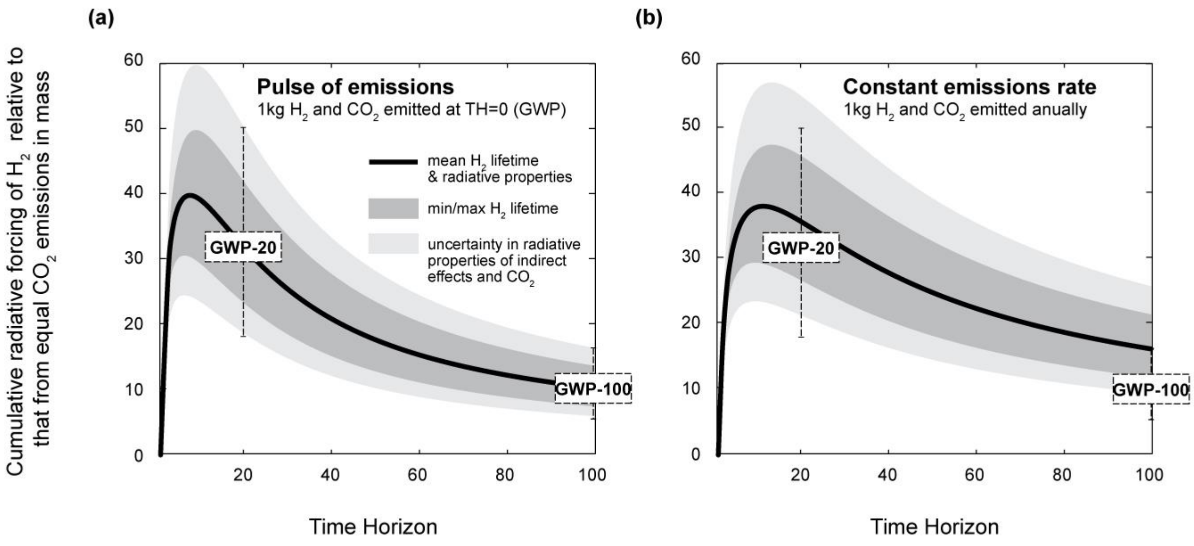

Figure 3: Warming potency of hydrogen relative to carbon dioxide using cumulative radiative forcing as a proxy for (a) a one-time pulse of equal emissions in mass (equals hydrogen's Global Warming Potential) and (b) a constant emissions rate of both hydrogen and carbon dioxide for equal emissions in 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.

I think Fig. 3 is very misleading as it shows a timeline with years after technology switch with cumulative radiative forcing and does not take lifetime into account if I understand this correctly.

This figure is based on the GWP equations using a constant emissions rate, and therefore lifetimes are certainly taken into account (such as impacts of CO2 building up in the atmosphere whereas H2 and CH4 are shorter-lived on the order of decades). This is why there are more benefits to H2 the longer the time horizon, because you are avoiding an accumulation of CO2 in the atmosphere.

However, our original analysis and figure did not take into account the individual lifetimes of H2's indirect effects given the lack of quantification in published research at the time of submission (this is why we had averaged the results from years 0-5). However, with the publication of Warwick et al. (2022), we are able to greatly improve our analysis, and now we are able to make use of new GWP equations that specifically tease out the individual impacts of each H2 indirect effect over time (methane, tropospheric ozone, and stratospheric water vapor). Therefore, we use these equations to look at impacts from continuous emissions (constant emissions rate) of H2, CH4, and CO2 and their impact on cumulative radiative forcing for each time horizon. The new figure is as follows:

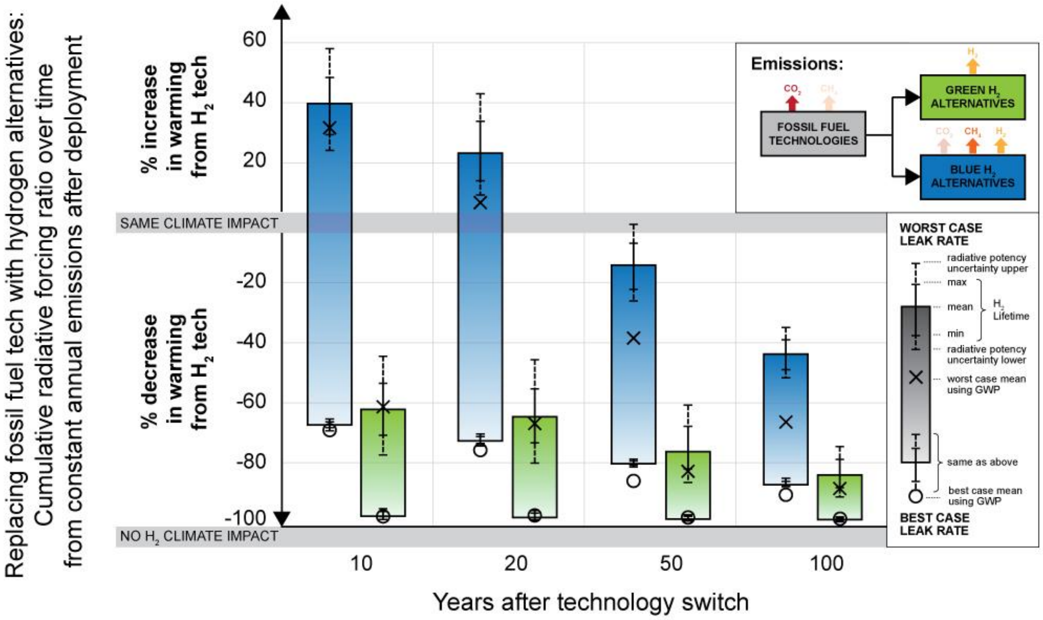

Figure 4: Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for a generic case. *Ratio of cumulative radiative forcing of a constant emissions rate from deploying 1 kg of H_2 continuously is used as a proxy of relative warming impacts. Emissions from hydrogen alternatives are hydrogen for green hydrogen and hydrogen and methane from blue 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.*

Figure 4 is even more misleading as it shows a -timeline- of ECS, and not transient. You then assume that the climate has reached equilibrium in an instant? This comment also goes to Fig 5. I do not agree that these figures can be published.

We appreciate the feedback and agree with the referee that showing a temporal evolution of temperature responses based on ECS misrepresents the physics and is confusing. We have therefore removed this figure and completely revised original Fig. 5 as to not frame the analysis as anticipated temperature impact in a certain year, but rather the eventual warming impact from a sustained level of H2 demand based on several leak rates. The new figure is as follows:

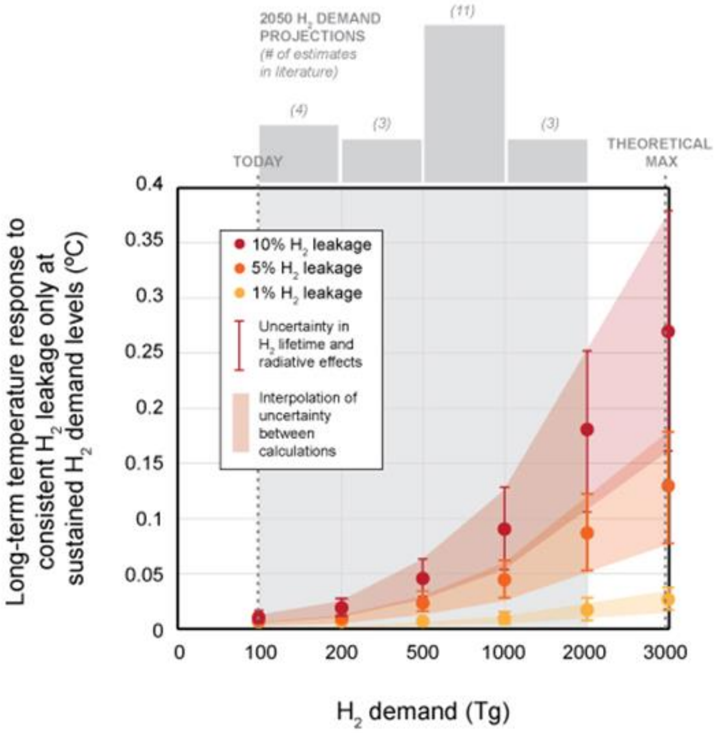

Figure 6: Long-term temperature responses (ºC) to different levels of hydrogen leakage based on sustained hydrogen demand levels (Tg). *Red/orange/yellow markers and shading represent leakage levels of 10/5/1%. Uncertainty is based on uncertainties in both hydrogen's soil sink and therefore lifetime (~±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.*

3. Data

The authors are not very clear in their abstract that all the data they interpret is one data set from one model - and that data set is already published. It is totally fine to do that – but it must be stated clearly that this is an interpretation of already published data.

We agree that this needs to be more explicitly stated. However, we note that we take data from several sources overall, and that the hydrogen data is now from two studies that are consistent with one another in terms of the total radiative efficiency of a change in the burden of hydrogen. The abstract now reads (Line 15): *"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."* And the intro now reads (Line 149): *"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 with minor improvements to the standard GWP metric to assess impacts over time and account for constant emissions."*

L347: "In the absence of models capable of interactively simulating the chemistry, radiation, and temperature responses in the full atmosphere to hydrogen emissions, we apply the simple approach used by Paulot et al. (2021) to approximate temperature responses to the three hydrogen demand scenarios discussed in Sect. 4.1.1." Paulot et al 2021 did use a model capable of simulating chemistry and radiation response to hydrogen emissions, that is what their paper is about - the way this is written it seems like you are calculating these effects yourself? Again, this is repeated in L471: "To our knowledge, no model is currently capable of interactively simulating the chemistry, radiative forcings, and temperature impacts from hydrogen emissions into the full atmosphere." Then I am left to wonder – why do you rely so heavily on the GFDL model from Paulot et al. 2021 in your analysis, if you don't believe in the results? We apologize for the misunderstanding here. We never mean to imply that we don't "believe in" the results of Paulot et al. 2021 nor did we mean to misrepresent the Paulot et al. study and our own. Paulot et al. 2021 was a major step in the scientific understanding of hydrogen's full impacts on both the troposphere and stratosphere. We were only referring to the point that Paulot et al. (2021) used a model that (at the time) was not capable of a fully interactive simulation of climate responses to hydrogen emissions. Specifically, the response of methane's lifetime on methane concentrations is not accounted for in the model because methane concentrations are prescribed (page 13454). Therefore, they must conduct another experiment where they increase methane concentrations separately. They also use a simple approximation of temperature impact instead of a model-simulated one, and we assume that if the model was capable of assessing temperature impacts to hydrogen emissions, they would have used the model and not the simple estimate.

Our main point was that no models we were aware of could perform the simulations needed to estimate a transient temperature response to hydrogen emissions, and therefore for now we would rely on a simple calculation to at least get a sense of order of magnitude and to hopefully inspire more sophisticated modeling assessments to look into this. This being said, we have been in conversations with different modeling groups that are actively working on integrating hydrogen chemistry and indirect radiative effects into their models, and we are aware of a few efforts to conduct further experiments and simulations. Therefore, we have removed any text referring to models' current limitations, because the science is moving fast and we do not want to misrepresent others' work. For example, in the few months since we submitted our paper, a new study (Warwick et al. 2022) was published that used sophisticated modeling with a different model than Paulot et al. to advance scientific understanding even further.

Other comments sorted by line number:

L70: ".. approach as there are currently no formal models we are aware of that can simulate the full climate responses to hydrogen emissions". What would it take to meet the criteria of this sentence and make one apply something else than this simple methodology? We have been working with scientists to answer this exact question. It seems like, depending on the desired objective, what is needed are: historical and projected emissions; more robust measurements of hydrogen's atmospheric concentrations; more data on the soil sink; and interactive emissions, chemistry, concentrations, and radiation. However, as described in the previous comment, we have removed language on limitations of existing models given the fast pace of this field. Instead, we further justify our "simple" method in the introduction section (Line 149): *"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 with minor improvements to the standard GWP metric to assess impacts over time and account for constant emissions."*

L98: "..but the majority presenting results in terms of GWP-100". Many of these also state radiative forcing from different sources in addition to GWP100.

We did point out the studies that calculate radiative forcing, but still maintain that the majority of existing studies present their results in GWP-100. Original Line 96: *"The others have focused on tropospheric effects, with a few calculating climate forcings for select leakage rates and hydrogen demand scenarios (Prather, 2003; Schultz et al., 2003; Wuebbles et al., 2010), but the majority presenting results in terms of GWP-100 (Derwent et al., 2001, 2006; Derwent, 2018; Derwent et al., 2020; Field and Derwent, 2021)."*

In response to this comment, we have rephrased this sentence. The text now reads (Line 130): "*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."*

L101: ".. the combination of GWP-100 downplaying hydrogen's true potency and the recent insights into the full atmospheric". I am not sure that downplaying is clear in this case, the long-term effect of excess carbon in the climate system should not be downplayed either? Also, which recent insights are we talking about here?

Yes, we see how this can be confusing. We were trying to make the point that while previous studies have concluded that H2 leakage is not a major concern for the climate, they were based on long-term impacts of hydrogen's tropospheric impacts only. CO2's effects should not be "downplayed" either, which is why we always present our results for multiple timeframes in both the near- and long-term. This text has now been revised to be more clear, and we do not use the word "downplayed" (Line 130): *"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."*

L117: Here you should add that the lifetime of methane is much longer than hydrogen, and this will have an effect when integrating their effects.
Based on new research (Warwick et al. 2022), the best available science indicates that some of hydrogen's effects can last as long as methane's (because half of them are due to its effects on methane). Therefore, we have added (Line 71): *"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)."*

Line135: ". However, even a 20-year time horizon is long for a gas that only lasts a few years in the atmosphere". Hydrogen has no direct climate effects; hence its own lifetime is not the only time value important to this type of consideration. One primary effect of hydrogen is the lengthening of the lifetime of methane. Methane's lifetime is much longer than that of hydrogen, hence this sentence is somewhat ambiguous.
Yes, great point, and with our revised analysis incorporating the new derivations of H2-specific GWP equations, this sentence has been removed as we have found that GWP-20 is sufficient for conveying H2's effects.

Line 146: "When continuous emissions are considered as opposed to just one pulse at time = 0, the potency of hydrogen relative to carbon dioxide is on average double that of the pulse approach (Fig. 2); this is true for long-term effects as well" Are you comparing the appropriate things to each other here?
Yes, we were comparing cumulative radiative forcing from a constant equal emissions rate of *both* hydrogen and carbon dioxide. We have clarified this in the text (Line 351): *"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."*

Table 1: I assume there is a typo here, and the carbon dioxide avoided from H2 consumed should be 11 as in the other columns.
Yes, this should have been 11. However, we have modified this table to be simpler and it no longer includes avoided CO2 emissions:

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).

L255: “To determine emissions of methane when considering blue hydrogen production, 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).” One study - is there any uncertainties here?

The amount of CH4 needed will depend on the composition of the natural gas, the efficiency of the reformer, and how much is needed as feedstock and fuel combined. Unfortunately, it is difficult to find published values, and based on public documents and private communications we’ve found it can range anywhere from 2.5 to 4.5 times the mass of hydrogen. Therefore, we use a central estimate of 3 times the mass of hydrogen because it is in the middle for the published values, but it is on the lower end of all estimates we’ve come across. This makes methane emissions assumptions from blue hydrogen applications potentially on the conservative end.

We’ve expanded discussion of this in the text to clarify (Line 268): *“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. ”*

L279: “To estimate how much carbon dioxide emissions are avoided from deployment of one unit of hydrogen (which will ultimately depend on the specific technology), we use estimates from the Hydrogen Council (2017) that quantify avoided carbon dioxide emissions from a scenario of replacing 18% of final fossil fuel-derived energy demand in 2050 with hydrogen applications.” Hydrogen has a lot of indirect effects, as the authors also state, but so has CO2. How is that reflected in the numbers for emitted CO2 (11 kg CO2 avoided per 1 kg H2 consumed)? I think the decay functions need to be explained better. Also, how did the authors include the decay of methane into their GWP20 for hydrogen? The Methods needs to be better explained.

First, CO2’s radiative efficiency uncertainty is also now reflected in the error bars in new Fig. 4. Second, based on this comment and others, we have decided to include a sensitivity assessment to explore how different levels of avoided CO2 emissions per 1 kg H2 consumed would influence our results. Below is the new Fig. 5 and the text referring to the results.

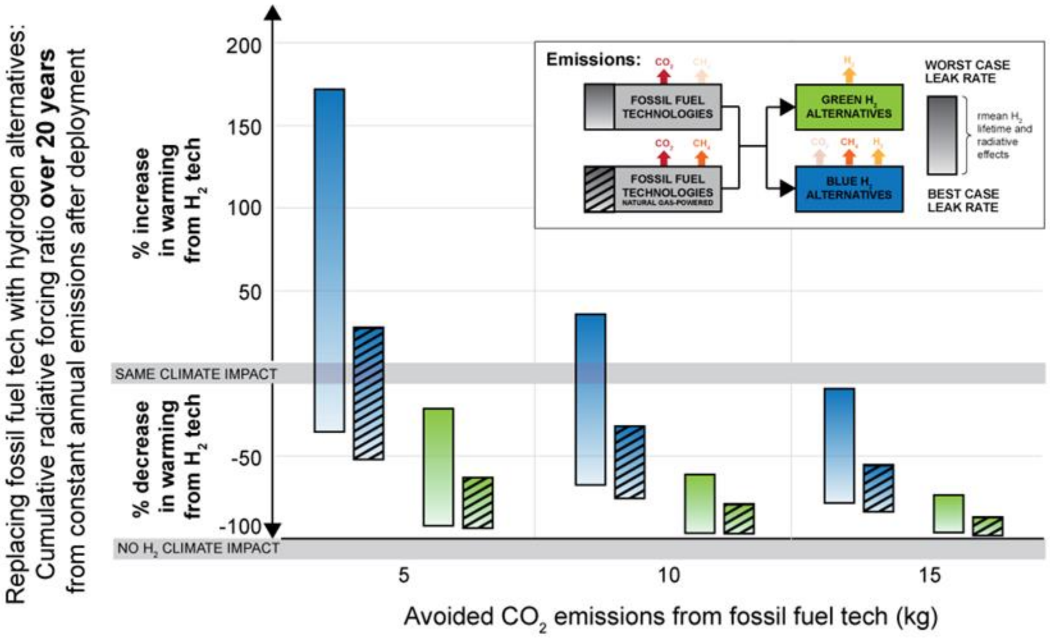

Figure 5: Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for different levels of avoided carbon dioxide and methane emissions. *Ratio of cumulative radiative forcing of a constant emissions rate from deploying 1 kg of H_2 continuously 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 (solid bars) and carbon dioxide and methane (lined bars). 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.*

Line 437: *"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 CO2 avoided, which will vary depending on the technology that is replaced. Therefore, to test the sensitivity of our results to the amount of CO2 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 CO2 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 CO2 are on the higher end, both worst-case blue and green hydrogen would yield climate benefits, reducing warming by 10 and 75%, respectively."*

Third, we have rewritten our methods section to be clearer, and provided all equations used (which includes AGWP equations for methane and CO2, as well as their decay functions; the new H2 AGWP equations which accounts for methane's lifetime; and input parameters used in all). See below for equations and inputs.

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

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

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

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

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

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

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

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

Variable	**Definition**	**Unit**	**Value**	**Source**
$\boldsymbol{H}$	Time horizon	Years	1 – 100	N/A
$\boldsymbol{AGWP_{CO_2}}$				
$\boldsymbol{A_{CO_2}}$	Radiative forcing scaling factor	W m^{-2} ppb^{-1}	1.33e-5	Forster et al. 2021
$\boldsymbol{a_{0-3}}$	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
$\boldsymbol{\tau_{1-3}}$	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
$\boldsymbol{AGWP_{CH_4}}$				
$\boldsymbol{A_{CH_4}}$	Radiative forcing scaling factor	W m^{-2} ppb^{-1}	3.88e-4	Forster et al. 2021
$\boldsymbol{\tau}$	Perturbation lifetime	Years	11.8	Forster et al. 2021
$\boldsymbol{f_1}$	Tropospheric ozone indirect effect scaling	unitless	0.37	Forster et al. 2021
$\boldsymbol{f_2}$	Stratospheric water vapor indirect effect scaling	unitless	0.106	Forster et al. 2021
$\boldsymbol{AGWP_{H_2}}$				

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).*

L318: ".. based on their decay functions and radiative efficiencies". Are these decay functions generally well-known for a gas such as H2 that has various indirect effects on climate?
No, and this was certainly a limitation of our original analysis – how to handle hydrogen's multiple indirect effects with different timescales. This had not been sufficiently researched in the literature. However, as stated previously, new research has been published that comprehensively considers this, and therefore we use the new H2-specific AGWP derivations in our study which account for varying timelines of effects.

L329: "Methane and carbon dioxide radiative properties and atmospheric lifetimes are taken from Forster et al. (2021), but we do not include climate-carbon feedbacks associated with methane to be consistent with what is included with hydrogen." In principle one could argue that this too should be compared to the results in the Paulot model to retain consistency.
We have changed our analysis to include climate-carbon feedbacks associated with methane.

L351: "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 CO2 (Forster et al., 2021). This suggests a climate efficacy of 0.96 °C (W m2) -1." Would it be more concise to compare to the ECS of the GFDL model, and not to the CMIP6 ensemble at large?
We're not sure, because Paulot et al. also used the CMIP6 average as opposed to the ECS that matched their model.

L376: "The benefit of the Technology Warming Potential method is that we can analyse climate impacts over multiple time periods of interest—in the near-, medium-, and long-term—insights that are not available with the use of the GWP-100 metric. This is important when short-lived climate pollutants are emitted as they are often reported and assessed based on the long-term impact of a pulse emission, which overlooks their true impacts during the time they are active in the atmosphere." As stated above; I am missing a thoroughly discussion of GWP and other possible metrics such as GWP* or cGTP which are more widely discussed in the literature. There is hardly any discussion about the uncertainties using their own metric, especially about how they compare the short lifetime of hydrogen and the long lifetime of CO2, which is a problem about this manuscript.

Again, we apologize for the misunderstandings about our methods. "Our" metric is just GWP with a constant emissions rate and as a function of time horizon. It has the same uncertainties as GWP, and we have now included all of the relevant equations and inputs. We hope that our new methods section and removal of most of the metrics discussion helps clarify our study and refocuses the work on the insights of the analysis and not the issues with metrics. We use GWP because of its accessibility, but improve it slightly. With our major revisions of the paper, we do not see the need to go into more detail on other possible metrics.