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Comment on "Climate consequences of hydrogen emissions" by Ocko and Hamburg (2022)

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Abstract

In this commentary, we provide additional context for Ocko and Hamburg (2022) related to the climate consequences of replacing fossil fuels with clean hydrogen alternatives. To develop a better understanding of the climate impact from atmospheric hydrogen additions, we first provide a step-by-step tutorial for the derivations of underlying differential equations that describe radiative forcing of hydrogen emissions, which differ slightly from equations relied on by previous studies. Ocko and Hamburg (2022) used a time-integrated metric on radiative forcing and considered a continuous emission scenario, while we present both the time-evolving radiative forcing and global mean temperature response results under a unit pulse and continuous emissions scenarios. Our analysis covers timescales of 500 years and results on short-term timescales (e.g., 20 years) are qualitatively consistent with previous studies. Some qualitative results are clear: radiative forcing from hydrogen emission is smaller compared to the same quantity of methane emission, both of which decay with time and show less long-term influence than carbon dioxide. On the time scale of a few decades, the radiative forcing from a continuous emission of hydrogen or methane is proportional to emission rates, whereas the radiative forcing from a continuous emission of carbon dioxide is closely related to cumulative emissions. After a cessation of clean hydrogen consumption, the earth cools rapidly, whereas after a cessation of carbon dioxide emissions, the earth continues to warm somewhat and remains warm for many centuries. These longer-term differences may be important to consider in a policy context. Hydrogen leakage has the potential to reduce near-term climate benefits of hydrogen use, but methane is likely to play a more substantial role. In our analysis, consideration of methane emission associated with fossil fuel combustion is a critical factor for determining the relative short-term climate benefits of clean hydrogen alternatives. In the main cases, consideration of methane leakage substantially increases the climate impacts of fossil fuels and could result in net climate benefits for blue hydrogen even in the near-term. Regardless, our results support the conclusion of Ocko and Hamburg (2022) that, if methane were a feedstock for hydrogen production, any possible near-term consequences will depend critically on the issue of methane leakage.

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1. Introduction

Hydrogen (H_2) may be an important component of a future low-carbon-emission global economy, especially in hard-to-decarbonize, energy-intensive sectors, and as long-term seasonal storage to help balance renewable electricity generation and demand (Gielen et al., 2021; Griffiths et al., 2021; Seck et al., 2022). Meanwhile, the potential climate benefits of large-scale deployment of clean hydrogen technologies associated with hydrogen and methane emissions through the value-chain remains a question of study (Derwent et al., 2020; Paulot et al., 2021; Warwick et al., 2022; Ocko and Hamburg, 2022). In a recent paper, Ocko and Hamburg (2022) examined the climate consequences of replacing fossil fuel technologies with clean hydrogen alternatives using published data. The paper accounted for a range of hydrogen and methane emission rates for two types of clean hydrogen production pathways, i.e., green hydrogen produced via renewables and water, and blue hydrogen produced via steam methane reforming with carbon capture, usage, and storage (CCUS). They calculated the time-integrated radiative forcing using equations derived recently for hydrogen based on sophisticated chemistry-climate modeling experiments (Warwick et al., 2022). Ocko and Hamburg (2022) found that the climate effect of hydrogen depends strongly on timescales and emission rates. High emission rates of hydrogen could diminish net climate benefits for clean hydrogen technologies across different timescales, and high emissions of methane might lead to net climate disbenefits for blue hydrogen in the near terms (e.g., 20-year timescale).

Here we provide context for understanding the results of Ocko and Hamburg (2022) in three different ways: (1) We present equations underlying the time evolution of hydrogen and its radiative and thermal consequences, and solve them analytically for a unit pulse and continuous hydrogen emissions scenarios. Our equations differ slightly from equations developed by Warwick et al. (2022), which are used in Ocko and Hamburg (2022). (2) We present radiative forcing in the time domain instead of the integrated metrics presented by Ocko and Hamburg (2022). The radiative forcing function can also be combined with a climate response function (Gasser et al., 2017) to calculate global mean surface temperature response across different timescales. (3) We discuss alternative scenarios that may be applied to understand the climate effects of different choices. In our analysis, we examine three emission scenarios, including a unit pulse emission, continuous emissions for a fraction of the time period under consideration, and continuous emissions for the entire time period under consideration. We focus on a wide

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range of timescales covering 500 years. To facilitate comparisons, we apply the parameter values used by Ocko and Hamburg (2022) in our calculations.

Ocko and Hamburg (2022) focused on the short-term climate impact and emphasized that there could be net warming effect in the first few decades after replacing fossil fuels with clean hydrogen alternatives under high leakage rate assumptions. Our results, using newly developed equations for impulse and continuous hydrogen perturbations, confirm their results under consistent assumptions. Meanwhile, we show the impact of various uncertainties and distinct features in long-term climate impacts between fossil fuel and clean hydrogen sources. We argue that both short-term (e.g., a few decades) and long-term (e.g., more than a hundred year) timescales are important as they represent different aspects of potential risks (e.g., wildfire events in the short-term and glacier melting in the long-term), and it is valuable to make them clear to facilitate the decision-making process. Our aim here is to complement Ocko and Hamburg (2022)'s analysis, which emphasizes the near term, with an analysis that places greater emphasis on long-term outcomes.

2. Methods and Equations

2.1. Indirect forcing from hydrogen

The system that describes the radiative forcing for hydrogen emissions, as modeled by Warwick et al. (2022) and Ocko and Hamburg (2022), is a representation of the following underlying differential equations.

The change of H_2 molar mass relative to an unperturbed background condition is represented by a source function $f_{H_2}(t)$ and a decay term $\frac{m_{H_2}}{\tau_{H_2}}$, where m_{H_2} is the molar mass of hydrogen and τ_{H_2} is the lifetime of H_2:

$$\frac{dm_{H_2}}{dt} = f_{H_2}(t) - \frac{m_{H_2}}{\tau_{H_2}} \quad (1)$$

The presence of additional hydrogen in the atmosphere changes the decay of atmospheric methane (CH_4), and also results in the production of ozone (O_3) and stratospheric water vapor (H_2O). Underlying equations for perturbations to atmospheric molar masses of CH_4, O_3, and stratospheric H_2O induced from additional atmospheric H_2 (denoted by superscribe) are:

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$$\frac{dm_{CH_4}^{H_2}}{dt} = a_{CH_4} m_{H_2} - \frac{m_{CH_4}^{H_2}}{\tau_{CH_4}} \quad (2a)$$

$$\frac{dm_{O_3}^{H_2}}{dt} = a_{O_3} m_{H_2} - \frac{m_{O_3}^{H_2}}{\tau_{O_3}} \quad (2b)$$

$$\frac{dm_{H_2O}^{H_2}}{dt} = a_{H_2O} m_{H_2} - \frac{m_{H_2O}^{H_2}}{\tau_{H_2O}} \quad (2c)$$

where $m_{CH_4}^{H_2}$, $m_{O_3}^{H_2}$, and $m_{H_2O}^{H_2}$ are molar masses of CH_4, O_3, and H_2O resulting from additional atmospheric H_2, a_{CH_4}, a_{O_3}, and a_{H_2O} are factors representing the impact of remaining hydrogen in the atmosphere on the atmospheric molar mass of different species, and τ_{CH_4}, τ_{O_3}, and τ_{H_2O} are lifetimes of these species.

For the special case of a unit pulse perturbation of hydrogen into an unperturbed background condition at time zero, these equations can be solved analytically. The solutions to equations (1) and (2) under the following conditions $m_{H_2}(0) = 1$, $f_{H_2}(t) = 0$, $m_{CH_4}^{H_2}(0) = 0$, $m_{O_3}^{H_2}(0) = 0$, and $m_{H_2O}^{H_2}(0) = 0$ are:

$$m_{H_2}(t) = e^{-\frac{t}{\tau_{H_2}}} \quad (3)$$

$$m_{CH_4}^{H_2}(t) = \frac{a_{CH_4}}{\left(\frac{1}{\tau_{H_2}}\right) - \left(\frac{1}{\tau_{CH_4}}\right)} \left(e^{-\frac{t}{\tau_{CH_4}}} - e^{-\frac{t}{\tau_{H_2}}} \right) \quad (4a)$$

$$m_{O_3}^{H_2}(t) = \frac{a_{O_3}}{\left(\frac{1}{\tau_{H_2}}\right) - \left(\frac{1}{\tau_{O_3}}\right)} \left(e^{-\frac{t}{\tau_{O_3}}} - e^{-\frac{t}{\tau_{H_2}}} \right) \quad (4b)$$

$$m_{H_2O}^{H_2}(t) = \frac{a_{H_2O}}{\left(\frac{1}{\tau_{H_2}}\right) - \left(\frac{1}{\tau_{H_2O}}\right)} \left(e^{-\frac{t}{\tau_{H_2O}}} - e^{-\frac{t}{\tau_{H_2}}} \right) \quad (4c)$$

and the corresponding instantaneous radiative forcing is the product of resulted molar mass and scaling factors A_{CH_4}, A_{O_3}, and A_{H_2O} that convert molar mass to $W\ m^{-2}$. Ocko and Hamburg

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(2022) considered adjusted radiative forcing, $A^*_{CH_4}$, from methane forcing using factors f_1 and f_2, which can be represented as:

$$A^*_{CH_4} = (1 + f_1 + f_2)A_{CH_4} \tag{5}$$

The indirect radiative forcing from a unit pulse emission of hydrogen, R_{H_2}, is thus the sum of radiative forcing from all three radiatively active perturbations:

$$R_{H_2}(t) = A^*_{CH_4} m^{H_2}_{CH_4}(t) + A_{O_3} m^{H_2}_{O_3}(t) + A_{H_2O} m^{H_2}_{H_2O}(t) \tag{6a}$$

Inserting equation (4) we have:

$$R_{H_2}(t) = \frac{A^*_{CH_4} a_{CH_4}}{\left(\frac{1}{\tau_{H_2}}\right) - \left(\frac{1}{\tau_{CH_4}}\right)}\left(e^{-\frac{t}{\tau_{CH_4}}} - e^{-\frac{t}{\tau_{H_2}}}\right)$$

$$+ \frac{A_{O_3} a_{O_3}}{\left(\frac{1}{\tau_{H_2}}\right) - \left(\frac{1}{\tau_{O_3}}\right)}\left(e^{-\frac{t}{\tau_{O_3}}} - e^{-\frac{t}{\tau_{H_2}}}\right) + \frac{A_{H_2O} a_{H_2O}}{\left(\frac{1}{\tau_{H_2}}\right) - \left(\frac{1}{\tau_{H_2O}}\right)}\left(e^{-\frac{t}{\tau_{H_2O}}} - e^{-\frac{t}{\tau_{H_2}}}\right) \tag{6b}$$

For a 1 kg unit pulse emission case, the time-integrated radiative forcing to a specified time horizon, H, is defined to be the Absolute Global Warming Potential (AGWP) (Myhre et al., 2014). Thus, AGWP can be represented as:

$$AGWP_{H_2}(H) = \int_0^H R_{H_2}(t)\, dt \tag{7a}$$

which can be rewritten as:

$$AGWP_{H_2}(H) = \frac{A^*_{CH_4} a_{CH_4} \tau_{H_2} \tau_{CH_4}\left(\tau_{CH_4}\left(1 - e^{-\frac{H}{\tau_{CH_4}}}\right) - \tau_{H_2}\left(1 - e^{-\frac{H}{\tau_{H_2}}}\right)\right)}{\tau_{CH_4} - \tau_{H_2}}$$

$$+ \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3}\left(\tau_{O_3}\left(1 - e^{-\frac{H}{\tau_{O_3}}}\right) - \tau_{H_2}\left(1 - e^{-\frac{H}{\tau_{H_2}}}\right)\right)}{\tau_{O_3} - \tau_{H_2}}$$

$$+ \frac{A_{H_2O} a_{H_2O} \tau_{H_2} \tau_{H_2O}\left(\tau_{H_2O}\left(1 - e^{-\frac{H}{\tau_{H_2O}}}\right) - \tau_{H_2}\left(1 - e^{-\frac{H}{\tau_{H_2}}}\right)\right)}{\tau_{H_2O} - \tau_{H_2}} \tag{7b}$$

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Equation (7) is the response to a unit pulse emission of hydrogen taking into consideration radiative forcing adjustments to methane as in Ocko and Hamburg (2022). Because we are considering a linear system, we can use this impulse response function to derive the radiative forcing from an arbitrary hydrogen emission function f_{H_2}:

$$\widehat{R_{H_2}}(t) = \int_0^t f_{H_2}(\tau)\, R_{H_2}(t-\tau)d\tau \tag{8}$$

Considering a continuous unit emission scenario where:

$$f_{H_2}(t) = 1 \tag{9}$$

which leads to radiative forcing under a continuous emission scenario:

$$\begin{aligned} R_{H_2,cont}(t) = & \frac{A^*_{CH_4} a_{CH_4} \tau_{H_2} \tau_{CH_4} \left(\tau_{H_2} \left(e^{-\frac{t}{\tau_{H_2}}} - 1 \right) - \tau_{CH_4} \left(e^{-\frac{t}{\tau_{CH_4}}} - 1 \right) \right)}{\tau_{CH_4} - \tau_{H_2}} \\ & + \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3} \left(\tau_{H_2} \left(e^{-\frac{t}{\tau_{H_2}}} - 1 \right) - \tau_{O_3} \left(e^{-\frac{t}{\tau_{O_3}}} - 1 \right) \right)}{\tau_{O_3} - \tau_{H_2}} \\ & + \frac{A_{H_2O} a_{H_2O} \tau_{H_2} \tau_{H_2O} \left(\tau_{H_2} \left(e^{-\frac{t}{\tau_{H_2}}} - 1 \right) - \tau_{H_2O} \left(e^{-\frac{t}{\tau_{H_2O}}} - 1 \right) \right)}{\tau_{H_2O} - \tau_{H_2}} \end{aligned} \tag{10}$$

In a linear system, the time-integrated radiative forcing from a unit pulse emission to some time horizon t_0 is mathematically equivalent to the instantaneous radiative forcing at time t_0 from a sustained unit emission:

$$AGWP_{H_2}(t_0) = R_{H_2,cont}(t_0) \tag{11}$$

Therefore, Ocko and Hamburg (2022) used a metric that is equal to the time integrated radiative forcing of sustained emission to time horizon H. Since AGWP has been defined as the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance (Myhre et al., 2014), here we define the time-integrated radiative forcing under a continuous emission scenario as CAGWP:

$$CAGWP_{H_2}(H) = \int_0^H R_{H_2,cont}(t)dt \tag{12a}$$

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$$= \int_0^H \int_0^t R_{H_2}(\tau)\, d\tau\, dt \tag{12b}$$

$$= \int_0^H AGWP_{H_2}(t) dt \tag{12c}$$

$$= \int_0^H (H - t) R_{H_2}(t) dt \tag{12d}$$

Comparing Equation (12) with Equation (7a), we can see that the CAGWP metric is equivalent to the AGWP metric, except that the radiative forcing at time 0 is weighted by H, and the radiative forcing at time H is weighted at 0, with a linear ramping of weights in-between by the number of years to the end of the time horizon.

Expanding Equation (12), we have:

$$CAGWP_{H_2}(H) = \frac{A^*_{CH_4} a_{CH_4} \tau_{H_2} \tau_{CH_4} \left(\tau^2_{H_2} \left(1 - e^{-\frac{H}{\tau_{H_2}}} \right) - \tau^2_{CH_4} \left(1 - e^{-\frac{H}{\tau_{CH_4}}} \right) + H\left(\tau_{CH_4} - \tau_{H_2}\right) \right)}{\tau_{CH_4} - \tau_{H_2}}$$

$$+ \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3} \left(\tau^2_{H_2} \left(1 - e^{-\frac{H}{\tau_{H_2}}} \right) - \tau^2_{O_3} \left(1 - e^{-\frac{H}{\tau_{O_3}}} \right) + H\left(\tau_{O_3} - \tau_{H_2}\right) \right)}{\tau_{O_3} - \tau_{H_2}} \tag{13}$$

$$+ \frac{A_{H_2O} a_{H_2O} \tau_{H_2} \tau_{H_2O} \left(\tau^2_{H_2} \left(1 - e^{-\frac{H}{\tau_{H_2}}} \right) - \tau^2_{H_2O} \left(1 - e^{-\frac{H}{\tau_{H_2O}}} \right) + H\left(\tau_{H_2O} - \tau_{H_2}\right) \right)}{\tau_{H_2O} - \tau_{H_2}}$$

Equations (10) and (13) consider continuous emissions through the whole period. Equations considering a continuous emission to time tp are shown in **Supplementary Information Text S1**. Reproductions of the three components in Warwick et al. (2022) and Ocko and Hamburg (2022) are shown in **Supplementary Text S2**. We believe these equations better reflect the underlying conceptual model, but numerical differences between our equations and equations presented by Warwick et al. (2022) are small and are unlikely to make a material difference.

2.2. Forcing from CO_2 and CH_4

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Here we show radiative forcing and time-integrated radiative forcing functions for carbon dioxide (CO_2) and methane emissions (CH_4). Radiative forcing for a unit pulse emission of CO_2 and CH_4 is represented as (Myhre et al., 2014):

$$R_{CO_2}(t) = A_{CO_2}\left(a_0 + \sum_{i=1}^{3} a_i e^{-\frac{t}{\tau_i}}\right) \quad (14)$$

$$R_{CH_4}(t) = (1 + f_1 + f_2)A_{CH_4} e^{-\frac{t}{\tau_{CH_4}}} \quad (15)$$

And AGWP for a unit pulse emission is:

$$AGWP_{CO_2}(H) = A_{CO_2}\left(a_0 H + \sum_{i=1}^{3} a_i \tau_i \left(1 - e^{-\frac{H}{\tau_i}}\right)\right) \quad (16)$$

$$AGWP_{CH_4}(H) = (1 + f_1 + f_2)A_{CH_4}\tau_{CH_4}(1 - e^{-\frac{H}{\tau_{CH_4}}}) \quad (17)$$

Radiative forcing for continuous emissions of CO_2 and CH_4 can be represented as:

$$R_{CO_2,cont}(t) = A_{CO_2}\left(a_0 t + \sum_{i=1}^{3} a_i \tau_i \left(1 - e^{-\frac{t}{\tau_i}}\right)\right) \quad (18)$$

$$R_{CH_4,cont}(t) = (1 + f_1 + f_2)A_{CH_4}\tau_{CH_4}(1 - e^{-\frac{t}{\tau_{CH_4}}}) \quad (19)$$

And corresponding CAGWP is:

$$CAGWP_{CO_2}(H) = A_{CO_2}\left(\frac{a_0 H^2}{2} + \sum_{i=1}^{3} a_i \tau_i \left(H + \tau_i \left(e^{-\frac{H}{\tau_i}} - 1\right)\right)\right) \quad (20)$$

$$CAGWP_{CH_4}(H) = (1 + f_1 + f_2)A_{CH_4}\tau_{CH_4}\left(H + \tau_{CH_4}\left(e^{-\frac{H}{\tau_{CH_4}}} - 1\right)\right) \quad (21)$$

2.3. The global mean temperature response

For a linear system, the absolute global temperature change potential (AGTP), defined as change of global mean surface temperature realized at a given time horizon from a pulse or continuous emission of any gas i, can be represented as a convolution function (Myhre et al., 2014; Gasser et al., 2017):

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$$AGTP_i(H) = \int_0^H R_i(t)T(H-t)dt \quad (22)$$

In equation (22), $R_i(t)$ is the radiative forcing for a unit pulse or continuous emission of gas i, and $T(t)$ indicates the temperature response to a unit forcing that can be represented as a sum of exponentials:

$$T(t) = \lambda \sum_{j=1}^{M} \frac{c_j}{d_j} e^{-\frac{t}{d_j}} \quad (23)$$

Where λ is a constant that corresponds to the equilibrium climate sensitivity, $\sum_{j=1}^{M} c_j = 1$, and d_j is the response time. Two exponential terms ($M = 2$) are normally used in previous studies, with the first term be associated with the response of the ocean mixed layer and the higher order be associated with the response of the deep ocean (Gasser et al., 2017). In our central cases, we focus on using the equation from Geoffroy et al. (2013):

$$T(t) = 0.885 * \left(\frac{0.587}{4.1} * e^{-\frac{t}{4.1}} + \frac{0.413}{249} * e^{-\frac{t}{249}}\right) \quad (24)$$

We compare results of equation (24) with results of the following: equation from Boucher and Reddy (2008):

$$T(t) = 1.06 * \left(\frac{0.595}{8.4} * e^{-\frac{t}{8.4}} + \frac{0.405}{409.5} * e^{-\frac{t}{409.5}}\right) \quad (25)$$

OSCAR v2.2 (average of ensemble):

$$T(t) = 0.852 * \left(\frac{0.572}{3.50} * e^{-\frac{t}{3.50}} + \frac{0.428}{166} * e^{-\frac{t}{166}}\right) \quad (26)$$

and equation from Caldeira and Myhrvold (2013) using CMIP5 ensemble results:

$$T(t) = 0.987 * \left(\frac{0.551}{3.62} * e^{-\frac{t}{3.62}} + \frac{0.449}{219} * e^{-\frac{t}{219}}\right) \quad (27)$$

2.4. Climate impact of hydrogen and fossil fuels

As in Ocko and Hamburg (2022), we focus on comparing the climate impact of replacing fossil fuel technologies with clean hydrogen alternatives. Climate impacts from hydrogen or fossil

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fuels are the summation of climate impacts of one or more components in a linear system. For green hydrogen, radiative forcing and temperature response from hydrogen emissions (L_{H_2}) are:

$$R_{green-hydrogen} = R_{H_2} * L_{H_2} \quad (28a)$$

$$AGTP_{green-hydrogen} = AGTP_{H_2} * L_{H_2} \quad (28b)$$

For blue hydrogen, both hydrogen and methane leakages (L_{H_2} and L_{CH_4}) are included, and radiative forcing and temperature response are represented as:

$$R_{blue-hydrogen} = R_{H_2} * L_{H_2} + R_{CH_4} * L_{CH_4} \quad (29a)$$

$$AGTP_{blue-hydrogen} = AGTP_{H_2} * L_{H_2} + AGTP_{CH_4} * L_{CH_4} \quad (29b)$$

For fossil fuel, we only consider the avoided CO_2 emissions (E_{CO_2}) in our central cases in line with Ocko and Hamburg (2022):

$$R_{fossil-fuel} = R_{CO_2} * E_{CO_2} \quad (30a)$$

$$AGTP_{fossil-fuel} = AGTP_{CO_2} * E_{CO_2} \quad (30b)$$

and we compared results with those that included both CO_2 and methane emissions:

$$R_{fossil-fuel} = R_{CO_2} * E_{CO_2} + R_{CH_4} * L_{CH_4} \quad (31a)$$

$$AGTP_{fossil-fuel} = AGTP_{CO_2} * E_{CO_2} + AGTP_{CH_4} * L_{CH_4} \quad (31b)$$

We quantify ratios between clean hydrogen and fossil fuels for different time horizons. Results for 20-, 100-, 500-year horizons are summarized in Table S1 to S4.

Results

Climate impact of individual gases. Before comparing the climate impact of hydrogen and fossil fuels, we first examine the climate impact from emissions of carbon dioxide (CO_2), methane (CH_4), and hydrogen (H_2), respectively. We focus on the time-evolving changes in radiative forcing and global mean temperature response, and we consider three emission scenarios: a 1 kg pulse emission, a 0.01 kg yr^{-1} continuous emission lasting for 100 years, and a 0.01 kg yr^{-1} continuous emission lasting for 500 years. To facilitate comparisons with Ocko and Hamburg (2022), our calculations of radiative forcing use the same parameter values from their paper.

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Figure 1 shows the climate impact of individual species under various emission scenarios. Results showing ratios of methane and hydrogen to CO_2 are plotted in Figure S1. For the 1 kg pulse emission scenario, all species produce the largest climate impacts (i.e., radiative forcing and temperature rise) within the first few years and decay over time. Methane and hydrogen show orders of magnitude larger impacts at the very beginning of emission compared to CO_2. Note that the global warming potential is typically defined for a 1 kg pulse emission of gas (Myhre et al., 2014), which will lead to different immediate changes in their atmospheric concentration when viewed on a molar basis. Figure S2 shows that when considering the same 1 ppb increase of these gases, methane will still generate a much larger warming potential, whereas hydrogen and CO_2 show the same order of magnitude impacts on radiative forcing and temperature response in the first decade.

The climate impacts of methane and hydrogen decay substantially faster as their atmospheric concentrations decrease (lifetime is 11.8 years for methane and 1.9 years for hydrogen). For example, the radiative forcing of methane and hydrogen for 1 kg pulse emission scenarios is smaller than that of CO_2 after about 65 and 50 years, and approaches zero after 100 years. Note that we do not consider conversions of the decayed CH_4 to CO_2, which will add more long-term climate impacts for CH_4 emissions as shown in Fig.S3. This conversion should not be considered in the case of CH_4 perturbations brought about by H_2 emissions, because there is no net addition of carbon to the atmosphere in this case. In contrast, the radiative forcing of CO_2 is still 28% of its maximum value at the 500-year time horizon. Temperature response behaves similarly to radiative forcing, but at a slower rate due to the inertia of the climate system, such as the deep ocean circulation. Impacts of considering different hydrogen lifetimes (i.e., 1.4 and 2.5 years) are shown in Figure S4.

For 0.01 kg yr^{-1} continuous emission cases, there is an accumulation of CO_2 concentration in the atmosphere, leading to monotonic increases in radiative forcing and temperature rise. If emissions stop abruptly after 100 years, the climate impacts of CO_2 slowly converge with those under the 1 kg emission case and stay roughly stable, because effects of atmospheric concentration decrease are approximately offset by effects of ocean warming. Due to the shorter lifetime of methane and hydrogen, their atmospheric concentrations reach equilibrium under continuous emission scenarios with magnitudes depending on the emission rates, and radiative forcing reaches a stable level after a few decades. Global mean temperature continues to increase

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slowly due to the thermal inertia of the climate system. If emissions of methane and hydrogen stop abruptly after 100 years, their atmospheric concentrations would decrease rapidly, and reach zero within decades. Temperatures would also begin to decrease rapidly, but over a longer time scale, due to the thermal inertia in the climate system. The longer atmospheric lifetime of CO_2 results in more prominent longer-term climate impacts under both pulse and continuous emission scenarios.

Climate impact of hydrogen and fossil fuels. In this section, we analyze the climate impact per 1 kg consumptions of green and blue hydrogen, and the corresponding climate impacts from the avoided CO_2 emissions. We consider consistent assumptions as in Ocko and Hamburg (2022). For example, the kg amount of methane required to produce blue hydrogen is 3 times the kg amount of hydrogen used; 1 kg consumption of hydrogen would avoid 11 kg of CO_2 emissions (additional cases, i.e., 5 kg or 15 kg of avoided CO_2 emissions, are examined as well); and burning 1 kg of natural gas or methane would emit 2.75 kg of CO_2. Also, we take the same emission rates for methane and hydrogen to generate two central cases: a low leakage case with a 1% hydrogen and a 1% methane leakage rate, and a high leakage case with a 10% hydrogen and a 3% methane leakage rate (see detailed discussion regarding these assumptions in their paper). We analyze three emission scenarios: a 1 kg pulse consumption, a 0.01 kg yr^{-1} continuous consumption lasting for 100 years, and a 0.01 kg yr^{-1} continuous consumption lasting for 500 years.

Under the low leakage scenario considered (i.e., 1% hydrogen and 1% methane leakage rate), both green and blue hydrogen produce smaller radiative forcing and global mean temperature increases compared to the avoided CO_2 emissions (Fig. 2 and 3). This indicates net climate benefits of replacing fossil fuels with clean hydrogen alternatives. Compared to green hydrogen produced via renewables and water, leakages of methane from blue hydrogen adds substantial additional warming within the first few decades. For the 1 kg pulse consumption scenario, the climate impact of both green and blue hydrogen sources decays rapidly to zero within the first few decades (conversion of decayed CH_4 to CO_2 not included), whereas the climate impact of avoided CO_2 emissions becomes roughly stable with time. Continuous consumptions of hydrogen would lead to stable radiative forcing and temperature change at longer timescales with magnitudes depending on emission rates, due mainly to the short lifetimes of methane and hydrogen, and such climate impacts will adjust quickly if future emission rates change.

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Meanwhile, continuous consumption of fossil fuels leads to accumulation of CO_2 concentration and increasing climate responses. Even if CO_2 emission is ceased, its impacts would last for hundreds of years and keep affecting the climate.

Under the high leakage scenario, the additional leakage of hydrogen (i.e., 10% vs. 1% hydrogen leakage rate) reduce the short-term climate benefits of green hydrogen, and the additional leakage of methane (i.e., 3% vs. 1% methane leakage rate) further lead to net disbenefits for blue hydrogen in the first few years, when compared to avoided CO_2 emissions. In both the lowest and highest leakage cases, methane adds more warming than does hydrogen (Fig. S5). Because of the shorter lifetimes of hydrogen and methane, net climate benefits for blue hydrogen are observed after ~ 12 and 20 years under different emission scenarios for the high leakage case. The climate impacts of the avoided CO_2 emissions become orders of magnitude larger than those of hydrogen as time evolves.

In our central cases, we do not include methane leakages when calculating climate impacts for the avoided CO_2 emissions. But methane leakages are added for blue hydrogen. Under all emission scenarios, considering the same methane leakage rates (Fig. S6 and S7) substantially increases the warming potentials from the avoided CO_2 emissions, especially for the short-term responses, leading to net benefits of replacing fossil fuels with both clean hydrogen alternatives. Consideration of the decayed methane to CO_2 further increases the long-term climate impacts for both blue hydrogen and the avoided CO_2 emissions cases that contain methane leakage (Fig. S6 and S7). As examined in Ocko and Hamburg (2022), considering different amounts of avoided CO_2 emission for per kg hydrogen consumption (e.g., 5 or 15 kg CO_2 avoided per kg hydrogen consumption) can affect both short-term and long-term climate impacts (Fig. S8). In contrast, considering different hydrogen lifetimes or climate response functions has only minor impacts (Fig. S6, S7, and S9). Here we do not cover all possible uncertainties, but give some first-level impressions of how different parameters can affect results presented in this analysis.

Finally, Ocko and Hamburg (2022) quantified the net climate benefits of consuming hydrogen compared to the avoided CO_2 emissions by comparing the time-integrated radiative forcing from continuous emissions of both gases. This metric over-predicts the amount of warming that would be produced by methane and hydrogen leakage relative to the warming that would have been caused by the avoided CO_2 emissions over time (Fig. S10). This result is similar to that of (Allen et al., 2016) showing that, for pulse emissions and any time horizon longer than a decade, the

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global mean relative temperature response metric (i.e., GTP) would be lower than values of the time-integrated relative radiative forcing (i.e., GWP).

Discussion

While we confirm the results presented in Ocko and Hamburg (2022), it is clear that over longer time horizons (e.g., 100 years) substituting blue or green hydrogen for fossil fuels will result in much less climate change.

Many important uncertainties persist. For example, we considered fast adjustments to radiative forcing for methane, as considered by Ocko and Hamburg (2022). Carbon dioxide, ozone and other radiatively active gases may also have substantial fast radiative forcing adjustments (Smith et al., 2018). The radiative forcing calculations presented here are linear approximations, with radiative forcing increasing linearly with concentration, when in fact absorption bands become increasingly saturated at higher concentrations, and this results in less sensitivity at higher concentrations. These radiative forcing calculations assume an unchanging background atmospheric composition, whereas it is likely that the radiative and temperature effects of an emission will depend on the background state of the climate system (Duan et al., 2019; Robrecht et al., 2019). For instance, the indirect radiative forcing of hydrogen through its effect on methane's lifetime might depend on the background methane concentration. The effectiveness of radiative forcing at effecting temperature change can vary substantially from gas to gas (Hansen et al., 1997; Modak et al., 2018). Despite the large number of uncertainties, none of these considerations are expected to be of sufficient magnitudes to qualitatively alter key conclusions presented here.

Ocko and Hamburg (2022) proposes a metric, which we call CAGWP, that involves the integral of radiative forcing for a sustained emission, which differs from the standard GWP metric based on a unit emission of 1 kg of gas. While the Global Warming Potential metric (GWP) has been widely used to compare the climate impact of different greenhouse gases, it may not be the best predictor of climate impacts. For example, Allen et al. (2016) have argued that the GWP metric over-emphasizes the long-term climate effect of short-lived gases such as methane. The CAGWP metric proposed by Ocko and Hamburg (2022) emphasizes short-lived gases to an even greater extent than the customary GWP metrics. We have shown that the CAGWP metric is equivalent to a double-integral of a pulse emission, equivalent to the integral of the AGWP of a pulse

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emission, and equivalent to a front-loaded weighted integral of a pulse emission. The 100-year CAGWP metric weights the first year after an emission 99 times, whereas it weights the 99th year after an emission only once. Metrics that emphasize near-term outcomes may be useful for addressing near-term concerns, and metrics that emphasize longer-term outcomes may be more useful for addressing longer-term concerns.

There are different motivations for reducing warming at various timescales. One motivation is to avoid near-term climate damage that might come, for example, from increasing storm or drought intensity. Another motivation is to avoid long-term climate damage that might come, for example, from the melting of the large ice sheets (Pattyn et al., 2018) or making parts of the tropics effectively uninhabitable (Dunne et al., 2013; Sun et al., 2019). Decision-making has to carefully balance addressing near-term and long-term risks, and look for opportunities to address both kinds of risk simultaneously.

Different climate forcing agents differ in their degree of reversibility. To a close approximation, on the time scale of decades or more, temperature change from methane or hydrogen emissions are proportional to rates of emission whereas temperature change from carbon dioxide is proportional to cumulative emission. This important distinction is not captured by any of the metrics discussed here. Our analysis compares the climate impact of different hydrogen technologies, while considering how different market sizes would affect the overall impact of hydrogen is beyond the scope of this analysis. Blue hydrogen, despite its larger climate impacts, is currently the dominate way of producing hydrogen. Meanwhile, the additional climate benefits from green hydrogen have been recognized that will likely play a greater role in some regions (e.g., EUR-Lex, 2022) in the future. It is clear that electrolytic hydrogen made with carbon-emission-free electricity would produce less climate change than hydrogen made using methane as a feedstock; people use steam-methane reforming of methane to produce hydrogen typically because it costs less than electrolysis.

Conclusion

Our analysis confirms the results of Ocko and Hamburg (2022) under consistent assumptions but complements their presentation with additional uncertainty analysis and a longer-term perspective. We have developed a step-by-step tutorial for the derivations of underlying differential equations that describe radiative forcing of hydrogen emissions, which differ slightly

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from equations relied on by previous studies. Our results have shown that on the time scale of a few decades, both the radiative forcing and global mean temperature response from hydrogen and methane are proportional to the underlying emission rates, whereas climate impacts from carbon dioxide are closely related to cumulative emissions. High emission rates of methane contribute primarily to the high warming potential of methane-derived hydrogen production, with high hydrogen leakage rates playing a secondary role. When following Ocko and Hamburg (2022)'s calculations, relative to fossil carbon fuels, blue hydrogen with a methane leakage rate of 3% and a hydrogen leakage rate of 10% could produce more warming in the first 20 years after the release. However, even with these high leakage rates, warming from blue hydrogen 100 years later would be only a small portion of the warming from the fossil fuels it replaced. After a cessation of methane or hydrogen emissions their climate impacts decay rapidly. Whereas after a cessation of carbon dioxide emissions the climate impacts remain relatively stable for many centuries due to its long lifetime in the atmosphere.

Our results also indicate that, when assessing relative climate impact of replacing fossil fuel technologies with clean hydrogen alternatives, the decision whether or not to consider methane leakage associated with burning natural gas can have a substantial effect on results. Under Ocko and Hamburg (2022)'s central assumptions, each kg consumption of the blue hydrogen would need less amount of methane for hydrogen production than that for combustion as fossil fuel sources. As a result, including the methane leakage associated with fossil fuel combustion would substantially increase its short-term climate impact and may suggest net climate benefit for blue hydrogen across all time scales. Other factors, including the hydrogen lifetime and different climate response functions, are relatively less important.

Ocko and Hamburg (2022) proposes that the climate impact of blue and green hydrogen be evaluated with the use of a metric that is equivalent to a form of the GWP metric based on continuous emissions – a metric that strongly weights near-term radiative forcing relative to long-term radiative forcing from individual emissions. However, Allen et al. (2016) have shown that the customary GWP metric over-emphasize the climate effect of short-lived gases such as methane; the metric proposed by Ocko and Hamburg (2022) emphasizes the role of short-lived gases to an even greater extent.

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We emphasize that to reduce the near-term warming impact of the use of "blue" methane-derived hydrogen, it is important to address the issue of methane leakage. To attain near-term climate benefits from "blue" hydrogen that dominates current market depends critically on achieving low methane leakage rates. "Green" hydrogen produced by electrolysis using carbon-emission-free electricity has a small climate impact relative to the impact of the fossil fuels that hydrogen would replace, while very high hydrogen leakage rates could pose some climate concern and undercut accomplishing net zero emission goals. Safety considerations may motivate reduction of hydrogen leakage (Nugroho et al., 2022), In all cases considered, relative to fossil fuel combustion and associated emissions, both "blue" and "green" hydrogen show large long-term climate benefits even with high leakage rates.

Code availability

Scripts used to derive equations presented in this analysis are written in Wolfram Mathematica and are available online at https://doi.org/10.5281/zenodo.7346379. Scripts used to calculate numbers and plot figures in this analysis are written in Python and are available online at https://doi.org/10.5281/zenodo.7346379.

Author contribution

Lei Duan and Ken Caldeira designed the simulations, developed the equations, and did the calculations. Lei Duan prepared the initial manuscript and both of them reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Atmospheric Chemistry and Physics Discussions

Reference

Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., and Forster, P. M.: New use of global warming potentials to compare cumulative and short-lived climate pollutants, Nat. Clim. Chang., 6, 773–776, 2016.

EUR-Lex: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301, last access: 23 November 2022.

Boucher, O. and Reddy, M. S.: Climate trade-off between black carbon and carbon dioxide emissions, Energy Policy, 36, 193–200, 2008.

Caldeira, K. and Myhrvold, N. P.: Projections of the pace of warming following an abrupt increase in atmospheric carbon dioxide concentration, Environ. Res. Lett., 2013.

Derwent, R. G., Stevenson, D. S., Utembe, S. R., Jenkin, M. E., Khan, A. H., and Shallcross, D. E.: Global modelling studies of hydrogen and its isotopomers using STOCHEM-CRI: Likely radiative forcing consequences of a future hydrogen economy, Int. J. Hydrogen Energy, 45, 9211–9221, 2020.

Duan, L., Cao, L., and Caldeira, K.: Estimating contributions of sea ice and land snow to climate feedback, J. Geophys. Res., 124, 199–208, 2019.

Dunne, J. P., Stouffer, R. J., and John, J. G.: Reductions in labour capacity from heat stress under climate warming, Nat. Clim. Chang., 3, 563–566, 2013.

Gasser, T., Peters, G. P., Fuglestvedt, J. S., Collins, W. J., Shindell, D. T., and Ciais, P.: Accounting for the climate–carbon feedback in emission metrics, Earth Syst. Dyn., 8, 235–253, 2017.

Geoffroy, O., Saint-Martin, D., Olivié, D. J. L., Voldoire, A., Bellon, G., and Tytéca, S.: Transient Climate Response in a Two-Layer Energy-Balance Model. Part I: Analytical Solution and Parameter Calibration Using CMIP5 AOGCM Experiments, J. Clim., 26, 1841–1857, 2013.

Gielen, D., Gorini, R., Leme, R., Prakash, G., Wagner, N., Janeiro, L., Collins, S., Kadir, M., Asmelash, E., Ferroukhi, R., and Others: World energy transitions outlook: 1.5° C pathway, 2021.

Griffiths, S., Sovacool, B. K., Kim, J., Bazilian, M., and Uratani, J. M.: Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options, Energy Res. Soc. Sci., 80, 102208, 2021.

Hansen, J., Sato, M., and Ruedy, R.: Radiative forcing and climate response, J. Geophys. Res., 102, 6831–6864, 1997.

Modak, A., Bala, G., Caldeira, K., and Cao, L.: Does shortwave absorption by methane influence its effectiveness?, Clim. Dyn., 51, 3653–3672, 2018.

https://doi.org/10.5194/acp-2022-810
Preprint. Discussion started: 19 December 2022

Atmospheric Chemistry and Physics Discussions

Myhre, G., Shindell, D., and Pongratz, J.: Anthropogenic and Natural Radiative Forcing, in: Climate change 2013 : the physical science basis; Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T., Ludwig-Maximilians-Universität München, Cambridge, 659–740, 2014.

Nugroho, F. A. A., Bai, P., Darmadi, I., Castellanos, G. W., Fritzsche, J., Langhammer, C., Rivas, J. G., and Baldi, A.: Inverse Designed Plasmonic Metasurface with ppb Optical Hydrogen Detection, ChemRxiv, https://doi.org/10.26434/chemrxiv-2022-9vhsm, 2022.

Ocko and Hamburg: Climate consequences of hydrogen emissions, Atmos. Chem. Phys. Discuss., 2022.

Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N. R., Kuipers Munneke, P., Lenaerts, J. T. M., Nowicki, S., Payne, A. J., Robinson, A., Seroussi, H., Trusel, L. D., and van den Broeke, M.: The Greenland and Antarctic ice sheets under 1.5 °C global warming, Nat. Clim. Chang., 8, 1053–1061, 2018.

Paulot, F., Paynter, D., Naik, V., Malyshev, S., Menzel, R., and Horowitz, L. W.: Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing, Int. J. Hydrogen Energy, 46, 13446–13460, 2021.

Robrecht, S., Vogel, B., Grooß, J.-U., Rosenlof, K., Thornberry, T., Rollins, A., Krämer, M., Christensen, L., and Müller, R.: Mechanism of ozone loss under enhanced water vapour conditions in the mid-latitude lower stratosphere in summer, Atmos. Chem. Phys., 19, 5805–5833, 2019.

Seck, G. S., Hache, E., Sabathier, J., Guedes, F., Reigstad, G. A., Straus, J., Wolfgang, O., Ouassou, J. A., Askeland, M., Hjorth, I., Skjelbred, H. I., Andersson, L. E., Douguet, S., Villavicencio, M., Trüby, J., Brauer, J., and Cabot, C.: Hydrogen and the decarbonization of the energy system in europe in 2050: A detailed model-based analysis, Renew. Sustain. Energy Rev., 167, 112779, 2022.

Smith, C. J., Kramer, R. J., Myhre, G., Forster, P. M., Soden, B. J., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Hodnebrog, Ø., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Mülmenstädt, J., Olivié, D., Richardson, T., Samset, B. H., Shindell, D., Stier, P., Takemura, T., Voulgarakis, A., and Watson-Parris, D.: Understanding Rapid Adjustments to Diverse Forcing Agents, Geophys. Res. Lett., 45, 12023–12031, 2018.

Sun, Q., Miao, C., Hanel, M., Borthwick, A. G. L., Duan, Q., Ji, D., and Li, H.: Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming, Environ. Int., 128, 125–136, 2019.

Warwick, Griffiths, Keeble, Archibald, and Pyle: Atmospheric implications of increased Hydrogen use, AvaliableAt: https://assets, 2022.

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506 **Figure 1.** Climate impact from emissions of different species. Radiative forcing (**a-c**) and global
507 mean temperature response (**d-f**) caused by emissions of methane (CH_4), hydrogen (H_2), and
508 carbon dioxide (CO_2) under different scenarios. Three emission cases are used: a 1 kg pulse
509 emission, a 0.01 kg yr^{-1} continuous emission lasting for 100 years, and a 0.01 kg yr^{-1} continuous
510 emission lasting for 500 years. Note that CH_4 and H_2 share the same y-axis scale, which is 60
511 times the y-axis of CO_2. Radiative forcing from a continuous emission of hydrogen or methane is
512 proportional to emission rates, and decays rapidly once ceased, whereas radiative forcing from
513 carbon dioxide is closely related to cumulative emissions and will last for hundreds of years.
514 Figures showing only the 100-year results are plotted in Figure S12.

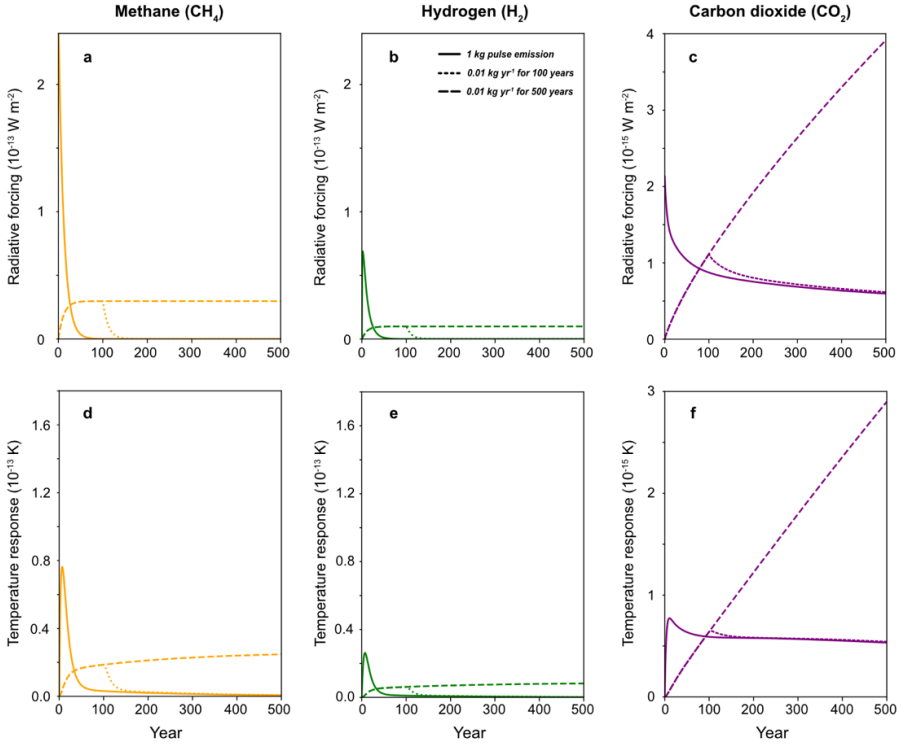

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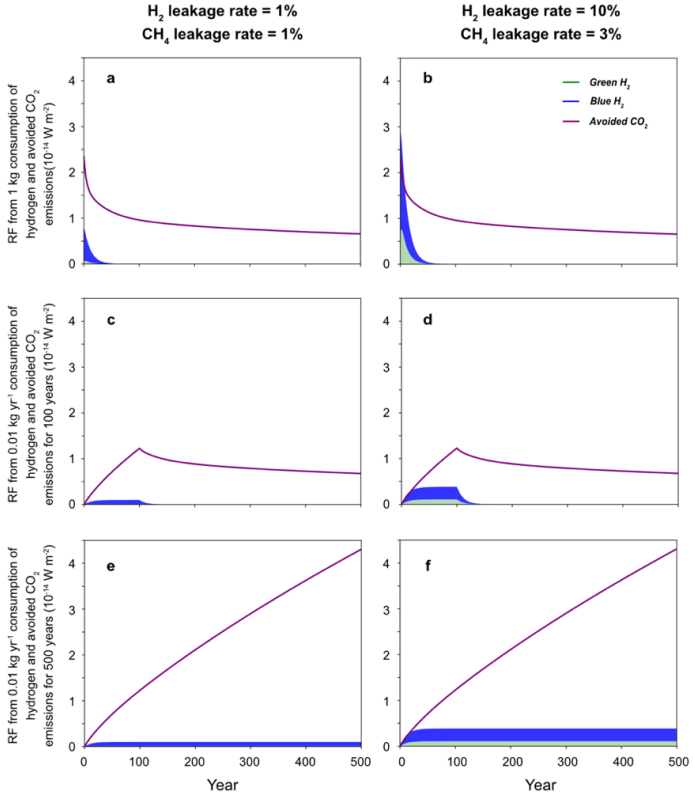
Figure 2. Radiative forcing from consumption of hydrogen and avoided CO_2 emissions. Radiative forcing for consumption of green hydrogen, blue hydrogen, and from the corresponding avoided CO_2 emissions under different scenarios. Three cases are considered: a 1 kg consumption of hydrogen (a and b), a 0.01 kg yr^{-1} continuous consumption of hydrogen lasting for 100 years (c and d), and a 0.01 kg yr^{-1} continuous consumption of hydrogen lasting for 500 years (e and f). The left column shows cases under the low leakage rate assumption with 1% hydrogen and 1% methane leakage, and the right column shows cases under the high leakage rate assumption with 10% hydrogen and 3% methane leakage. Methane leakage contributes primarily to the warming potential of blue hydrogen consumption, while hydrogen leakage plays a secondary role. For the longer-term, radiative forcing from carbon dioxide is substantially larger than that from clean hydrogen alternatives. Figures showing only the 100-year results are plotted in Figure S13.



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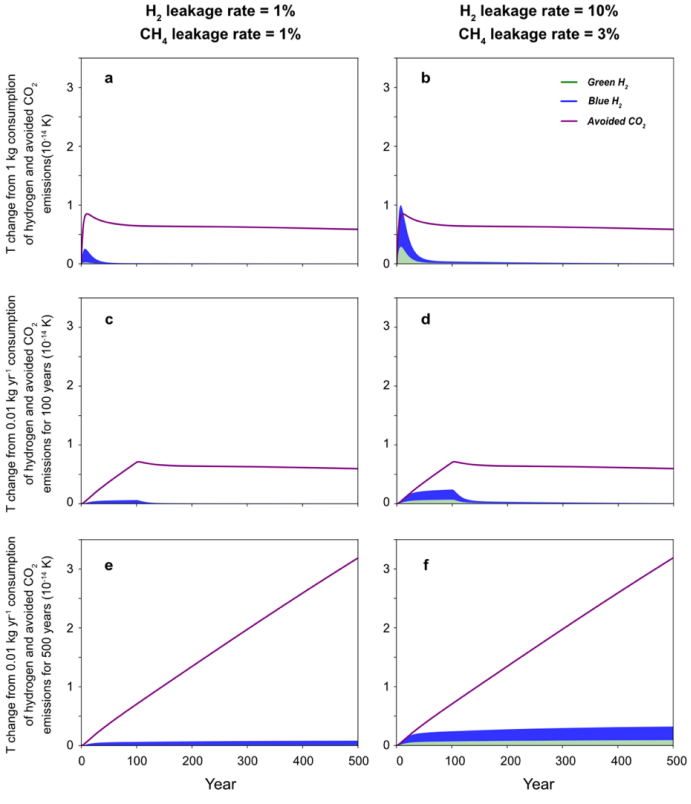
530 **Figure 3.** Same as Figure 2 but for global mean temperature response. Figures showing only the
531 100-year results are plotted in Figure S14.



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