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. We first provide a tutorial for the derivations of underlying differential equations that describe the radiative forcing of hydrogen emissions, which differ slightly from equations relied on by previous studies. Ocko and Hamburg (2022) defined a metric based on time-integrated radiative forcing from continuous emissions. To complement their analysis, we further present results for temperature and radiative forcing over the next centuries for unit pulse and continuous emissions scenarios. Our results are qualitatively consistent with previous studies, including Ocko and Hamburg (2022). Our results clearly show that for the same quantity of emissions, hydrogen shows a consistently smaller climate impact than methane. As with other short-lived species, the radiative forcing from a continuous emission of hydrogen 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. 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 primarily on methane leakage, and secondarily on hydrogen leakage.

1. Introduction

In a recent paper, Ocko and Hamburg (2022) examined the climate consequences of replacing fossil fuel technologies with clean hydrogen alternatives. 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 chemistry-climate modeling experiments (Warwick et al., 2022). Ocko and Hamburg (2022) found that high emission rates of hydrogen could diminish net climate benefits of clean hydrogen technologies, and high emissions rates of methane might lead to net climate disbenefits for blue hydrogen in the near term (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; (2) We present global mean temperature and radiative forcing in the time domain; (3) We examine three emission scenarios, including a unit pulse emission, a limited-duration (square-wave) emission, and continuous emissions. Our aim here is to complement Ocko and Hamburg (2022), which emphasizes the near term, with an analysis that places greater emphasis on long-term outcomes using newly developed equations.

2. Methods and Equations

We estimate the global mean temperature change from emissions of CO_2, CH_4, or H_2 using a linearized Green's function approach, and apply these equations to simple idealized cases. We derive and apply the equations underlying the estimate of radiative forcing from hydrogen emissions as presented by Warwick et al. (2022), relying heavily on parameter values from Ocko and Hamburg (2022), Table S1. Equations describing the radiative forcing of CO_2 and CH_4 is based on Myhre et al. (2013). The calculation of the global mean temperature response is based on Gasser et al. (2017).

2.1. Indirect forcing from hydrogen

The system that describes the radiative forcing from hydrogen emissions modeled by Warwick et al. (2022) and later used by 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, as a function of the time horizon *t* in units of year, 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 perturbation 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:

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

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

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

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 perturbation lifetime 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 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 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 $W\ m^{-2}$. The chemically-adjusted radiative forcing, $A^*_{CH_4}$, from methane forcing uses factors f_1 and f_2 (Myhre et al., 2013) to represent the effect on ozone and stratospheric water vapor:

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

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:

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

Inserting equation (4) we have:

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

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

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., 2013). Thus, AGWP can be represented as:

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

which can be rewritten as:

$$AGWP_{H_2}(H) = \frac{A^*_{CH_4} a_{CH_4} \tau_{H_2} \tau_{CH_4} \left(\tau_{CH_4} \left(1 - e^{-\frac{H}{\tau_{CH_4}}} \right) - \tau_{H_2} \left(1 - e^{-\frac{H}{\tau_{H_2}}} \right) \right)}{\tau_{CH_4} - \tau_{H_2}} + \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3} \left(\tau_{O_3} \left(1 - e^{-\frac{H}{\tau_{O_3}}} \right) - \tau_{H_2} \left(1 - e^{-\frac{H}{\tau_{H_2}}} \right) \right)}{\tau_{O_3} - \tau_{H_2}} + \frac{A_{H_2O} a_{H_2O} \tau_{H_2} \tau_{H_2O} \left(\tau_{H_2O} \left(1 - e^{-\frac{H}{\tau_{H_2O}}} \right) - \tau_{H_2} \left(1 - e^{-\frac{H}{\tau_{H_2}}} \right) \right)}{\tau_{H_2O} - \tau_{H_2}} \quad (7b)$$

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}:

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

Considering a continuous unit emission scenario where:

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

which leads to radiative forcing under a continuous emission scenario:

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

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 radiative forcing at time t_0 from a sustained unit emission:

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

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., 2013), here we define the time-integrated radiative forcing under a continuous emission scenario as CAGWP:

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

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

$$= \int_0^H \int_t^H R_{H_2}(\tau)\; dt\, d\tau \quad (12c)$$

$$= \int_0^H \left(\int_t^H dt \right) R_{H_2}(\tau) d\tau \quad (12d)$$

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

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. Equation (12) illustrates that time-integrated metrics under sustained emissions put heavy weights on the short-term effect.

Expanding Equation (12), we have:

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

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

$$+\frac{A_{H_2O}a_{H_2O}\tau_{H_2}\tau_{H_2O}\left(\tau_{H_2}^2\left(1-e^{-\frac{H}{\tau_{H_2}}}\right)-\tau_{H_2O}^2\left(1-e^{-\frac{H}{\tau_{H_2O}}}\right)+H\left(\tau_{H_2O}-\tau_{H_2}\right)\right)}{\tau_{H_2O}-\tau_{H_2}} \quad (13)$$

Equations (10) and (13) consider continuous emissions through the whole period. Equations considering a continuous emission to time tp are shown in the **Supplementary Information Text S1**. Reproductions of the three components in Warwick et al. (2022) and Ocko and Hamburg (2022) are shown in **Text S2**. When used to estimate radiative forcing for identical cases, 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

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., 2013):

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

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

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., 2013; Gasser et al., 2017):

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

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):

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

Uncertainty in the temperature response function is shown in **Text S3**.

2.4. Simulations and assumptions

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

fuels are the summation of climate impacts of one or more components in a linear system (**Text S4**).

In this commentary, we analyze the climate impact per 1 kg consumptions of green and blue hydrogen, and corresponding 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 underlying these assumptions in their paper).

We focus our discussions on 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. Results for 20-, 100-, 500-year horizons are summarized in Table S2 to S5.

Results

Climate impact of individual gas. We first examine the time-evolving climate impact from emissions of carbon dioxide (CO_2), methane (CH_4), and hydrogen (H_2), respectively. Similarly, 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.

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 within the first few years and decay over time. Soon after emission, per kg emitted, methane and hydrogen show much larger impacts compared to CO_2. The global warming potential is typically defined for a 1 kg pulse emission of gas (Myhre et al., 2013), 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 still generates 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 impact of methane and hydrogen decays substantially faster than CO_2 along with their concentrations (perturbation lifetime used is 11.8 years for methane and 1.9 years for hydrogen). For example, the radiative forcing of methane and hydrogen for the 1 kg pulse emission scenario is smaller than that of CO_2 after ~ 65 and 50 years, and approaches zero after 100 years. We do not consider conversions of the decayed CH_4 to CO_2, which will add more long-term impacts for CH_4 emissions (Forster et al., 2021) 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. Impacts of considering different hydrogen perturbation 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 perturbation 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 slowly due to the thermal inertia of the climate system. If emissions stop abruptly after 100 years, their concentrations would decrease rapidly, and reach zero within decades. The longer perturbation 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. We now consider climate impact from hydrogen consumptions. Under the low leakage scenario (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), indicating net climate benefits of replacing fossil fuels with clean hydrogen alternatives. Compared to green hydrogen, leakages of methane from blue hydrogen add substantial additional warming within the first few decades. For the 1 kg pulse consumption scenario, the climate impact of green and blue hydrogen 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, and such impacts will adjust quickly if future emission rates change. 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.

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 (Fig. 2 and 3). In both the low and high 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 hydrogen become orders of magnitude smaller than that of CO_2 emissions 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 included for blue hydrogen. Under all emission scenarios, using the same methane leakage rates for methane combustion and hydrogen production (Fig. S6 and S7) substantially increases the warming potentials from the avoided CO_2 emissions, especially for the short-term responses, leading to net climate benefits for both clean hydrogen alternatives. Consideration of conversion 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 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 perturbation lifetimes or climate response functions has minor effects (Fig. S6, S7, and S9). Here we do not cover all 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 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

The radiative forcing calculation presented here is a linear approximation, 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. The radiative forcing calculation assumes an unchanging background atmospheric composition, whereas it is likely that the climate impact of an emission will depend on the background climate state (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 affecting temperature can vary substantially from gas to gas (Hansen et al., 1997; Modak et al., 2018). In addition, the framework used here only compares hydrogen with the avoided CO_2 emissions, while fossil fuel adaptation are associated with emissions of other radiatively active species and air pollutants (on Climate Change, 2018).

Many important uncertainties persist. For example, we considered the chemical adjustments to radiative forcing for methane due to effects on ozone and stratospheric water vapor, as considered by Ocko and Hamburg (2022). There are other effects that have been included in previous works, which would affect the warming impact of methane emissions (Boucher et al., 2009; Shindell et al., 2009). There are uncertainties related to cloud radiative effects from thermodynamic adjustments and aerosol-cloud interactions (O'Connor et al., 2022). There are additional uncertainties related to the fast physical radiative forcing adjustments to dioxide, ozone and other radiatively active gases (Smith et al., 2018). Co-emissions from fossil fuel combustions (e.g., aerosol precursors) can also affect climate and public health (Lelieveld et al.,

2019). Unlike the long-lived CO_2, the climate impact of short-lived forcers might depend on locations of emissions (Persad and Caldeira, 2018; Burney et al., 2022). While their radiative forcing might diminish quickly after emission ceasing, indirect impacts from these short-lived forcers (e.g., by affecting carbon sinks and atmospheric CO_2 levels) could last longer, introducing additional uncertainties (Fu et al., 2020). 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 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 99^{th} year after an emission only once.

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 can balance 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 (Jones et al., 2006; Allen et al., 2009). This important distinction is not captured by the CAGWP metric proposed by Ocko and Hamburg (2022).

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 (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. 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.

We have developed a 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. In line with previous studies (Fuglestvedt et al., 2010; Allen et al., 2016; Balcombe et al., 2018), 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. For the same quantity of emissions, hydrogen shows consistently smaller climate impact than methane. 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. As shown by Ocko and Hamburg (2022), 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. In contrast to the climate impact of carbon dioxide emissions, which persist for many millennia (Archer, 2005; Solomon et al., 2009), climate impacts decay on the timescale of decades after a cessation of methane or hydrogen emissions.

Consideration of methane leakage associated with burning natural gas can have a substantial effect on results. Including the methane leakage associated with fossil fuel combustion would increase its short-term impact and might lead to net short-term climate benefit for blue hydrogen. 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 strongly weights near-term radiative forcing relative to long-term radiative forcing from individual pulse emissions.

We emphasize that 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 and cost 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. However, in the interest of transparency, we would like to point out that K.C. is an employee of a non-profit organization

that funds early commercial demonstration projects related to clean alternatives that can displace carbon-intensive technologies, and this can include clean hydrogen to decarbonize industry. In the further interest of transparency, note that L.D. is a consultant for a for-profit entity that has no known investments related to clean hydrogen.

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Figure 1. Climate impact from emissions of different species. (**a-c**) Radiative forcing and (**d-f**) global mean temperature response caused by emissions of methane (CH_4), hydrogen (H_2), and carbon dioxide (CO_2). Three emission scenarios are considered: 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. CH_4 and H_2 share the same y-axis, the maximum value of which is 60 times relative to that of CO_2. Radiative forcing from a continuous emission of hydrogen and methane is proportional to emission rates, and decays rapidly once ceased, whereas radiative forcing from carbon dioxide is closely related to cumulative emissions and will last for longer timescales. Figures showing only 100-year results are plotted in Figure S12.

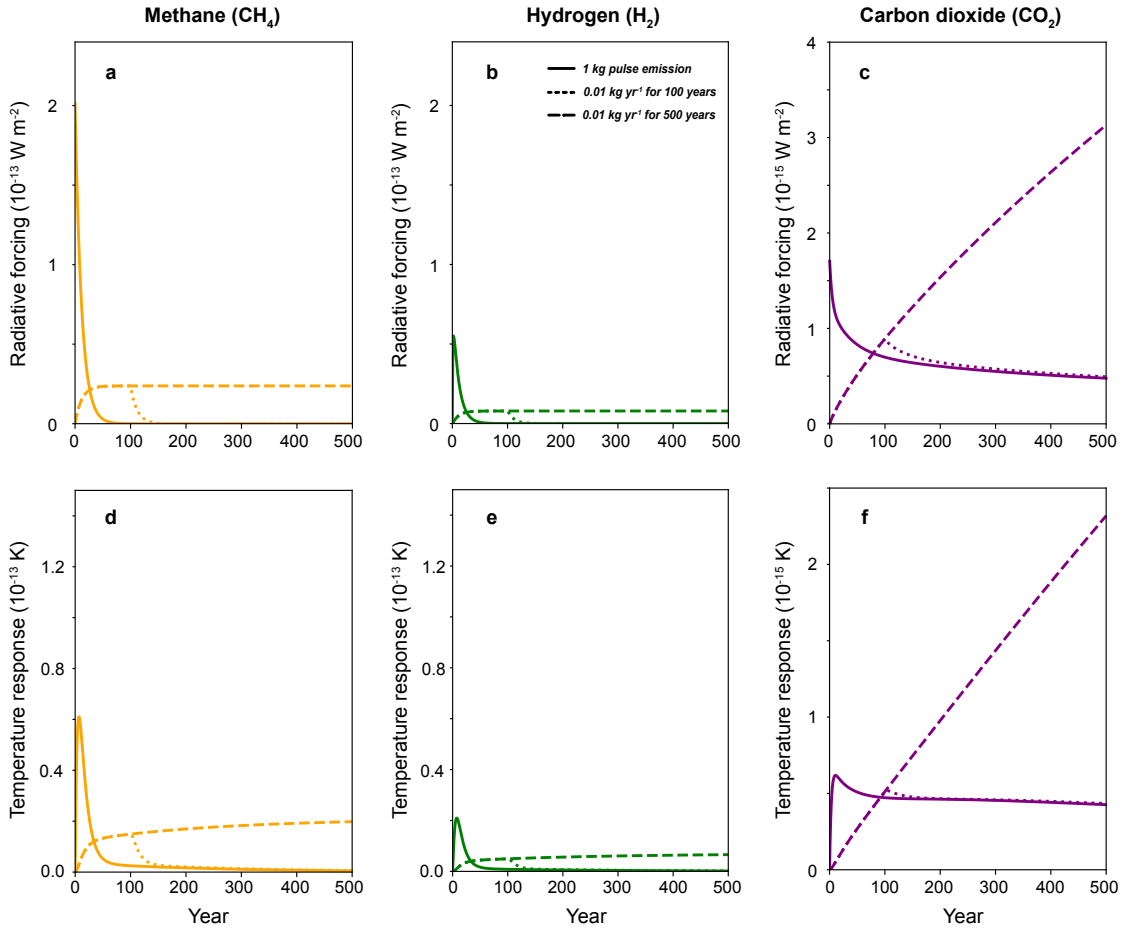

Figure 2. Radiative forcing from consumptions of green hydrogen, blue hydrogen, and avoided CO_2 emissions. Three cases are considered: (**a**-**b**) a 1 kg consumption of hydrogen, (**c**-**d**) a 0.01 kg yr^{-1} continuous consumption of hydrogen lasting for 100 years, and (**e**-**f**) a 0.01 kg yr^{-1} continuous consumption of hydrogen lasting for 500 years. The left column shows cases with 1% hydrogen and 1% methane leakage rates, and the right column shows cases with 10% hydrogen and 3% methane leakage rates. 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 100-year results are plotted in Figure S13.

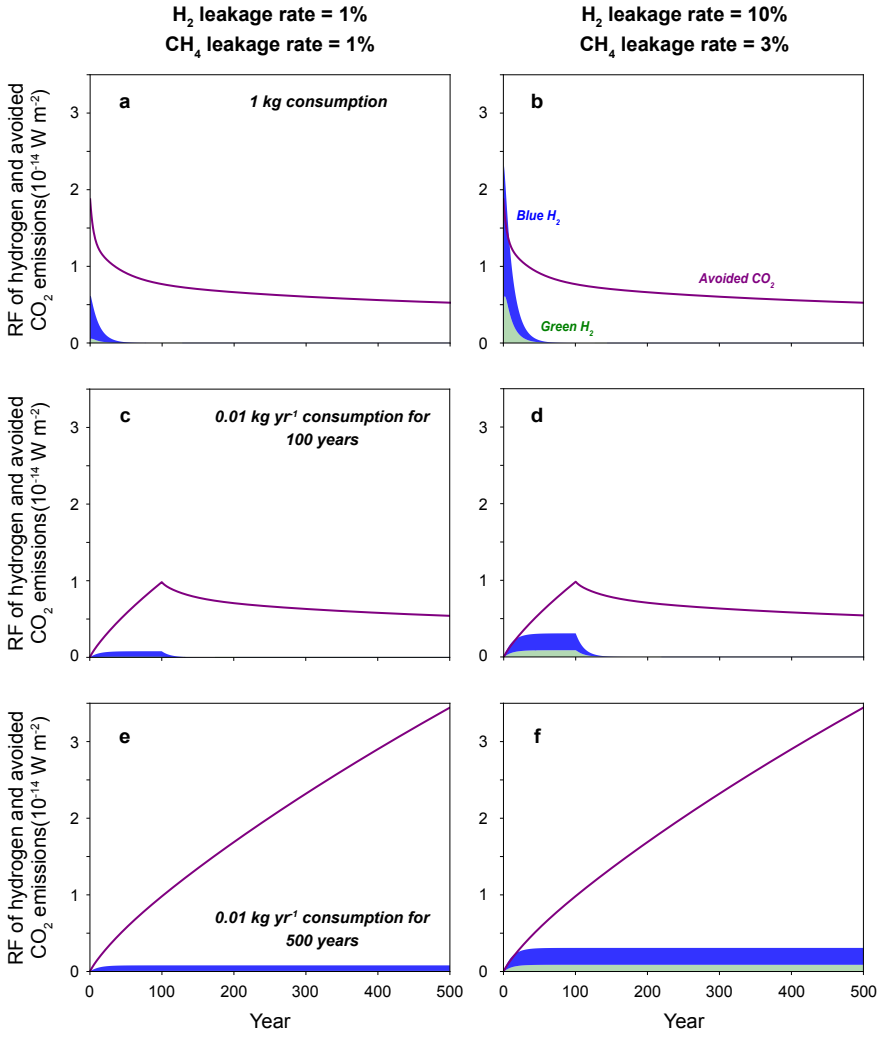

Figure 3. Same as Figure 2 but for the global mean temperature response. Figures showing only 100-year results are plotted in Figure S14.