Supporting Information for

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

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Text S1. Solutions with a continuous emission to tp

Warwick et al. (2022) considered a continuous emission scenario to the time tp. In our analytic solutions, considering a continuous unit emission scenario to time tp where:

$$\begin{cases} f_{H_2}(t) = 1 \text{, if } t \le \text{tp} \\ f_{H_2}(t) = 0 \text{, if } t > \text{tp} \end{cases} \tag{S1}$$

Radiative forcing can be represented as:

$$\widehat{R_{H_2}}(t) = \int_0^{\min(t,tp)} R_{H_2}(t-\tau)\, d\tau \tag{S2}$$

Radiative forcing is thus:

$$\begin{aligned} R_{H_2,cont}(t) = {} & \frac{A^*_{CH_4} a_{CH_4} \tau_{H_2} \tau_{CH_4} \left(\tau_{H_2} e^{-\frac{t}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{CH_4} e^{-\frac{t}{\tau_{CH_4}}} \left(e^{\frac{tp}{\tau_{CH_4}}} - 1 \right) \right)}{\tau_{H_2} - \tau_{CH_4}} \\ & + \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3} \left(\tau_{H_2} e^{-\frac{t}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{O_3} e^{-\frac{t}{\tau_{O_3}}} \left(e^{\frac{tp}{\tau_{O_3}}} - 1 \right) \right)}{\tau_{H_2} - \tau_{O_3}} \\ & + \frac{A_{H_2O} a_{H_2O} \tau_{H_2} \tau_{H_2O} \left(\tau_{H_2} e^{-\frac{t}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{H_2O} e^{-\frac{t}{\tau_{H_2O}}} \left(e^{\frac{tp}{\tau_{H_2O}}} - 1 \right) \right)}{\tau_{H_2} - \tau_{H_2O}} \end{aligned} \tag{S3}$$

Correspondingly, the time-integrated radiative forcing under a continuous emission scenario to time tp is:

$$\begin{aligned} & CAGWP_{H_2}(H) \\ & = \frac{A^*_{CH_4} a_{CH_4} \tau_{H_2} \tau_{CH_4} \left(\tau_{H_2}^2 e^{\frac{-H}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{CH_4}^2 e^{\frac{-H}{\tau_{CH_4}}} \left(e^{\frac{tp}{\tau_{CH_4}}} - 1 \right) + tp\left(\tau_{CH_4} - \tau_{H_2}\right) \right)}{\tau_{CH_4} - \tau_{H_2}} \\ & + \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3} \left(\tau_{H_2}^2 e^{\frac{-H}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{O_3}^2 e^{\frac{-H}{\tau_{O_3}}} \left(e^{\frac{tp}{\tau_{O_3}}} - 1 \right) + tp\left(\tau_{O_3} - \tau_{H_2}\right) \right)}{\tau_{O_3} - \tau_{H_2}} \end{aligned} \tag{S4}$$

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

Note that this equation differs slightly from that given in Warwick et al. (2022), which included a minor mistake in integration bounds.

The corresponding equations for continuous emissions of CO2 and CH4 to time tp can be represented as:

$$R_{CO_2,cont}(t) = A_{CO_2}\left(a_0 tp + \sum_{i=1}^{3} a_i \tau_i e^{-\frac{t}{\tau_i}}\left(e^{\frac{tp}{\tau_1}}-1\right)\right) \qquad (S5)$$

$$R_{CH_4,cont}(t) = (1+f_1+f_2)A_{CH_4}\tau_{CH_4} e^{-\frac{t}{\tau_{CH_4}}}\left(e^{\frac{tp}{\tau_{CH_4}}}-1\right) \qquad (S6)$$

And CAGWP for continuous emissions of CO2 and CH4 to time tp is:

$$CAGWP_{CO_2}(H) = \frac{A_{CO_2}}{2}\left(a_0 tp(2H-tp) + \sum_{i=1}^{3} 2a_i\tau_i\left(tp-\tau_i e^{-\frac{H}{\tau_i}}\left(e^{\frac{tp}{\tau_i}}-1\right)\right)\right) \qquad (S7)$$

$$CAGWP_{CH_4}(H) = (1+f_1+f_2)A_{CH_4}\tau_{CH_4}\left(tp-\tau_{CH_4} e^{-\frac{H}{\tau_{CH_4}}}\left(e^{\frac{tp}{\tau_{CH_4}}}-1\right)\right) \qquad (S8)$$

Text S2. CAGWP components from analytic solutions

In this section, we show equations calculating the three components used in Ocko and Hamburg (2022), which are denoted as CAGWP here. These equations are derived based on analytic solutions as discussed in the main text and are considered for continuous emissions scenarios. The physical meanings of these equations are explained in Warwick et al. (2022).

The first component ($CAGWP_{i_1}$) represents radiative forcing caused by chemical perturbations to radiative forcing during the emission period tp:

$$CAGWP_{i_1}(H) = \frac{A_i a_i \tau_{H_2} \tau_i \left(\tau_{H_2} \left(\left(1 - e^{-\frac{tp}{\tau_{H_2}}} \right) - tp \right) - \tau_i \left(\left(1 - e^{-\frac{tp}{\tau_i}} \right) - tp \right) \right)}{\tau_i - \tau_{H_2}} \qquad (S1)$$

Where A_i is the scaling factor that converts molar mass of species i (i.e., CH_4, O_3, or H_2O) to $W\ m^{-2}$, a_i is the factor representing the impact of remaining hydrogen in the atmosphere on the atmospheric molar mass of different species, τ_i is the lifetime of different species, τ_{H_2} is the lifetime of H_2, and tp is the emission period.

The second component ($CAGWP_{i_2}$) represents the chemical perturbation to radiative forcing at timescale H resulting from the emitted species remaining in the atmosphere following the end of the emission period:

$$CAGWP_{i_2}(H) = \frac{A_i a_i \tau_{H_2}^2 \tau_i \left(1 - e^{\frac{tp}{\tau_{H_2}}} \right) \left(\tau_{H_2} \left(e^{-\frac{tp}{\tau_{H_2}}} - e^{-\frac{H}{\tau_{H_2}}} \right) + \tau_i e^{-\frac{tp}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_i} - \frac{H}{\tau_i} - 1} \right) \right)}{\tau_i - \tau_{H_2}} \qquad (S2)$$

The third component ($CAGWP_{i_3}$) is the decay of radiative forcing generated during continuous emission period tp:

$$CAGWP_{i_3}(H) = \frac{A_i a_i \tau_{H_2} \tau_i^2 e^{-\frac{H\tau_{H_2} + tp(\tau_i + \tau_{H_2})}{\tau_i \tau_{H_2}}} \left(e^{\frac{H}{\tau_i}} - e^{\frac{tp}{\tau_i}} \right) \left(\tau_{H_2} e^{\frac{tp}{\tau_i}} \left(1 - e^{\frac{tp}{\tau_{H_2}}} \right) - \tau_i e^{\frac{tp}{\tau_{H_2}}} \left(1 - e^{\frac{tp}{\tau_i}} \right) \right)}{\tau_i - \tau_{H_2}} \qquad (S3)$$

As in Ocko and Hamburg (2022), the overall CAGWP for each species i under given period tp and timescale H is:

$$CAGWP_i(H) = CAGWP_{i_1}(H) + CAGWP_{i_2}(H) + CAGWP_{i_3}(H) \qquad (S4)$$

And CAGWP for emissions of hydrogen is:

$$CAGWP_{H_2}(H) = (1 + f_1 + f_2) CAGWP_{CH_4}(H) + CAGWP_{O_3}(H) + CAGWP_{H_2O}(H) \qquad (S5)$$

Comparisons between our newly derived equations and equations used in Ocko and Hamburg (2022) are shown in Figure S11. In addition, we tested our solutions by calculating the following cases:

Case 1: set $tp = 2$ and $H = 2$, which represents CAGWP at year 2 for a 2-year emission;

Case 2: set $tp = 1$ and $H = 2$, which represents CAGWP at year 2 for a 1-year emission;

Case 3: set $tp = 1$ and $H = 1$, which represents CAGWP at year 1 for a 1-year emission.

For a linear system, CAGWP for case 1 should equal the sum of CAGWP for case 2 and case 3. Equations from our analytic solutions give the same numerical values for the above cases, indicating robustness of our conceptual solutions.

Figure S1. Ratios of climate impact. Same as Figure 1, but showing ratios of the climate impact of methane and hydrogen to carbon dioxide emissions. While the residence time of hydrogen is substantially shorter than that of methane, hydrogen emissions result in an increase in methane concentration that decay on the methane time scale. Thus, while the effects of methane and hydrogen differ in magnitude, the temporal pattern of response is similar in both cases.

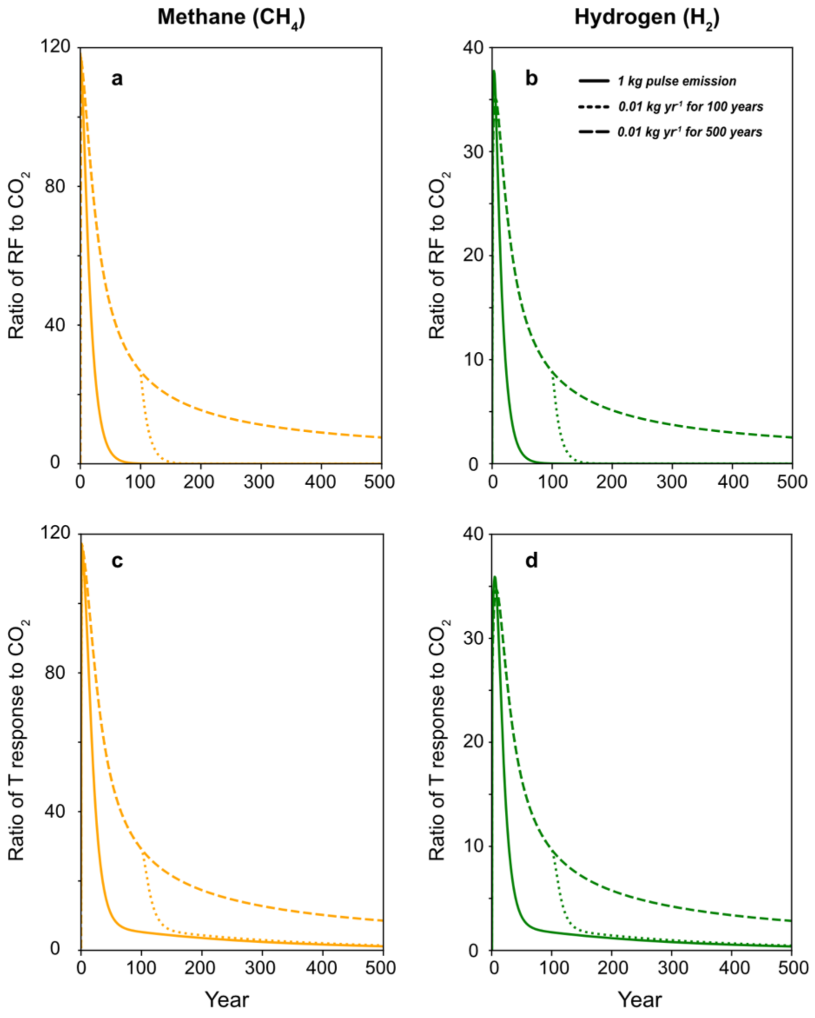
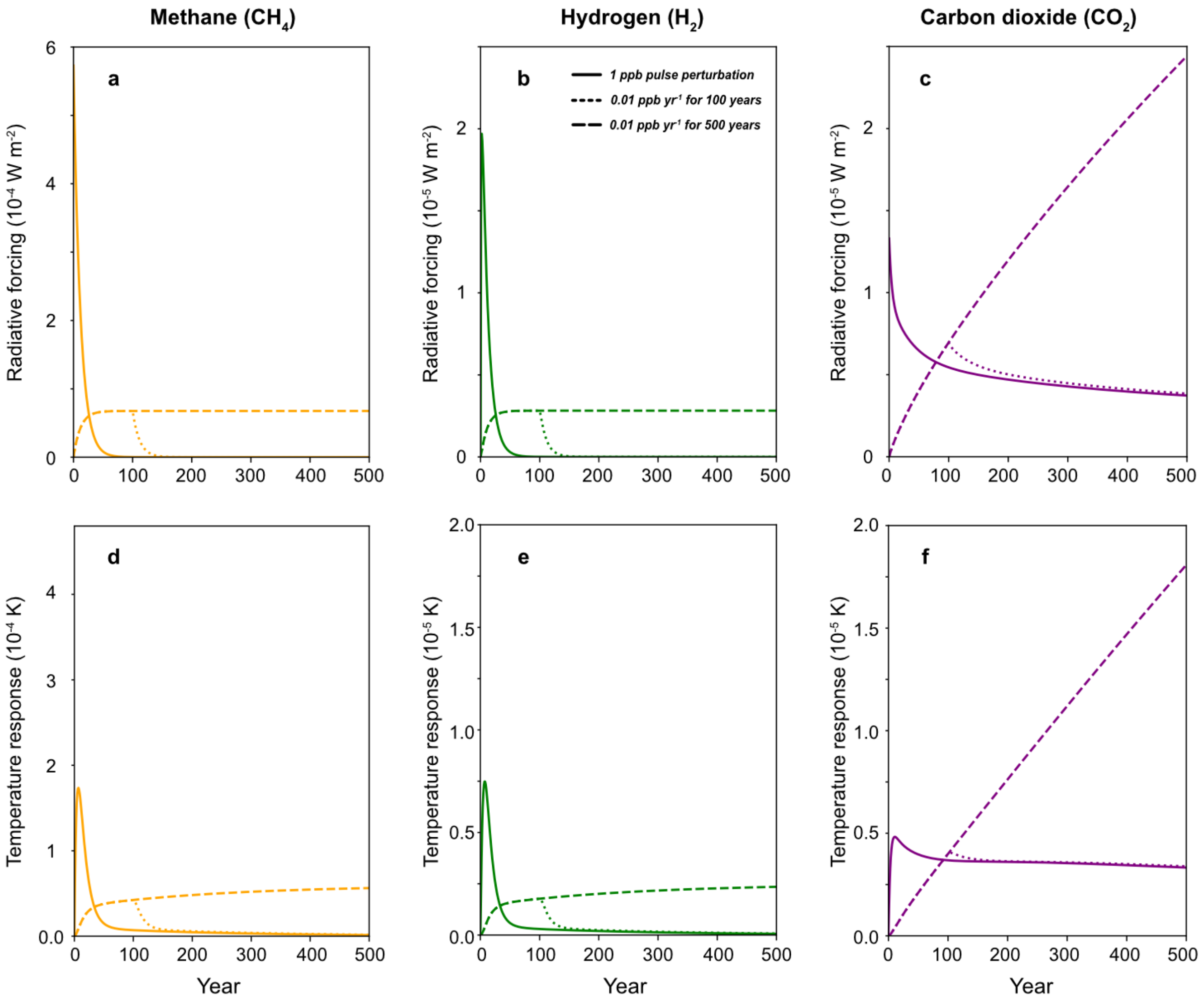


Figure S2. Climate impact from emissions of different species. Similar to Figure 1, but for 1 ppb increase scenarios. Note that CH_4 generates substantially more climate impacts and has a y-axis scale that is 24 times the y-axis of H_2 and CO_2.



83 **Figure S3.** Impact of considering decayed CH_4 to CO_2. In contrast to our central cases where

84 CH_4 decays over time, here we consider the conversion of decayed CH_4 to CO_2, which has a

85 longer lifetime and adds a long-term climate impact to the warming potential of methane.

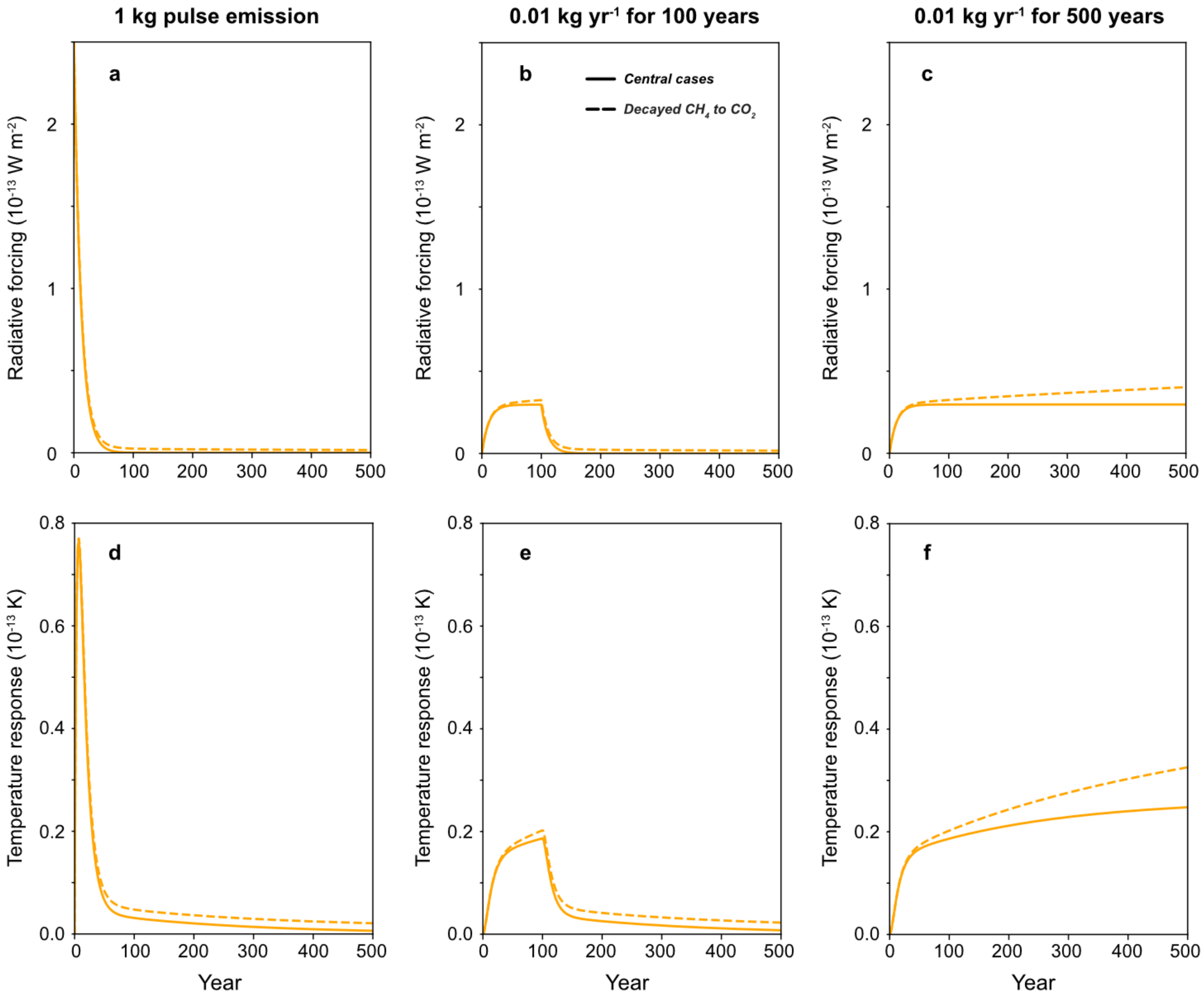


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Figure S4. Climate impact from different hydrogen lifetimes. Radiative forcing and the global mean temperature response from emission of hydrogen under different scenarios. Solid line shows results under our central case, and shaded area represents results considering different hydrogen lifetimes (i.e., 1.4 years and 2.5 years).

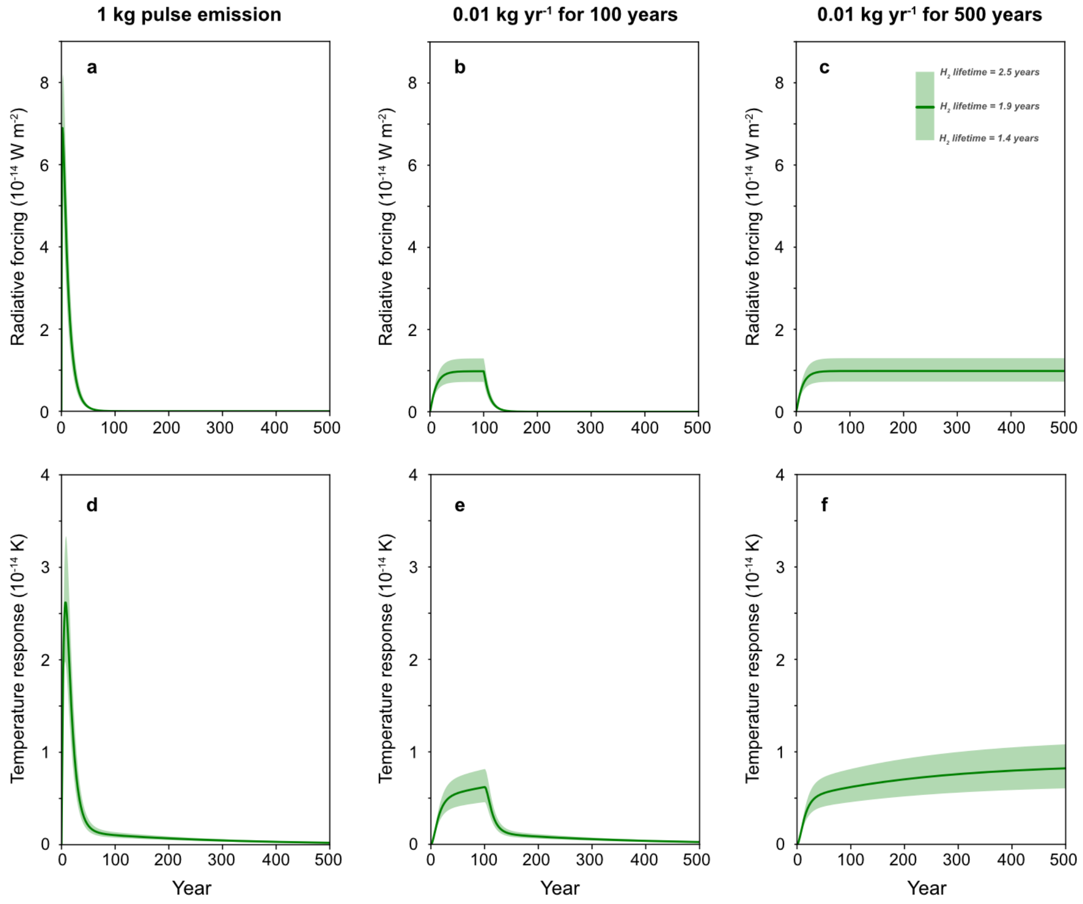

Figure S5. Contributions of methane and hydrogen to hydrogen warming potentials. Here we show contributions of hydrogen and methane to increases in radiative forcing and global mean temperature response between the low and high leakage cases. Our results show that additional leakages of methane (3 % in the high leakage case vs. 1 % in the low leakage case) contribute more warming to blue hydrogen, with hydrogen leakages (10 % in the high leakage case vs. 1 % in the low leakage case) playing a less important role. Results showing contributions for per percentage increase in leakage rate are plotted in **Figure S15**.

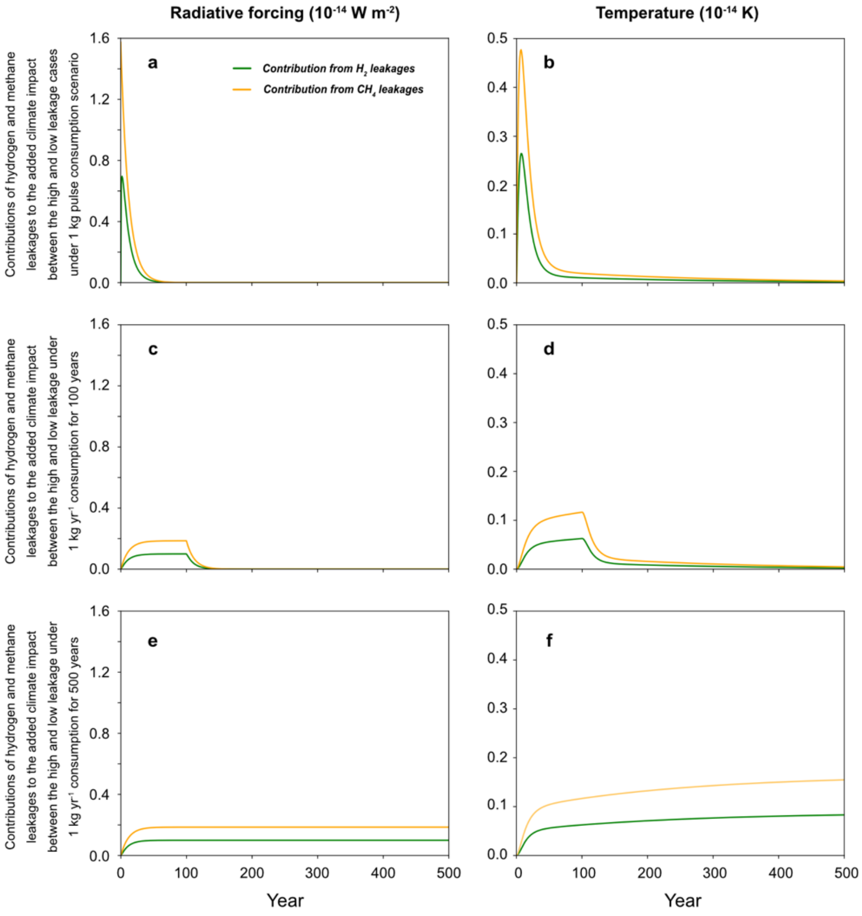

Figure S6. Factors influencing radiative forcing. Same as Figure 2, but considering radiative forcing changes associated with different parameters. These include: considering different hydrogen lifetimes (1.4 years or 2.5 years), include methane leakage for the avoided CO_2 emissions, and considering the conversion of the decayed methane to CO_2. The last two factors have substantial impacts on the climate impact of fossil fuels and the net climate impact of clean hydrogen, whereas hydrogen lifetime shows only a minor impact on our results.

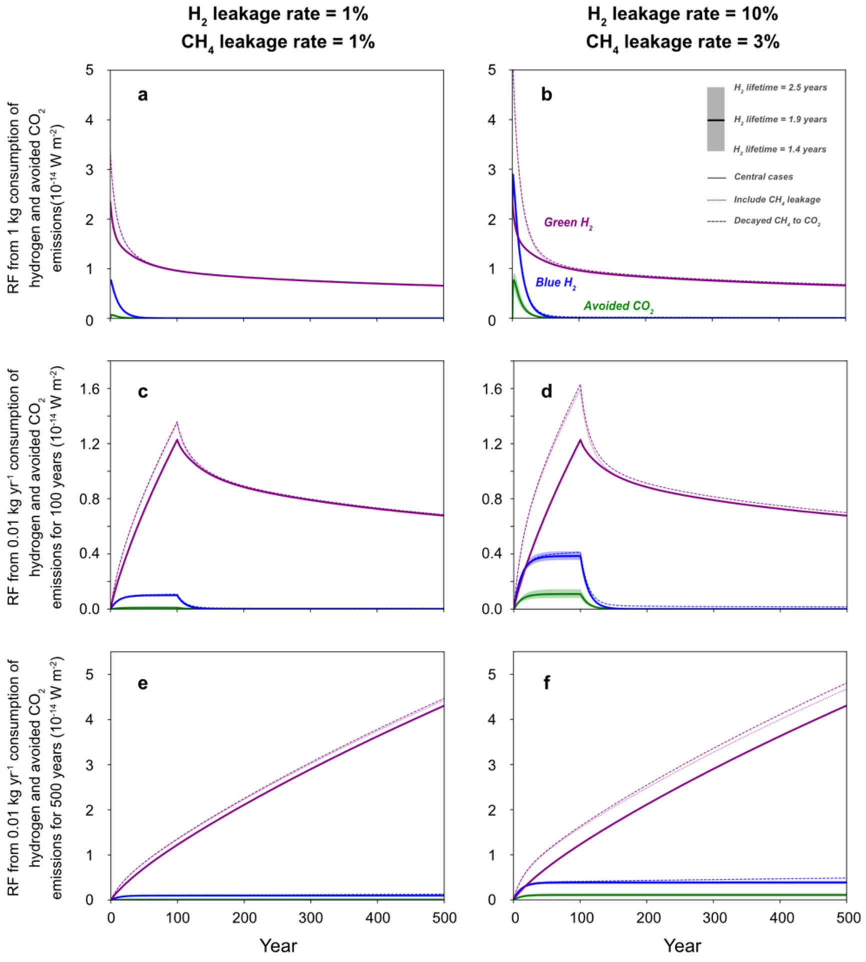

Figure S7. Factors influencing temperature response. Same as Figure S6, but considering temperature instead of radiative forcing.

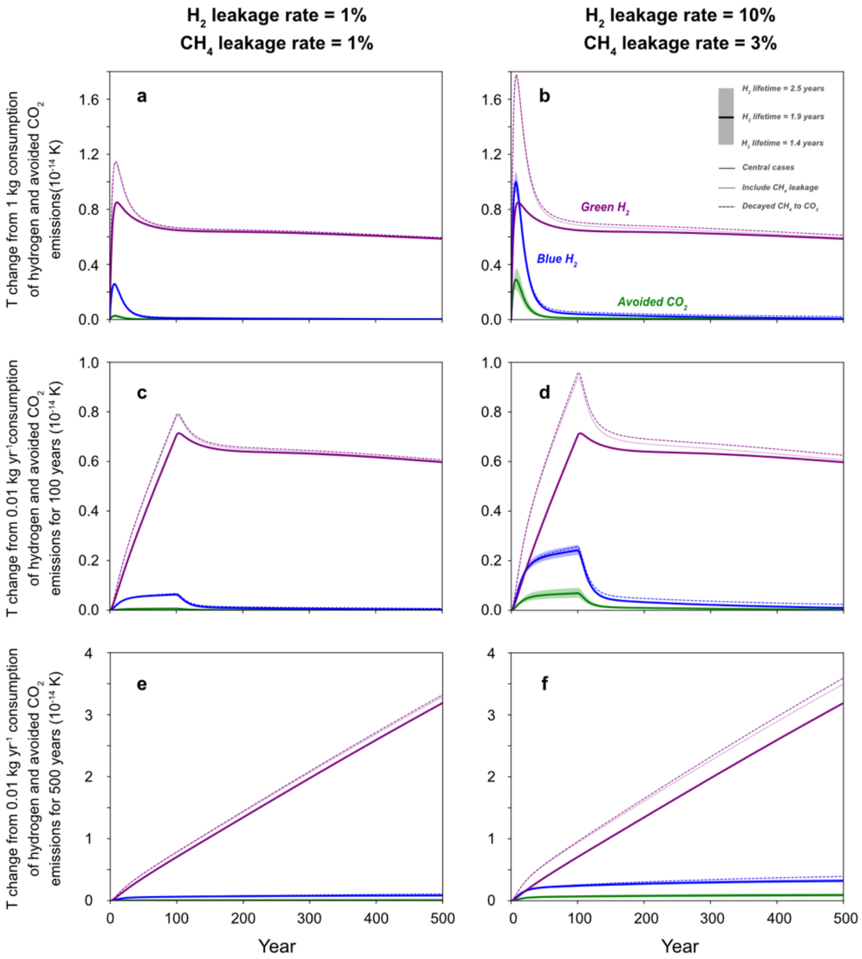

Figure S8. Uncertainty of avoided CO_2 amount. Radiative forcing and global mean temperature response under different assumptions of the avoided CO_2 amount per kg hydrogen consumption. Solid line represents results for our central case (11 kg) and shaded area represents results under alternative assumptions (i.e., 5 kg and 15 kg).

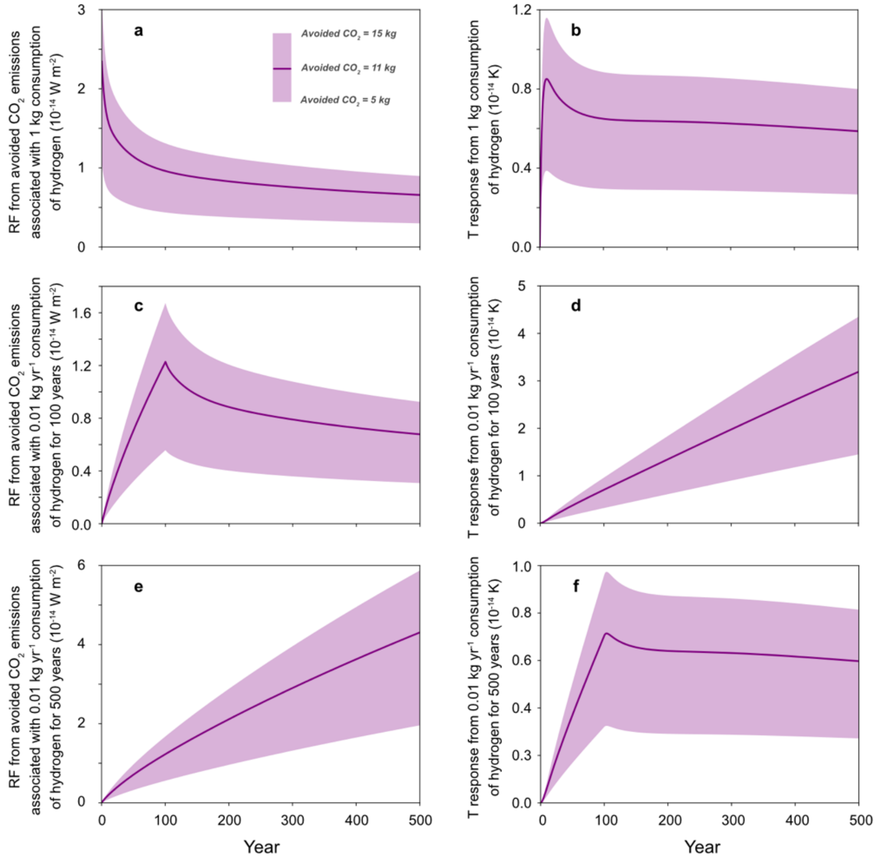

Figure S9. Uncertainty of the climate response function. Same as Figure 3, but combining the radiative forcing equations with different climate response functions.

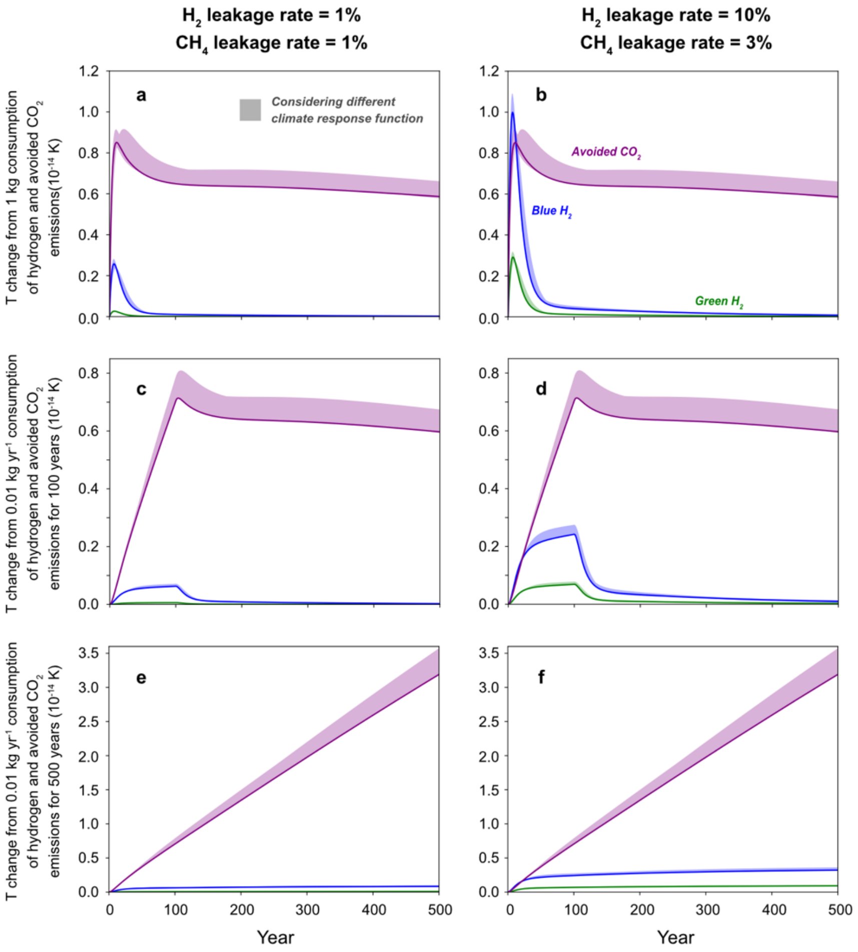

Figure S10. Comparisons of different metrics. Ratios of the time-integrated relative radiative forcing (CGWP) and ratios of the global mean temperature response (GTP) are compared under continuous emission scenarios. The solid lines are the ratios of the time-integrated radiative forcing shown in Figure 2 panel e and f, and dashed lines are the ratios of the temperature changes shown in Figure 3 panel e and f.

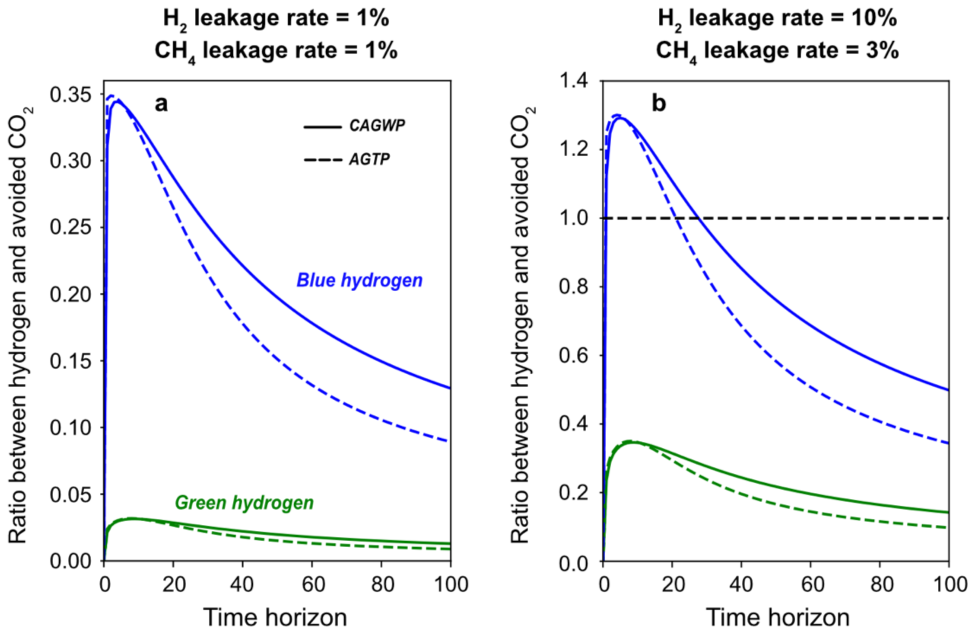

Figure S11. Comparisons between results from our newly derived equations and those used in Ocko and Hamburg (2022). Time-integrated radiative forcing (CAGWP defined in this analysis) from one-year emission and continuous emission scenarios are compared.

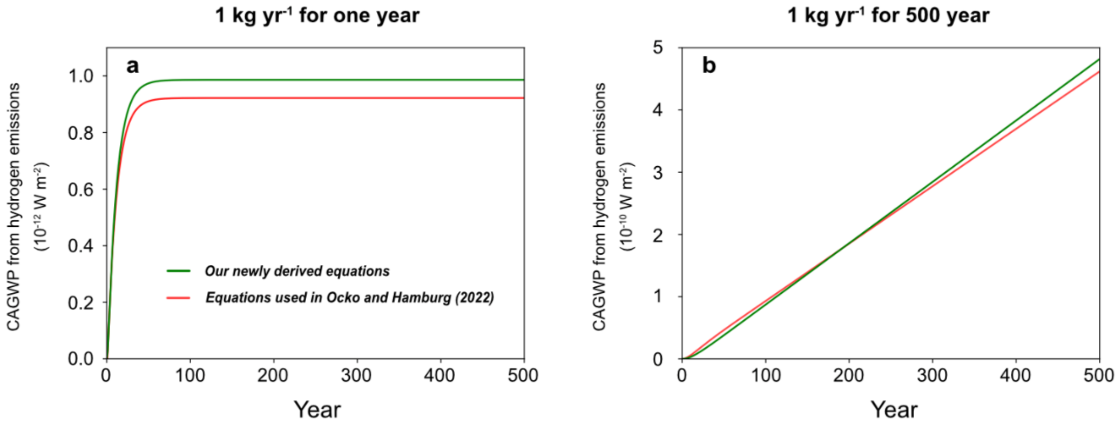

Figure S12. Similar to Figure 1 but for 100-year timescale.

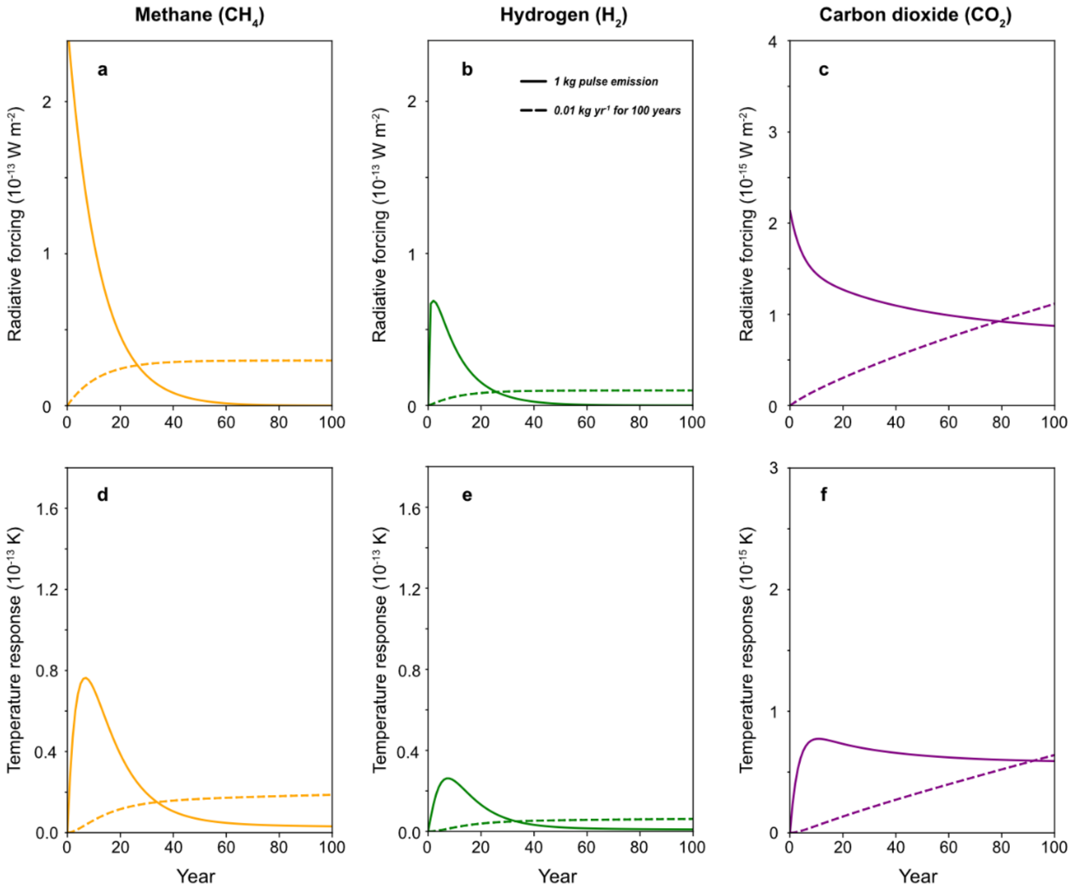

Figure S13. Similar to Figure 2 but for 100-year timescale.

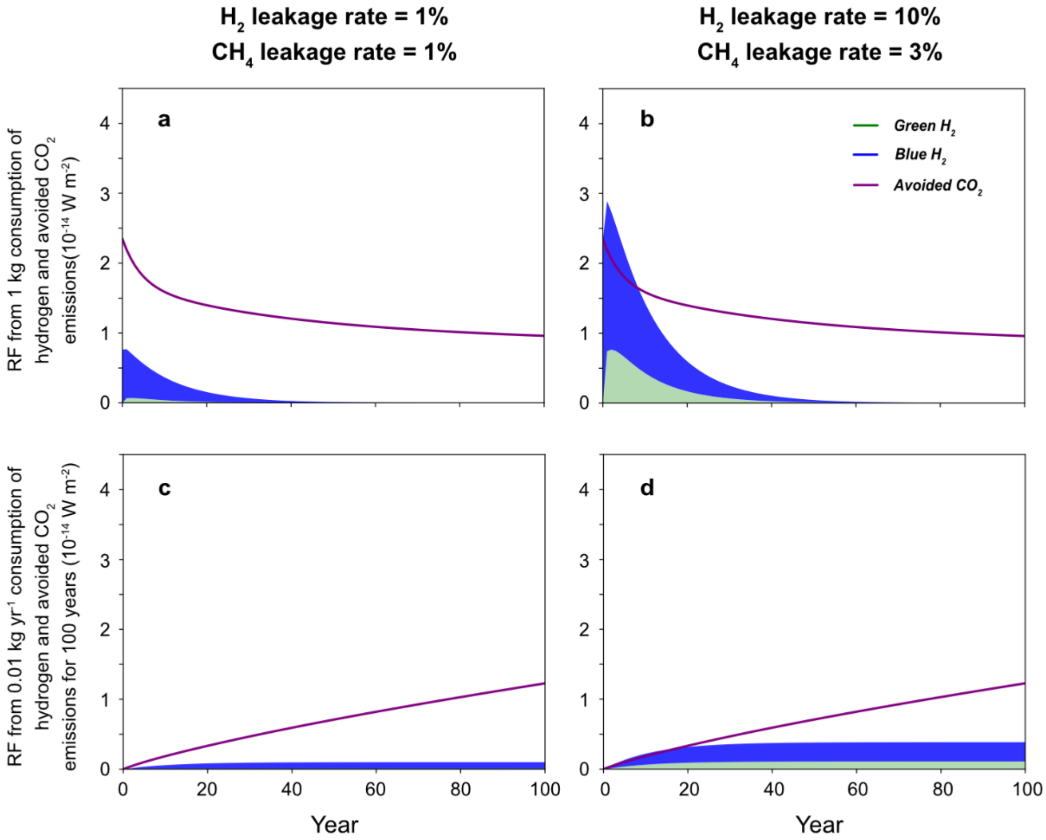

Figure S14. Similar to Figure 3 but for 100-year timescale.

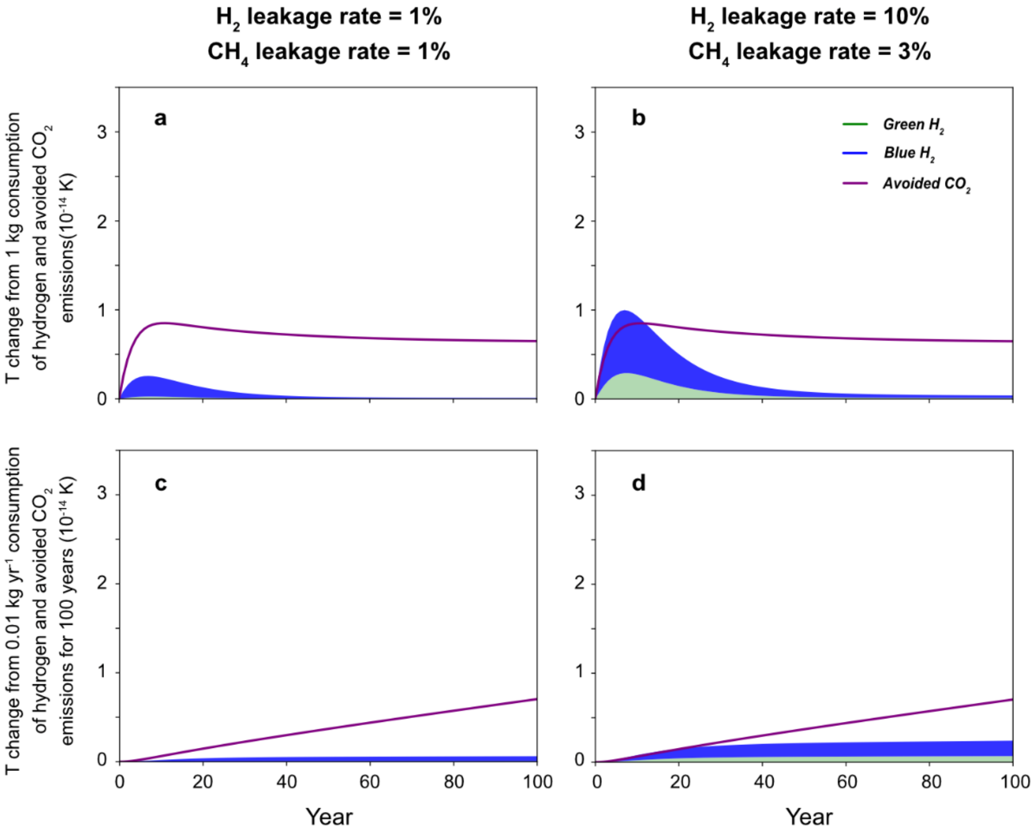

Figure S15. Similar to **Figure S5** but showing increases in climate impact for per percentage increase in the methane and hydrogen leakage rate.

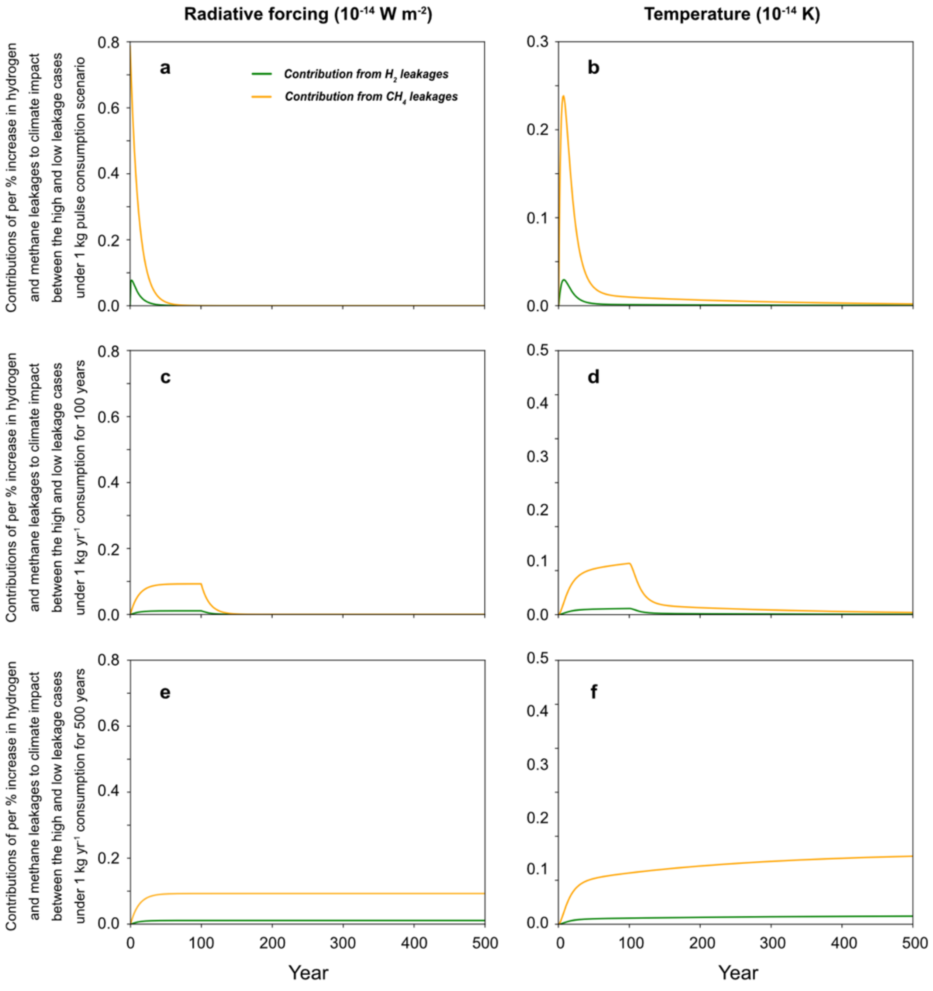

Table S1. Radiative forcing, absolute global warming potential (AGWP), absolute global temperature change potential (AGTP), and their ratios for 1 kg pulse emission of hydrogen, methane, and carbon dioxide under different timescales (i.e., 20, 100, and 500 years).

Time horizon			**20**	**100**	**500**
Hydrogen (H_2)	**RF**	**10^{-15} W m^{-2}**	15.17	0.01	0.00
	AGWP	**10^{-15} W m^{-2}**	818.78	986.26	986.43
	AGTP	**10^{-15} K**	13.18	1.03	0.20
Methane (CH_4)	**RF**	**10^{-15} W m^{-2}**	46.25	0.05	0.00
	AGWP	**10^{-15} W m^{-2}**	2426.52	2971.65	2972.27
	AGTP	**10^{-15} K**	38.68	3.11	0.61
Carbon dioxide (CO_2)	**RF**	**10^{-15} W m^{-2}**	1.27	0.87	0.60
	AGWP	**10^{-15} W m^{-2}**	30.35	111.61	391.55
	AGTP	**10^{-15} K**	0.73	0.59	0.53
Ratio of H_2 to CO_2	**RF**	**Unitless**	11.94	0.02	4.39E-17
	AGWP	**Unitless**	26.97	8.84	2.52
	AGTP	**Unitless**	18.02	1.74	0.38
Ratio of CH_4 to CO_2	**RF**	**Unitless**	36.39	0.06	1.67E-16
	AGWP	**Unitless**	79.94	26.63	7.59
	AGTP	**Unitless**	52.87	5.26	1.15

Table S2. Radiative forcing, absolute global warming potential (CAGWP), absolute global temperature change potential (AGTP), and their ratios for 0.01 kg yr^{-1} continuous emissions of hydrogen, methane, and carbon dioxide under different timescales (i.e., 20, 100, and 500 years).

Time horizon			**20**	**100**	**500**
Hydrogen (H_2)	**RF**	**10^{-15} W m^{-2}**	818.78	986.26	986.43
	CAGWP	**10^{-15} W m^{-2}**	10204.07	87233.27	481801.74
	AGTP	**10^{-15} K**	390.55	619.83	822.23
Methane (CH_4)	**RF**	**10^{-15} W m^{-2}**	2426.52	2971.65	2972.27
	CAGWP	**10^{-15} W m^{-2}**	30812.46	262161.26	1451060.68
	AGTP	**10^{-15} K**	1159.75	1866.75	2477.35
Carbon dioxide (CO_2)	**RF**	**10^{-15} W m^{-2}**	30.35	111.61	391.55
	CAGWP	**10^{-15} W m^{-2}**	327.65	6204.51	110166.33
	AGTP	**10^{-15} K**	13.41	64.04	289.99
Ratio of H_2 to CO_2	**RF**	**Unitless**	26.97	8.84	2.52
	CAGWP	**Unitless**	31.14	14.06	4.37
	AGTP	**Unitless**	29.12	9.68	2.84
Ratio of CH_4 to CO_2	**RF**	**Unitless**	79.94	26.63	7.59
	CAGWP	**Unitless**	94.04	42.25	13.17
	AGTP	**Unitless**	86.47	29.15	8.54

Table S3. Radiative forcing, absolute global warming potential (AGWP), absolute global temperature change potential (AGTP), and their ratios for 1 kg consumption of green and blue hydrogen, and corresponding avoided CO_2 emissions under different timescales (i.e., 20, 100, and 500 years).

Emission assumptions			**1% hydrogen and 1% methane**			**10% hydrogen and 3% methane**		
Time horizon			**20**	**100**	**500**	**20**	**100**	**500**
Green H_2	**RF**	**10^{-15} W m^{-2}**	0.15	0.00	0.00	1.69	0.00	0.00
	AGWP	**10^{-15} W m^{-2}**	8.27	9.96	9.96	90.98	109.58	109.60
	AGTP	**10^{-15} K**	0.13	0.01	0.00	1.46	0.11	0.02
Blue H_2	**RF**	**10^{-15} W m^{-2}**	1.55	0.00	0.00	5.98	0.01	0.00
	AGWP	**10^{-15} W m^{-2}**	81.80	100.01	100.03	316.12	385.30	385.38
	AGTP	**10^{-15} K**	1.31	0.10	0.02	5.05	0.40	0.08
Avoided CO_2	**RF**	**10^{-15} W m^{-2}**	13.98	9.60	6.58	13.98	9.60	6.58
	AGWP	**10^{-15} W m^{-2}**	333.90	1227.72	4307.03	333.90	1227.72	4307.03
	AGTP	**10^{-15} K**	8.05	6.49	5.87	8.05	6.49	5.87
Ratio of green H_2 to avoided CO_2	**RF**	**Unitless**	0.01	1.47E-05	4.03E-20	0.12	1.62E-04	4.43E-19
	AGWP	**Unitless**	0.02	0.01	2.31E-03	0.27	0.09	0.03
	AGTP	**Unitless**	0.02	1.60E-03	3.51E-04	0.18	0.02	3.86E-03
Ratio of blue H_2 to avoided CO_2	**RF**	**Unitless**	0.11	1.81E-04	5.00E-19	0.43	6.70E-04	1.85E-18
	AGWP	**Unitless**	0.24	0.08	0.02	0.95	0.31	0.09
	AGTP	**Unitless**	0.16	0.02	3.53E-03	0.63	0.06	0.01

Table S4. Radiative forcing, absolute global warming potential (CAGWP), absolute global temperature change potential (AGTP), and their ratios for 0.01 kg yr^{-1} continuous consumption of green and blue hydrogen, and corresponding avoided CO_2 emission under different timescales (i.e., 20, 100, and 500 years).

Emission assumptions			**1% hydrogen and 1% methane**			**10% hydrogen and 3% methane**		
Time horizon			**20**	**100**	**500**	**20**	**100**	**500**
Green H_2	**RF**	**10^{-15} W m^{-2}**	8.27	9.96	9.96	90.98	109.58	109.60
	CAGWP	**10^{-15} W m^{-2}**	103.07	881.14	4866.68	1133.79	9692.59	53533.53
	AGTP	**10^{-15} K**	3.94	6.26	8.31	43.39	68.87	91.36
Blue H_2	**RF**	**10^{-15} W m^{-2}**	81.80	100.01	100.03	316.12	385.30	385.38
	CAGWP	**10^{-15} W m^{-2}**	1036.78	8825.42	48838.22	3992.67	34016.83	188168.02
	AGTP	**10^{-15} K**	39.09	62.83	83.38	151.00	242.07	321.22
Avoided CO_2	**RF**	**10^{-15} W m^{-2}**	333.90	1227.72	4307.03	333.90	1227.72	4307.03
	CAGWP	**10^{-15} W m^{-2}**	3604.19	68249.57	1211829.61	3604.19	68249.57	1211829.61
	AGTP	**10^{-15} K**	147.54	704.40	3189.85	147.54	704.40	3189.85
Ratio of green H_2 to avoided CO_2	**RF**	**Unitless**	0.02	0.01	2.31E-03	0.27	0.09	0.03
	CAGWP	**Unitless**	0.03	0.01	4.02E-03	0.31	0.14	0.04
	AGTP	**Unitless**	0.03	0.01	2.60E-03	0.29	0.10	0.03
Ratio of blue H_2 to avoided CO_2	**RF**	**Unitless**	0.24	0.08	0.02	0.95	0.31	0.09
	CAGWP	**Unitless**	0.29	0.13	0.04	1.11	0.50	0.16
	AGTP	**Unitless**	0.26	0.09	0.03	1.02	0.34	0.10

Reference

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

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