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Supporting Information for

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

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Text S1 to S2

Figure S1 to S15

Table S1 to S4

17 **Text S1. Solutions with a continuous emission to tp**

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

$$20 \quad \begin{cases} f_{H_2}(t) = 1, & \text{if } t \leq tp \\ f_{H_2}(t) = 0, & \text{if } t > tp \end{cases} \quad (S1)$$

21 Radiative forcing can be represented as:

$$22 \quad \widehat{R}_{H_2}(t) = \int_0^{\min(t, tp)} R_{H_2}(t - \tau) d\tau \quad (S2)$$

23 Radiative forcing is thus:

$$24 \quad \begin{aligned} R_{H_2, cont}(t) = & \frac{A_{CH_4}^* a_{CH_4} \tau_{H_2} \tau_{CH_4} \left(\tau_{H_2} e^{-\frac{t}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{CH_4} e^{-\frac{t}{\tau_{CH_4}}} \left(e^{\frac{tp}{\tau_{CH_4}}} - 1 \right) \right)}{\tau_{H_2} - \tau_{CH_4}} \\ & + \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3} \left(\tau_{H_2} e^{-\frac{t}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{O_3} e^{-\frac{t}{\tau_{O_3}}} \left(e^{\frac{tp}{\tau_{O_3}}} - 1 \right) \right)}{\tau_{H_2} - \tau_{O_3}} \\ & + \frac{A_{H_2O} a_{H_2O} \tau_{H_2} \tau_{H_2O} \left(\tau_{H_2} e^{-\frac{t}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{H_2O} e^{-\frac{t}{\tau_{H_2O}}} \left(e^{\frac{tp}{\tau_{H_2O}}} - 1 \right) \right)}{\tau_{H_2} - \tau_{H_2O}} \end{aligned} \quad (S3)$$

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

27 $CAGWP_{H_2}(H)$

$$28 \quad = \frac{A_{CH_4}^* a_{CH_4} \tau_{H_2} \tau_{CH_4} \left(\tau_{H_2}^2 e^{\frac{-H}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{CH_4}^2 e^{\frac{-H}{\tau_{CH_4}}} \left(e^{\frac{tp}{\tau_{CH_4}}} - 1 \right) + tp(\tau_{CH_4} - \tau_{H_2}) \right)}{\tau_{CH_4} - \tau_{H_2}} \\ 29 \quad + \frac{A_{O_3} a_{O_3} \tau_{H_2} \tau_{O_3} \left(\tau_{H_2}^2 e^{\frac{-H}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{O_3}^2 e^{\frac{-H}{\tau_{O_3}}} \left(e^{\frac{tp}{\tau_{O_3}}} - 1 \right) + tp(\tau_{O_3} - \tau_{H_2}) \right)}{\tau_{O_3} - \tau_{H_2}} \quad (S4)$$

$$30 \quad + \frac{A_{H_2O} a_{H_2O} \tau_{H_2} \tau_{H_2O} \left(\tau_{H_2}^2 e^{\frac{-H}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_{H_2}}} - 1 \right) - \tau_{H_2O}^2 e^{\frac{-H}{\tau_{H_2O}}} \left(e^{\frac{tp}{\tau_{H_2O}}} - 1 \right) + tp(\tau_{H_2O} - \tau_{H_2}) \right)}{\tau_{H_2O} - \tau_{H_2}}$$

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

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

$$35 \quad R_{CO_2,cont}(t) = A_{CO_2} \left(a_0 tp + \sum_{i=1}^3 a_i \tau_i e^{-\frac{t}{\tau_i}} \left(e^{\frac{tp}{\tau_i}} - 1 \right) \right) \quad (S5)$$

$$36 \quad R_{CH_4,cont}(t) = (1 + f_1 + f_2) A_{CH_4} \tau_{CH_4} e^{-\frac{t}{\tau_{CH_4}}} \left(e^{\frac{tp}{\tau_{CH_4}}} - 1 \right) \quad (S6)$$

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

$$38 \quad CAGWP_{CO_2}(H) = \frac{A_{CO_2}}{2} \left(a_0 tp(2H - tp) + \sum_{i=1}^3 2a_i \tau_i \left(tp - \tau_i e^{-\frac{H}{\tau_i}} \left(e^{\frac{tp}{\tau_i}} - 1 \right) \right) \right) \quad (S7)$$

$$39 \quad CAGWP_{CH_4}(H) = (1 + f_1 + f_2) A_{CH_4} \tau_{CH_4} \left(tp - \tau_{CH_4} e^{-\frac{H}{\tau_{CH_4}}} \left(e^{\frac{tp}{\tau_{CH_4}}} - 1 \right) \right) \quad (S8)$$

40 **Text S2. CAGWP components from analytic solutions**

41 In this section, we show equations calculating the three components used in Ocko and Hamburg
 42 (2022), which are denoted as CAGWP here. These equations are derived based on analytic
 43 solutions as discussed in the main text and are considered for continuous emissions scenarios.
 44 The physical meanings of these equations are explained in Warwick et al. (2022).
 45 The first component ($CAGWP_{i_1}$) represents radiative forcing caused by chemical perturbations
 46 to radiative forcing during the emission period tp :

$$47 \quad CAGWP_{i_1}(H) = \frac{A_i a_i \tau_{H_2} \tau_i \left(\tau_{H_2} \left(\left(1 - e^{-\frac{tp}{\tau_{H_2}}} \right) - tp \right) - \tau_i \left(\left(1 - e^{-\frac{tp}{\tau_i}} \right) - tp \right) \right)}{\tau_i - \tau_{H_2}} \quad (S1)$$

48 Where A_i is the scaling factor that converts molar mass of species i (i.e., CH_4 , O_3 , or H_2O) to
 49 $W m^{-2}$, a_i is the factor representing the impact of remaining hydrogen in the atmosphere on the
 50 atmospheric molar mass of different species, τ_i is the lifetime of different species, τ_{H_2} is the
 51 lifetime of H_2 , and tp is the emission period.

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

$$55 \quad CAGWP_{i_2}(H) = \frac{A_i a_i \tau_{H_2}^2 \tau_i \left(1 - e^{-\frac{tp}{\tau_{H_2}}} \right) \left(\tau_{H_2} \left(e^{-\frac{tp}{\tau_{H_2}} - \frac{H}{\tau_{H_2}}} \right) + \tau_i e^{-\frac{tp}{\tau_{H_2}}} \left(e^{\frac{tp}{\tau_i} \frac{H}{\tau_i - 1}} \right) \right)}{\tau_i - \tau_{H_2}} \quad (S2)$$

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

$$58 \quad CAGWP_{i_3}(H) = \frac{A_i a_i \tau_{H_2} \tau_i^2 e^{-\frac{H\tau_{H_2} + tp(\tau_i + \tau_{H_2})}{\tau_i \tau_{H_2}}} \left(e^{\frac{H}{\tau_i}} - e^{\frac{tp}{\tau_i}} \right) \left(\tau_{H_2} e^{\frac{tp}{\tau_i}} \left(1 - e^{-\frac{tp}{\tau_{H_2}}} \right) - \tau_i e^{\frac{tp}{\tau_{H_2}}} \left(1 - e^{-\frac{tp}{\tau_i}} \right) \right)}{\tau_i - \tau_{H_2}} \quad (S3)$$

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

$$61 \quad CAGWP_i(H) = CAGWP_{i_1}(H) + CAGWP_{i_2}(H) + CAGWP_{i_3}(H) \quad (S4)$$

62 And CAGWP for emissions of hydrogen is:

$$63 \quad CAGWP_{H_2}(H) = (1 + f_1 + f_2) CAGWP_{CH_4}(H) + CAGWP_{O_3}(H) + CAGWP_{H_2O}(H) \quad (S5)$$

64 Comparisons between our newly derived equations and equations used in Ocko and Hamburg
65 (2022) are shown in Figure S11. In addition, we tested our solutions by calculating the following
66 cases:

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

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

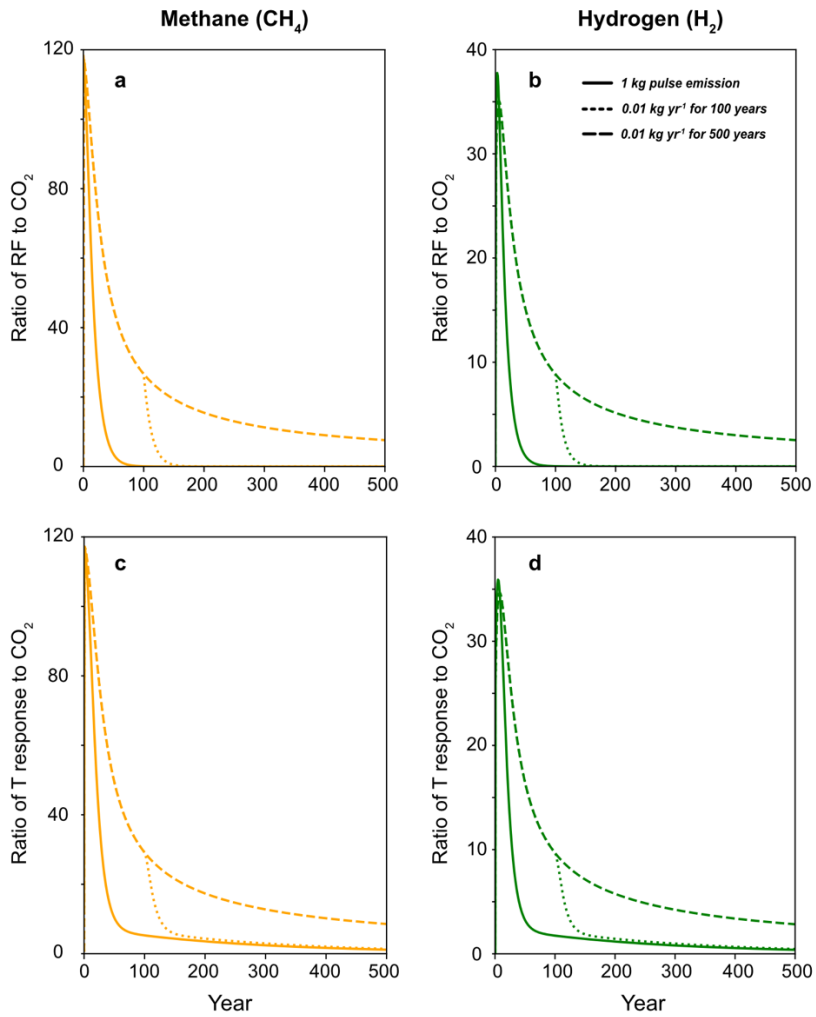
69 **Case 3:** set $tp = 1$ and $H = 1$, which represents CAGWP at year 1 for a 1-year emission.

70 For a linear system, CAGWP for case 1 should equal the sum of CAGWP for case 2 and case 3.

71 Equations from our analytic solutions give the same numerical values for the above cases,

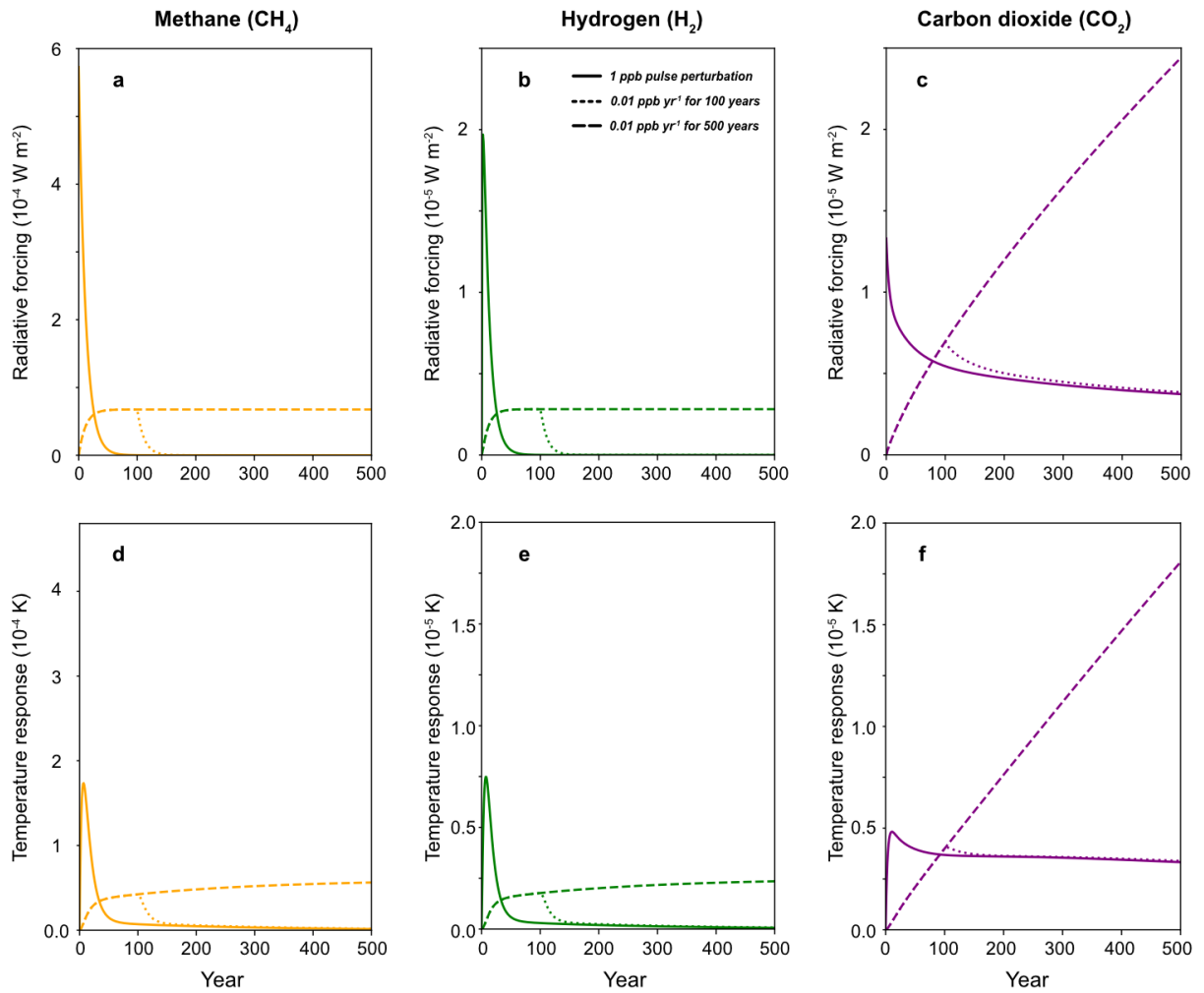
72 indicating robustness of our conceptual solutions.

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



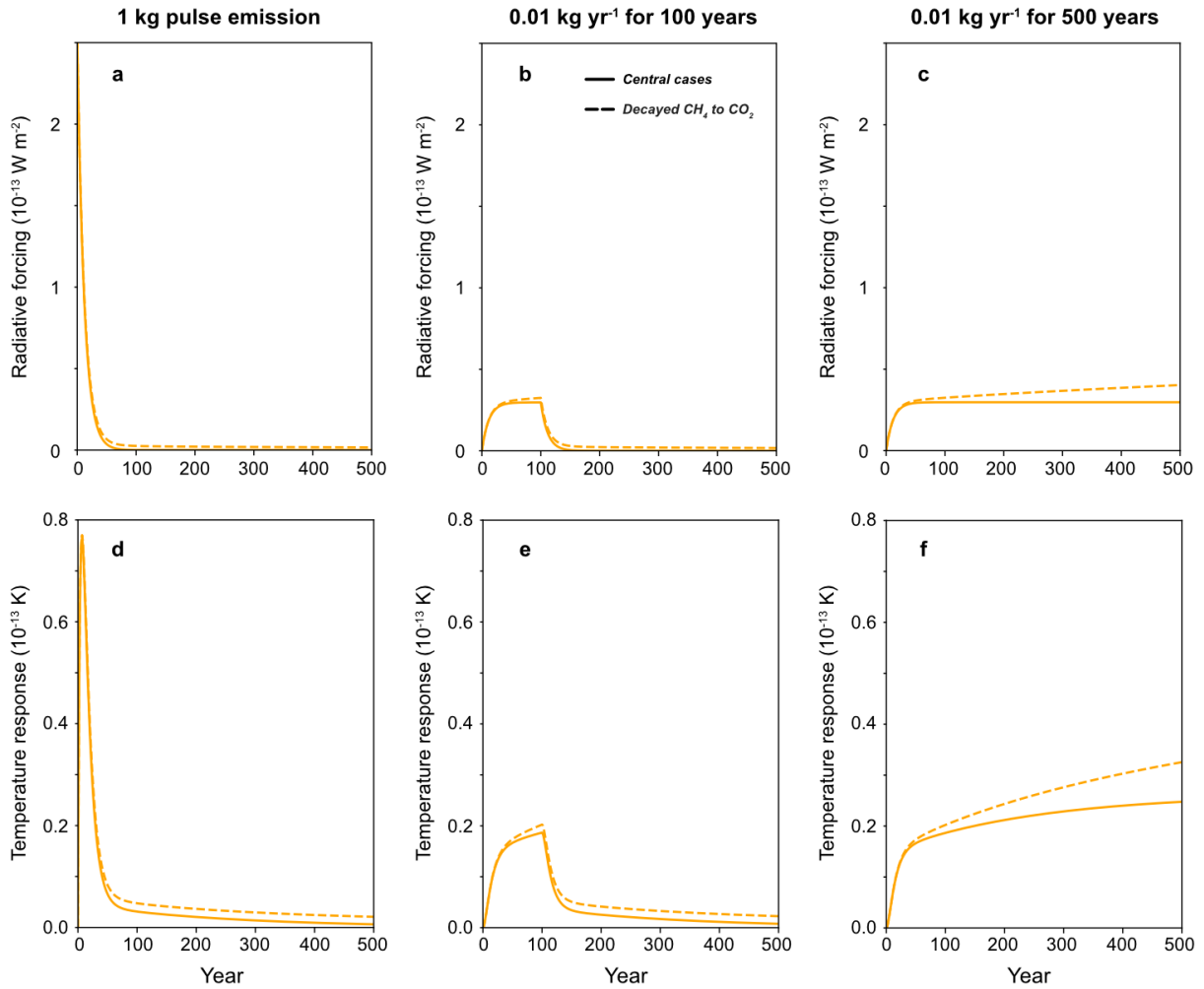
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79 **Figure S2.** Climate impact from emissions of different species. Similar to Figure 1, but for 1 ppb
 80 increase scenarios. Note that CH₄ generates substantially more climate impacts and has a y-axis
 81 scale that is 24 times the y-axis of H₂ and CO₂.



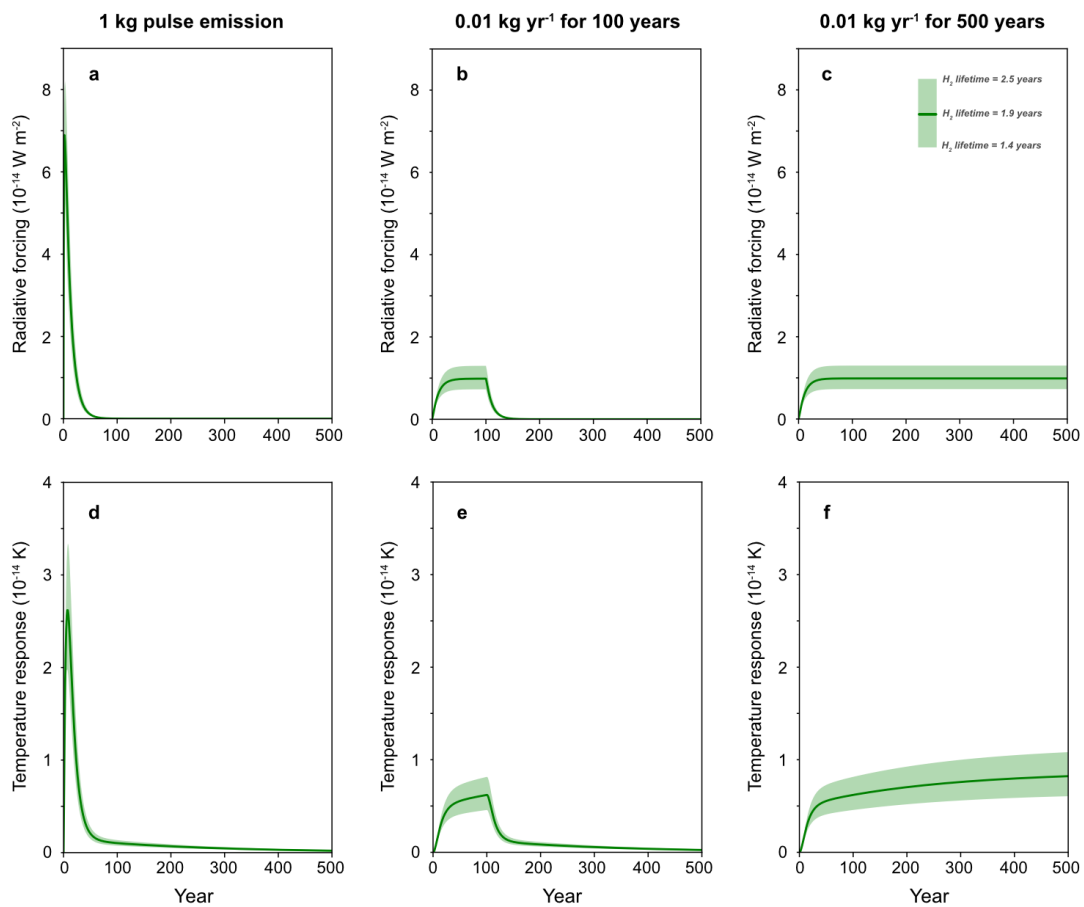
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83 **Figure S3.** Impact of considering decayed CH₄ to CO₂. In contrast to our central cases where
84 CH₄ decays over time, here we consider the conversion of decayed CH₄ to CO₂, which has a
85 longer lifetime and adds a long-term climate impact to the warming potential of methane.



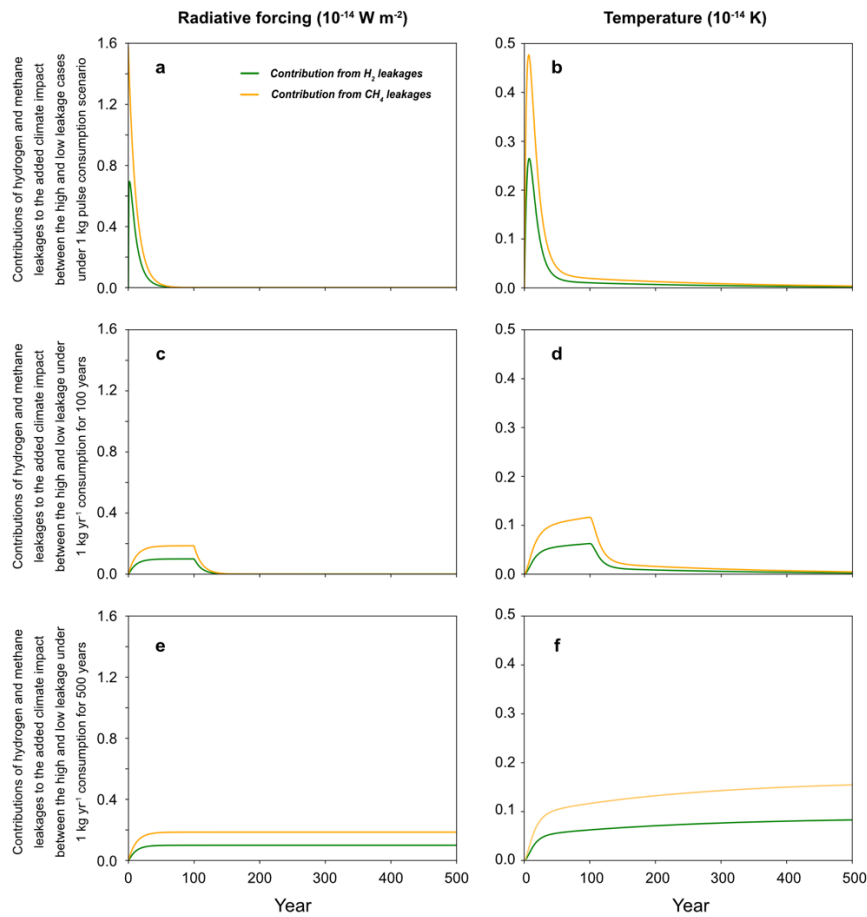
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87 **Figure S4.** Climate impact from different hydrogen lifetimes. Radiative forcing and the global
88 mean temperature response from emission of hydrogen under different scenarios. Solid line
89 shows results under our central case, and shaded area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



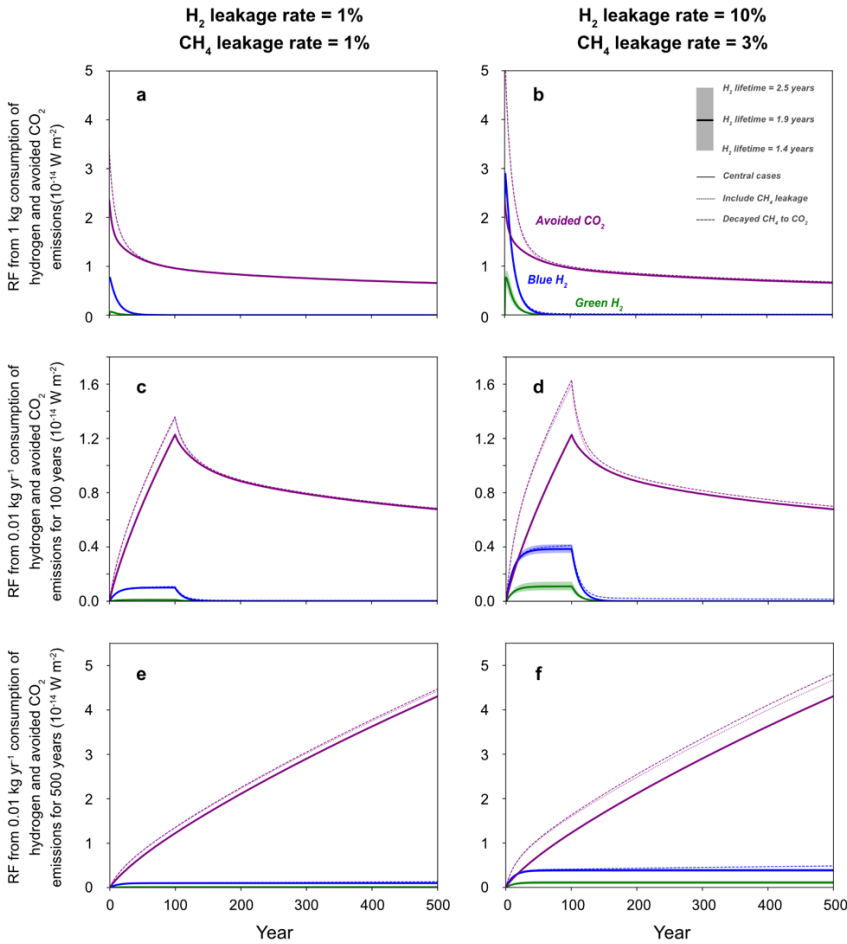
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92 **Figure S5.** Contributions of methane and hydrogen to hydrogen warming potentials. Here we
 93 show contributions of hydrogen and methane to increases in radiative forcing and global mean
 94 temperature response between the low and high leakage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



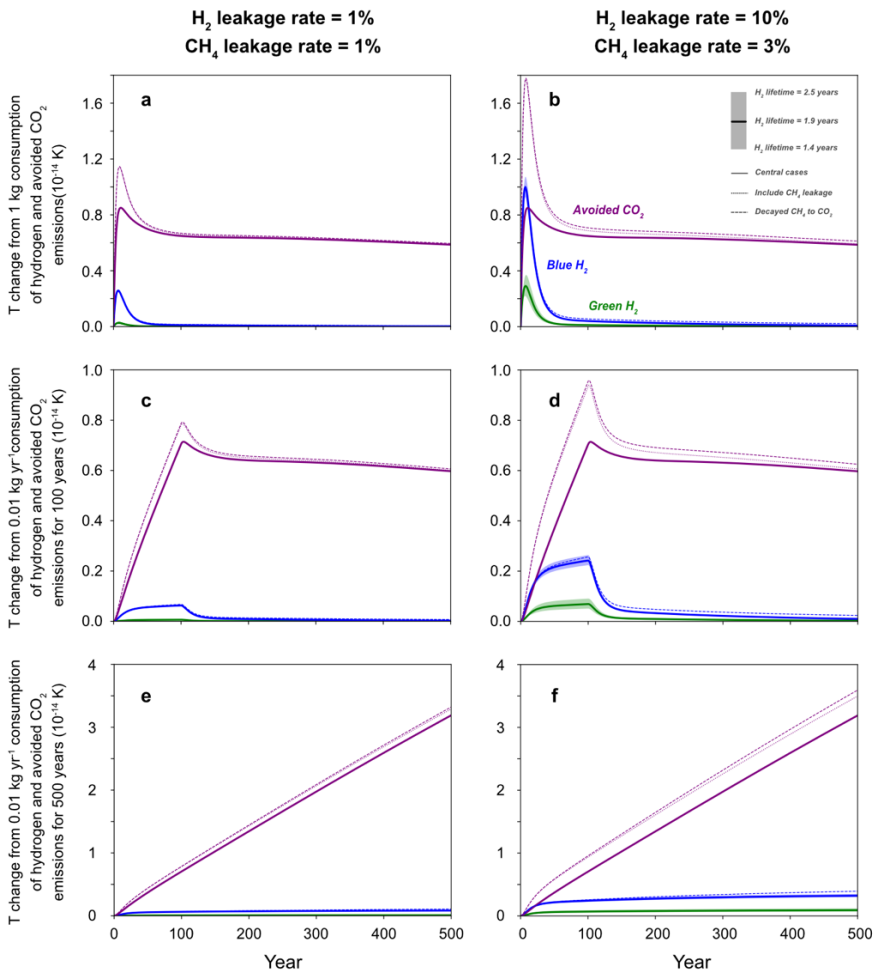
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100 **Figure S6.** Factors influencing radiative forcing. Same as Figure 2, but considering radiative
 101 forcing changes associated with different parameters. These include: considering different
 102 hydrogen lifetimes (1.4 years or 2.5 years), include methane leakage for the avoided CO₂
 103 emissions, and considering the conversion of the decayed methane to CO₂. The last two factors
 104 have substantial impacts on the climate impact of fossil fuels and the net climate impact of clean
 105 hydrogen, whereas hydrogen lifetime shows only a minor impact on our results.



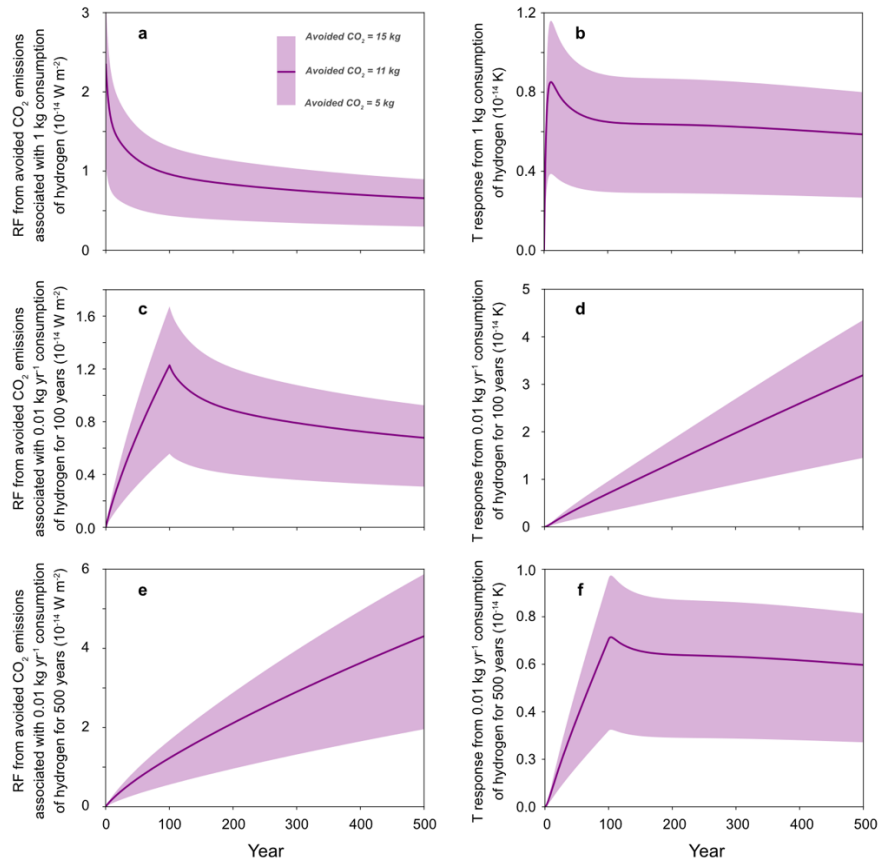
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107 **Figure S7.** Factors influencing temperature response. Same as Figure S6, but considering
 108 temperature instead of radiative forcing.



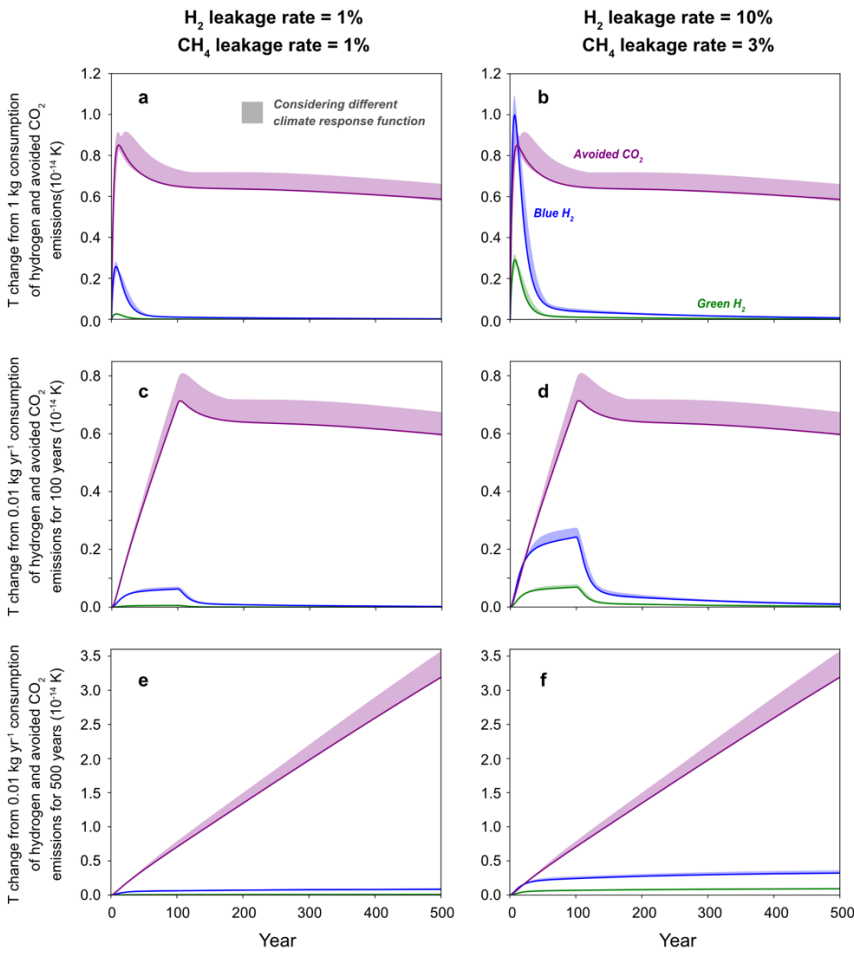
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110 **Figure S8.** Uncertainty of avoided CO₂ amount. Radiative forcing and global mean temperature
 111 response under different assumptions of the avoided CO₂ amount per kg hydrogen consumption.
 112 Solid line represents results for our central case (11 kg) and shaded area represents results under
 113 alternative assumptions (i.e., 5 kg and 15 kg).



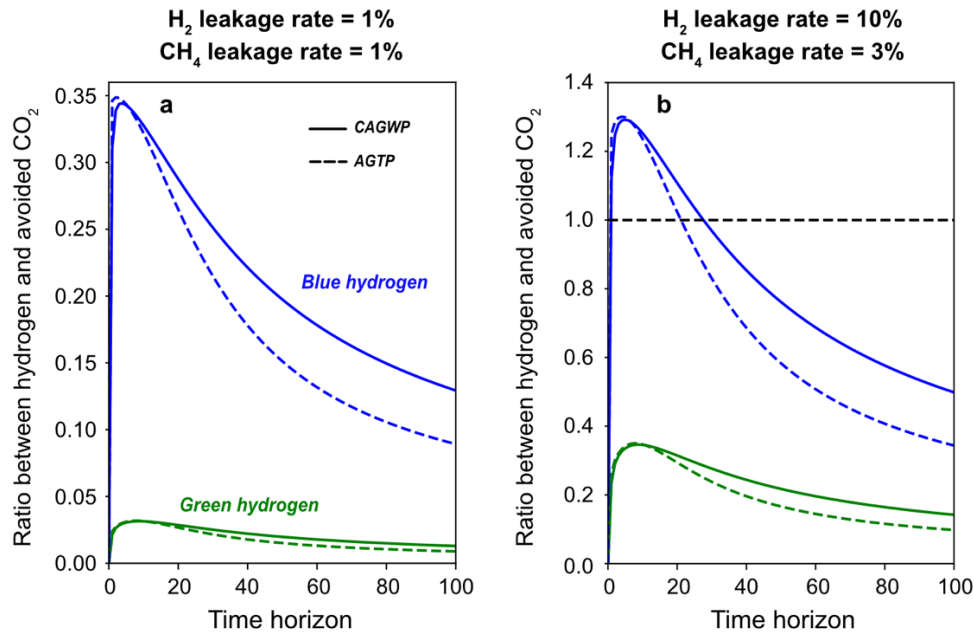
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115 **Figure S9.** Uncertainty of the climate response function. Same as Figure 3, but combining the
116 radiative forcing equations with different climate response functions.



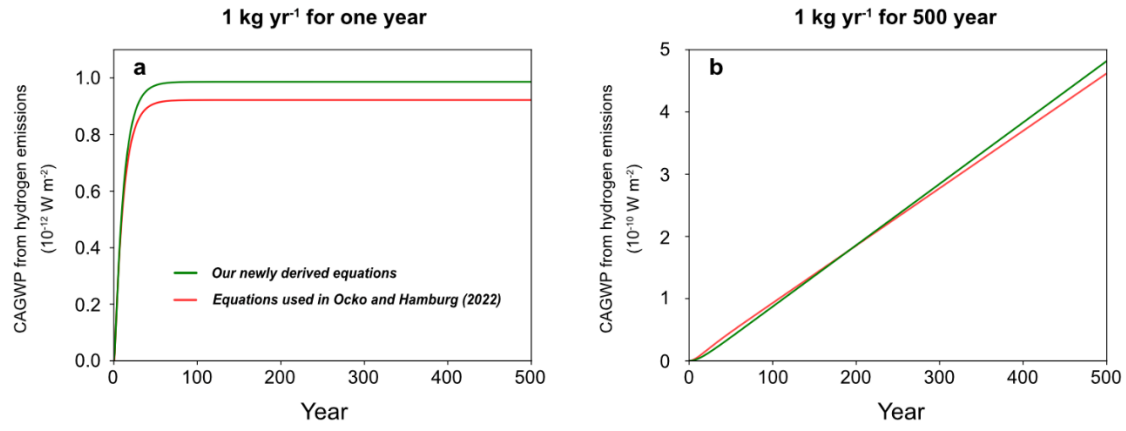
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118 **Figure S10.** Comparisons of different metrics. Ratios of the time-integrated relative radiative
 119 forcing (CGWP) and ratios of the global mean temperature response (GTP) are compared under
 120 continuous emission scenarios. The solid lines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



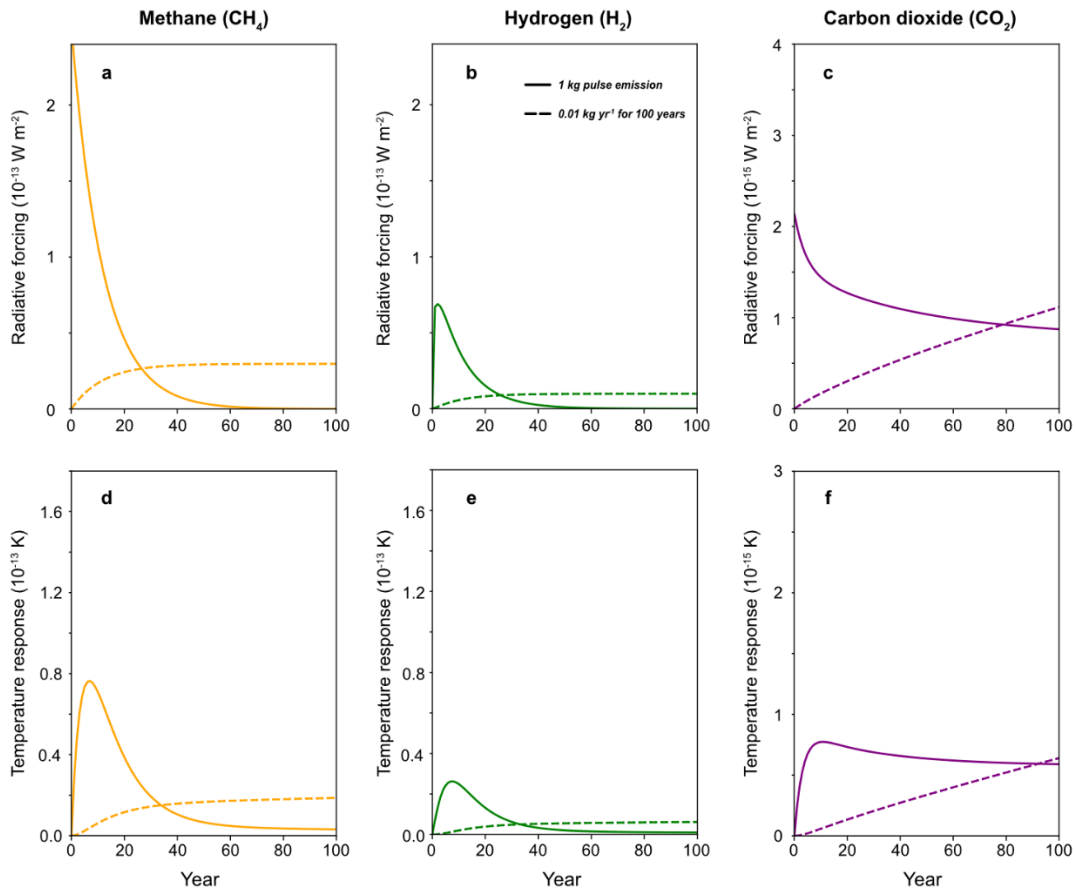
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124 **Figure S11.** Comparisons between results from our newly derived equations and those used in
125 Ocko and Hamburg (2022). Time-integrated radiative forcing (CAGWP defined in this analysis)
126 from one-year emission and continuous emission scenarios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



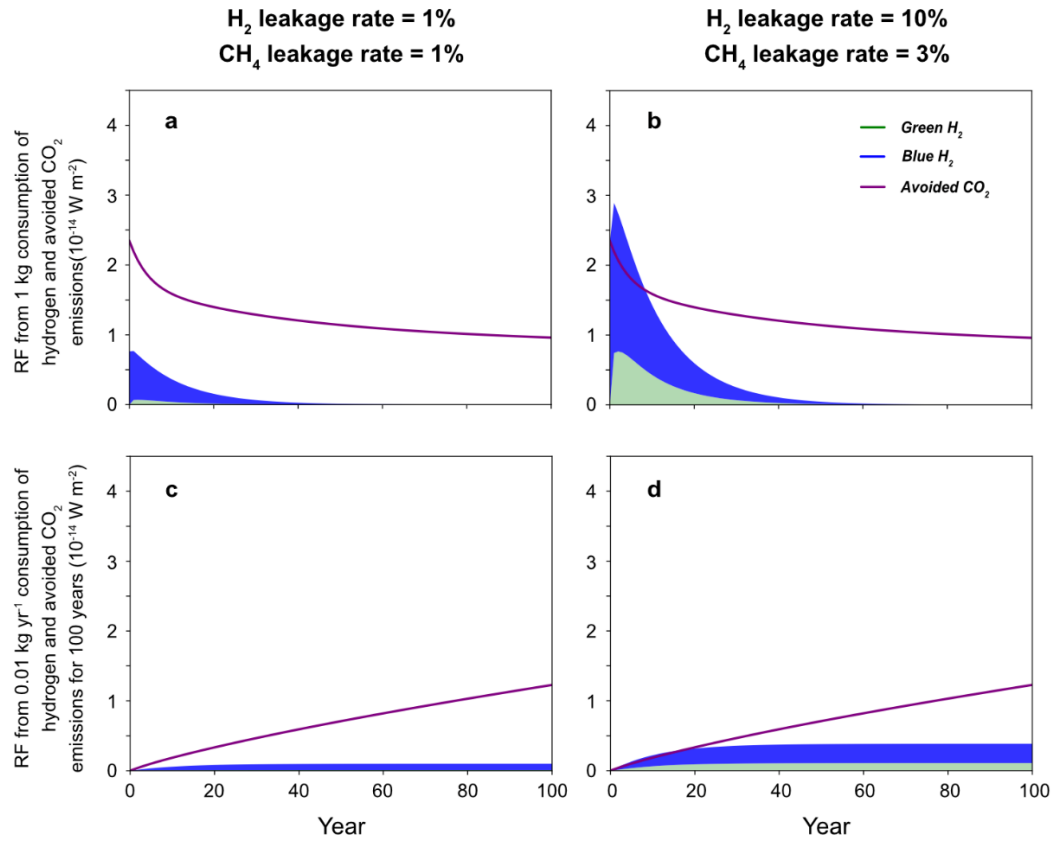
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128 **Figure S12.** Similar to Figure 1 but for 100-year timescale.



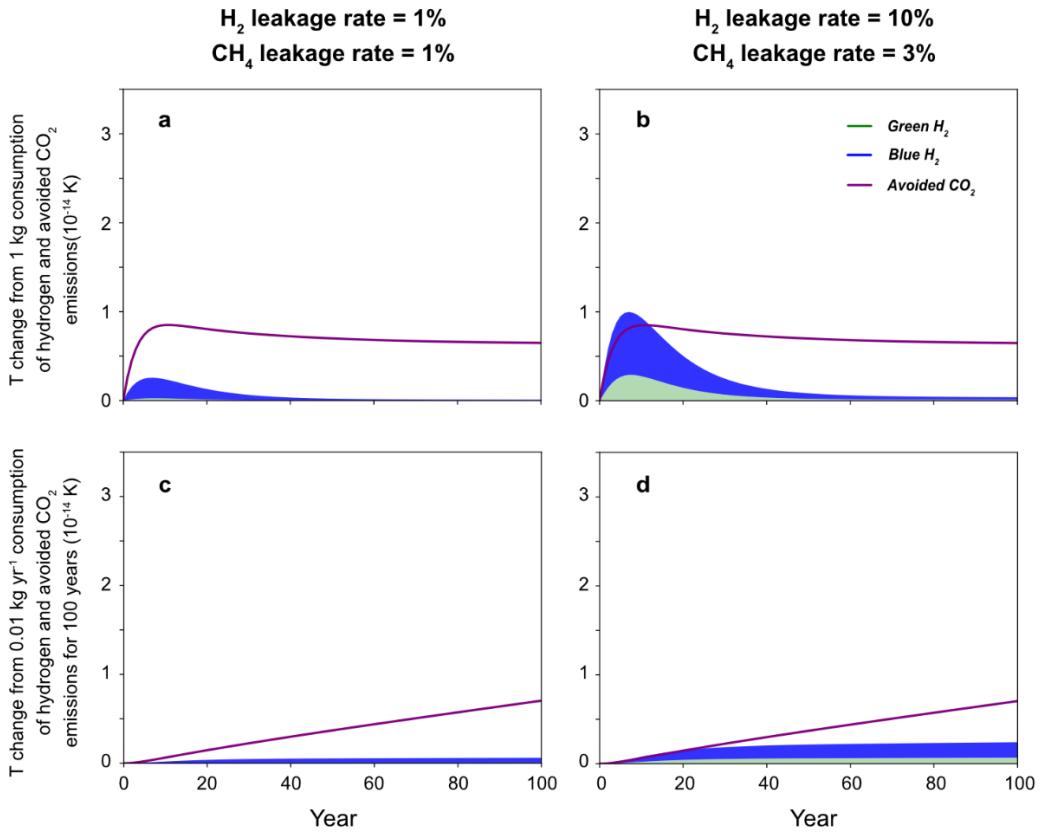
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130 **Figure S13.** Similar to Figure 2 but for 100-year timescale.



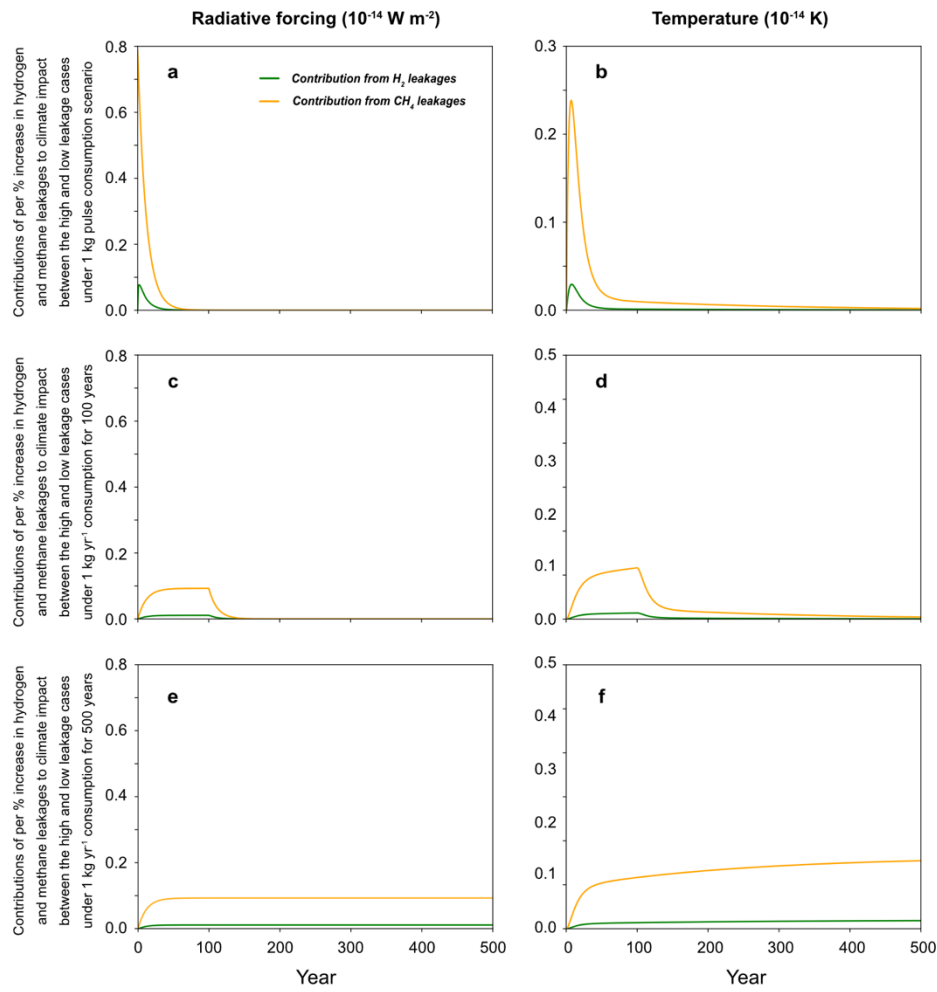
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132 **Figure S14.** Similar to Figure 3 but for 100-year timescale.



133

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



136

137 **Table S1.** Radiative forcing, absolute global warming potential (AGWP), absolute global
 138 temperature change potential (AGTP), and their ratios for 1 kg pulse emission of hydrogen,
 139 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

140

141 **Table S2.** Radiative forcing, absolute global warming potential (CAGWP), absolute global
 142 temperature change potential (AGTP), and their ratios for 0.01 kg yr⁻¹ continuous emissions of
 143 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

144

145 **Table S3.** Radiative forcing, absolute global warming potential (AGWP), absolute global
 146 temperature change potential (AGTP), and their ratios for 1 kg consumption of green and blue
 147 hydrogen, and corresponding avoided CO₂ emissions under different timescales (i.e., 20, 100,
 148 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

149

150 **Table S4.** Radiative forcing, absolute global warming potential (CAGWP), absolute global
 151 temperature change potential (AGTP), and their ratios for 0.01 kg yr⁻¹ continuous consumption
 152 of green and blue hydrogen, and corresponding avoided CO₂ emission under different timescales
 153 (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

154

155 **Reference**

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

158 Warwick, Griffiths, Keeble, Archibald, and Pyle: Atmospheric implications of increased
159 Hydrogen use, AvailableAt: <https://assets>, 2022.