

“What If” Explorer

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Background

The “What If” Explorer was designed to help people understand

1. The complexities of emissions pathways
2. How various factors influence the expected temperature increase in 2100
3. The effort required for various temperature mitigation strategies
4. The likely costs associated with an emissions pathway
5. The tradeoffs among reasonable emissions pathways
6. What a reasonable emissions pathway might be for planning purposes

The “What If” Explorer uses a “scenario emulator” to project the temperature increase from 2025 for either a “CO2 Only” emissions pathway or a pathway that includes the contribution to warming from other greenhouse gas emissions, aerosols, albedo changes, etc. By examining the output from two climate models (The IPCC’s AR6¹ and En-ROADs²) formulas were developed to

1. Calculate the expected increase in atmospheric CO2 based on CO2 emissions³
2. Calculate the expected radiative forcing from atmospheric CO2⁴
3. Calculate the expected radiative forcing from other greenhouse gas emissions, aerosols, albedo changes, etc.⁵
4. Calculate the temperature increase from the total radiative forcing⁶

Figure 1 shows that the emulator’s calculations for the temperature increase in 2100 track very closely to that from the IPCC’s AR6 data.

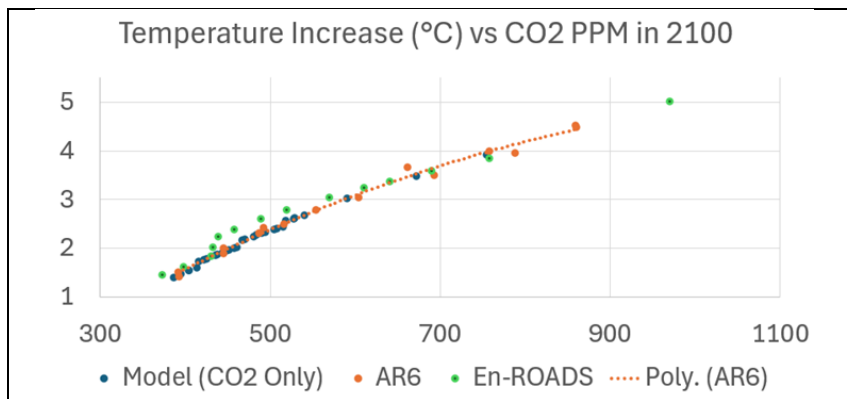


Figure 1. Temperature Increase vs. CO2 PPM in 2100

How the “What if” Explorer Works

Figure 2 shows a screenshot of “landing page” for the “What If” Explorer. The system starts by loading the data for “CO2 Only” emissions pathway that results roughly in a 2.0°C temperature increase.

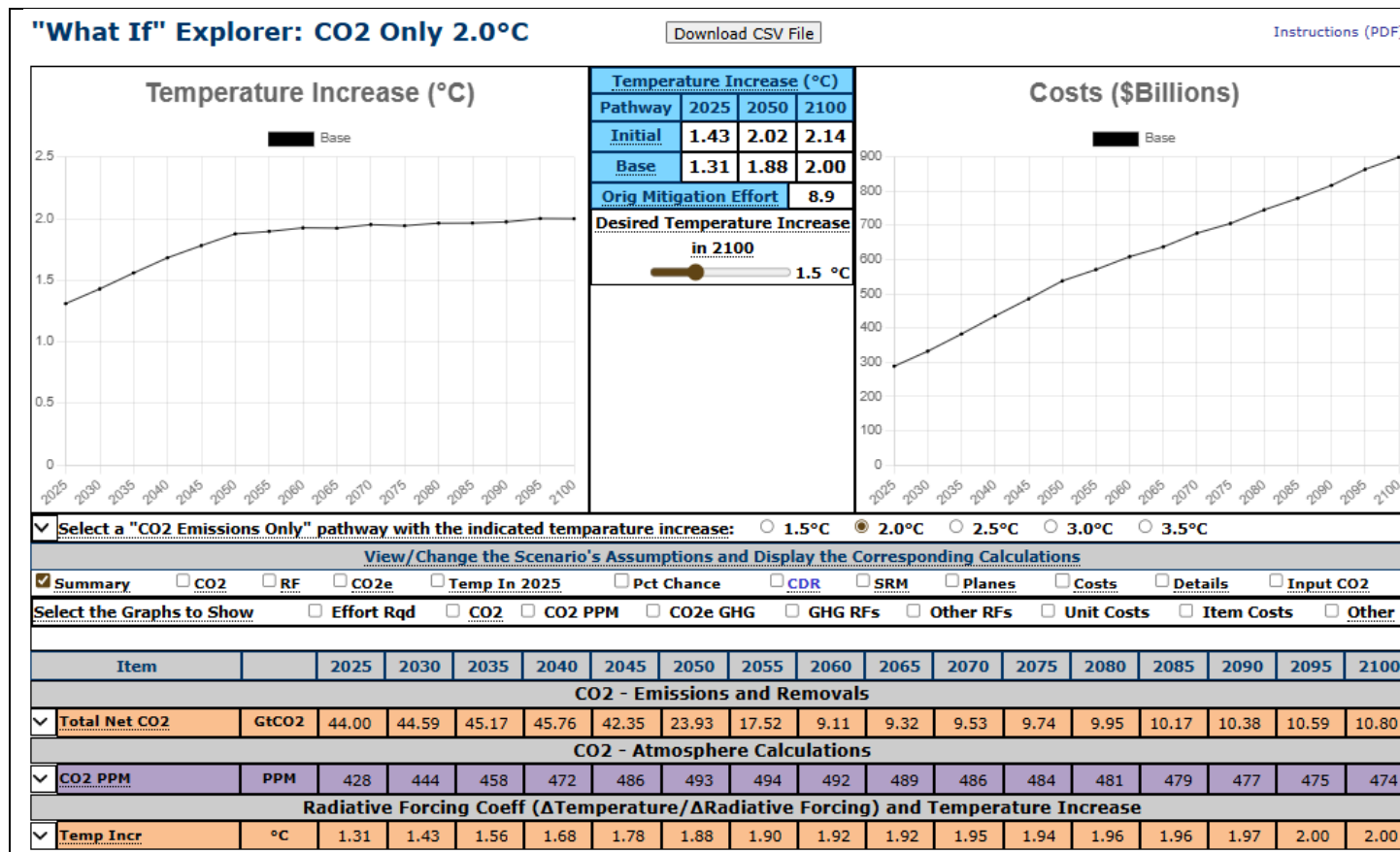


Figure 2. Screenshot of “landing page” for the “What If” Explorer

The text on the Web page that has a “dotted underline” has a corresponding “tool tip”. Simply “mouseover” the text to “popup” the “tool tip”.

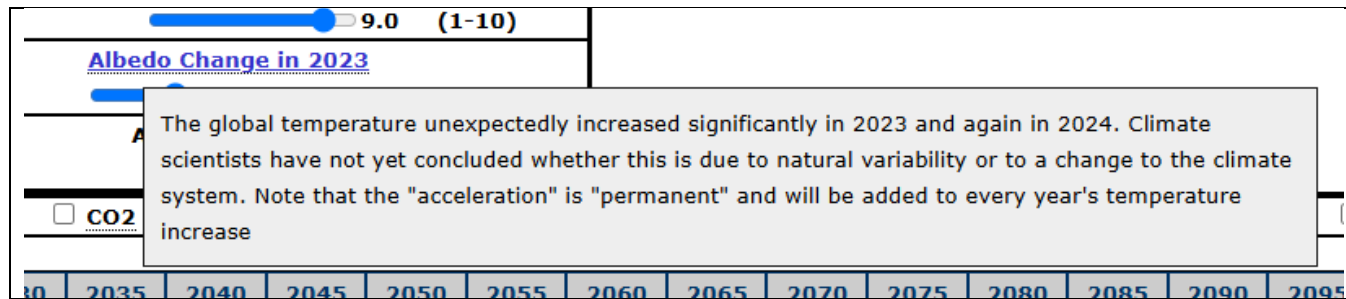


Figure 3.

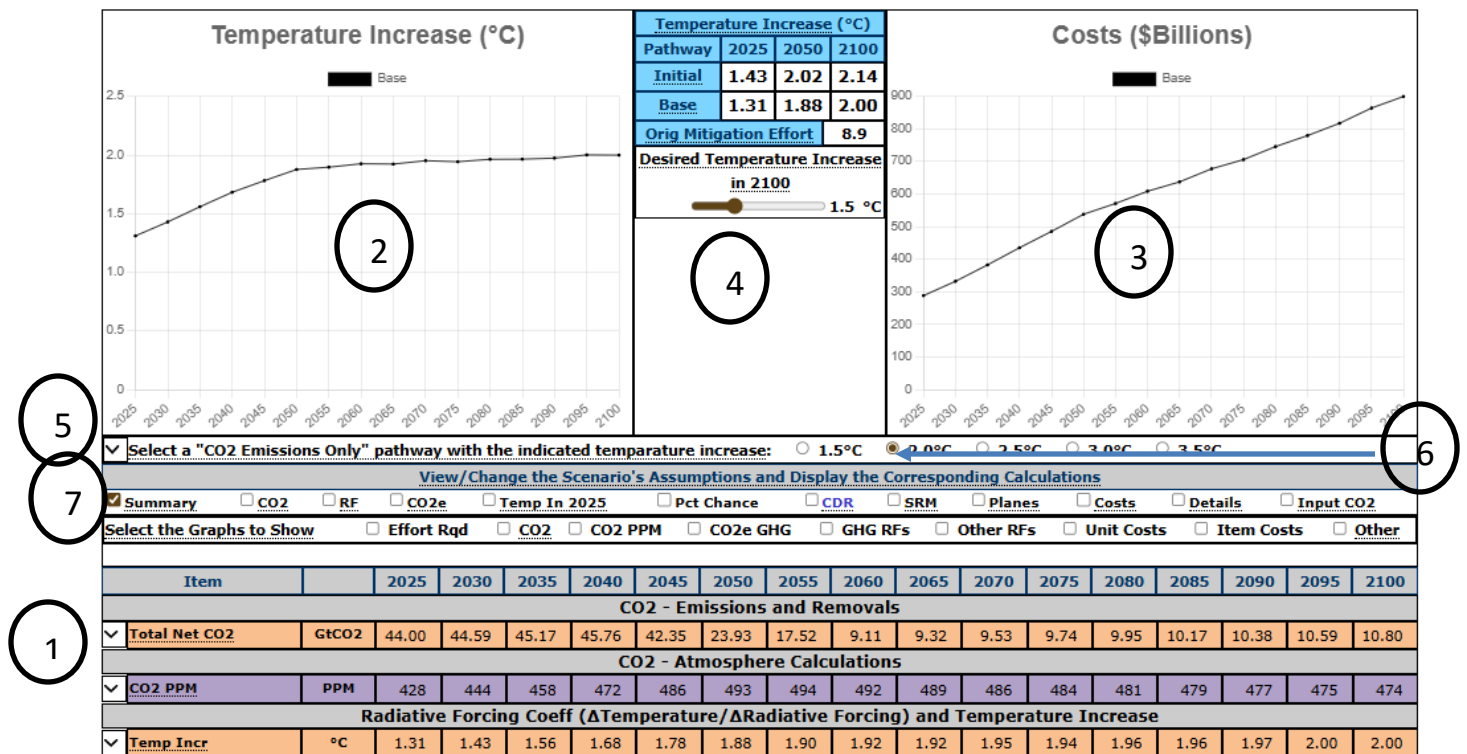


Figure 4. Annotated screenshot of "landing page" for the "What If" Explorer

1. The data for the net CO2 emissions, atmospheric CO2, and expected temperature increase are shown at the bottom of the Web form.
2. A graph of the temperature increase
3. A graph of the expected costs (initially due to sea level rise and disasters – more detail below)
4. "Dashboard"
 - a. Temperate Increases in 2025, 2050, and 2100 for the pathway.
 - i. "Scenario" - (not shown above) If the selected pathway/scenario includes a temperature increase (as it does for AR6 and En-ROADs scenarios), the corresponding values will be displayed.
 - ii. "Initial" - The values calculated by the emulator (using formulas derived from the AR6 data) based on the scenario's CO2 emissions and non-CO2 radiative forcing (if the latter is included in the scenario). Note that most of the AR6 scenarios projected a temperature increase of about 1.43°C in 2025
 - iii. Base – In order to adjust the pathway's calculations to more closely match the actual "starting values" (see Table 1), the Explorer sets the 2025 temperature increase to 1.31°C and adjusts the 2100 temperature increase accordingly. (The user can change this value – see below.) Note that the 0.2°C temperature spike in 2023 brings the 2025 temperature increase to about 1.5°C, which is much closer to the actual temperature increase.

	Projected
CO2 PPM	428
Total RF	3.13
Average temperature increase	1.31°C ⁸

Table 1. 2025 “Starting Values”

- b. As the user “explores” the pathway, “adjusted” temperature increases will also be shown.
 - c. “Orig Mitigation Effort”
 - i. The effort to mitigate the greenhouse gases other than CO2 has a large impact on the expected temperature increase. The “mitigation effort” is a value between 1 (minimum effort) and 10 (maximum effort). An “original mitigation effort” for the “2.0°C” pathway was set to 9 based on the expected atmospheric concentration of CO2 in 2100. The user can adjust this value (see below).
 - d. “Desired Temperature Increase in 2100”
 - i. The “Explorer” allows the user to specify several “intervention” techniques (see below) to cool the planet – the value set here is used to limit the temperature increase in 2100.
5. “Select an Emissions Pathway”
- a. The user can explore another emissions pathway by clicking one of the radio buttons to the right.
 - b. Options and additional pathways to be explored can be selected after clicking the “down arrow” to the left of the “Select” text
 - c. The “Validate” and “Show Scenario’s” check boxes are used to display additional data that shows how closely the Emulator’s calculations match the corresponding scenario data values (see below)

Select a "CO2 Emissions Only" pathway with the indicated temperature increase: <input type="radio"/> 1.5°C <input checked="" type="radio"/> 2.0°C <input type="radio"/> 2.5°C <input type="radio"/> 3.0°C <input type="radio"/> 3.5°C	
Validate: <input type="checkbox"/> CO2 to CO2 PPM <input type="checkbox"/> CO2 PPM to Temp Incr	Show Scenario's: <input type="checkbox"/> CO2 PPM <input type="checkbox"/> Temp Incr
IPCC AR6 Scenarios (Average of multiple scenarios with the specified temperature increase)	
<input type="radio"/> 1.5°C <input checked="" type="radio"/> 2.0°C <input type="radio"/> 2.5°C <input type="radio"/> 3.0°C <input type="radio"/> 3.5°C <input type="radio"/> 4.0°C <input type="radio"/> 4.5°C	
En-ROADS Scenarios (Sample scenarios with the specified temperature increase)	
<input type="radio"/> 1.4°C <input type="radio"/> 1.6°C <input type="radio"/> 1.8°C <input type="radio"/> 2.0°C <input type="radio"/> 2.2°C <input type="radio"/> 2.4°C <input type="radio"/> 2.6°C <input type="radio"/> 2.8°C	
<input type="radio"/> 3.0°C <input type="radio"/> 3.2°C <input type="radio"/> 3.4°C <input type="radio"/> 3.6°C <input type="radio"/> 3.8°C <input type="radio"/> 4.0°C	
Shared Socioeconomic Pathways (SSPs)	
<input type="radio"/> SSP1-19 <input type="radio"/> SSP1-26 <input type="radio"/> SSP2-45 <input type="radio"/> SSP3-Baseline <input type="radio"/> SSP4-34 <input type="radio"/> SSP4-60 <input type="radio"/> SSP5-34 <input type="radio"/> SSP5-Baseline	

# Years	Simplified Net-Zero Emission Scenarios			
	2025	2030	2035	2040
25	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
30	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
35	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
40	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 5. Options and Additional Pathways to Explore (more detail below)

6. “Select the Calculations to be Displayed”
 - a. Click a checkbox below the text to display the corresponding calculations
 - b. If the “Summary” box is checked, the net CO2 emissions, atmospheric CO2, and expected temperature increase will be shown at the bottom of the Web form.
 - c. The function of the other checkboxes is explained below
7. “Select the Graphs to Show”
 - a. Click a checkbox below the text to display the corresponding graphs
 - b. If the “CO2” box is checked, the following graphs will be displayed:

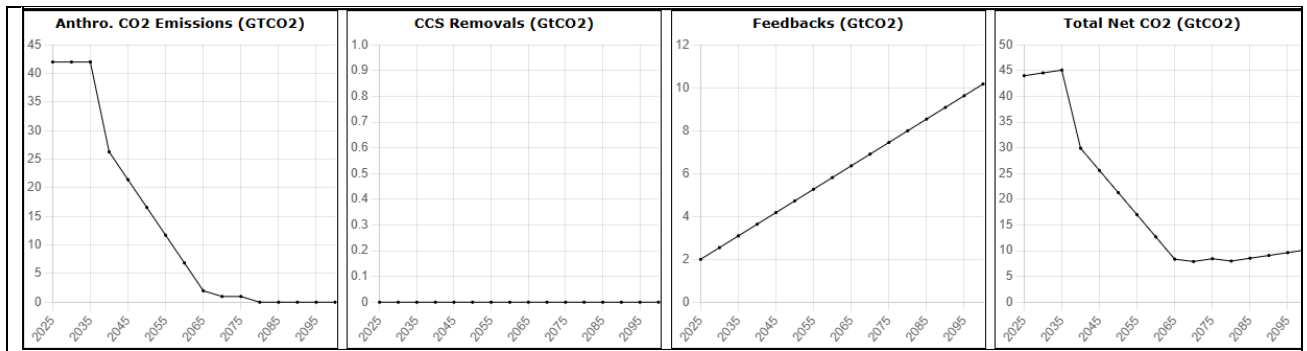


Figure 6. "CO2 Graphs"

c. The function of the other checkboxes is explained below

8. The "Validate" checkboxes

- a. "CO2 to CO2 PPM" (for the En-ROADS's scenarios, which were used to develop a formula to project the amount of CO2 added to the atmosphere based on CO2 emissions).

Figure 7 is a screenshot showing the Emulator's calculations for amount of CO2 added to the atmosphere based on CO2 emissions for an En-ROADS 2.6°C scenario. Notes:

1. The scenario includes a small amount of carbon capture and storage (CO2 removed during industrial processes)
2. The Emulator excludes emissions from carbon feedbacks
3. The airborne fractions are roughly at current values though 2030 and then decline slightly as CO2 emissions are reduced
4. The calculated CO2 PPM is very close to the scenario's PPM
5. The calculations for the amount of CO2 added to the atmosphere based on CO2 emissions are very close to the scenario's PPM only for the 1.6°C though 2.8°C scenarios, which are the main CO2 emission pathways that it makes sense to consider

☒ Select a "CO2 Emissions Only" pathway with the indicated temperature increase: ☐ 1.5°C ☐ 2.0°C ☐ 2.5°C ☐ 3.0°C ☐ 3.5°C ☐ 4.0°C

Validate: ☒ CO2 to CO2 PPM ☐ CO2 PPM to Temp Incr | Show Scenario's: ☒ CO2 PPM ☐ Temp Incr

IPCC AR6 Scenarios (Average of multiple scenarios with the specified temperature increase)
☐ 1.5°C ☐ 2.0°C ☐ 2.5°C ☐ 3.0°C ☐ 3.5°C ☐ 4.0°C

En-ROADS Scenarios (Sample scenarios with the specified temperature increase)
☐ 1.4°C ☐ 1.6°C ☐ 1.8°C ☐ 2.0°C ☐ 2.2°C ☐ 2.4°C ☒ 2.6°C ☐ 3.0°C ☐ 3.2°C ☐ 3.4°C ☐ 3.6°C ☐ 3.8°C ☐ 4.0°C

Shared Socioeconomic Pathways (SSPs)
☐ SSP1-19 ☐ SSP1-26 ☐ SSP2-45 ☐ SSP3-Baseline ☐ SSP4-34 ☐ SSP4-60 ☐ SSP5-34 ☐ SSP5-45

Select the calculations to be displayed:
☒ Summary ☐ CO2 ☐ RF ☐ CO2e ☐ Temp In 2025 ☐ Pct Chance ☐ CDR ☐ GHG

Select the Graphs to Show: ☐ Effort Rqd ☐ CO2 ☐ CO2 PPM ☐ CO2e GHG ☐ GHG RF

Item		2025	2030	2035	2040	2045	2050	2055	2060
CO2 - Emissions and Removals									
<input checked="" type="checkbox"/> Gross Anthro. CO2	GtCO2	43	41	36	32	29	27	25	24
<input checked="" type="checkbox"/> Crb Cpt&Str (CCS)	GtCO2	0.00	0.00	-0.01	-0.05	-0.11	-0.15	-0.18	-0.20
<input checked="" type="checkbox"/> CDR (DAC, etc.)	GtCO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<input checked="" type="checkbox"/> Carbon Rmvs (Scen)	GtCO2	0.00	0.00	-0.01	-0.05	-0.11	-0.15	-0.18	-0.20
<input checked="" type="checkbox"/> Cum Carb Rem CO2	GtCO2	0	0	0	0	-1	-1	-2	-3
<input checked="" type="checkbox"/> Total Anthro CO2	GtCO2	43.45	41.32	36.47	31.52	28.56	26.68	25.16	24.12
<input checked="" type="checkbox"/> Cum Anthro. CO2	GtCO2	43	255	450	620	770	908	1038	1161
<input checked="" type="checkbox"/> Carbon Feedbacks	GtCO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<input checked="" type="checkbox"/> Cum Feedback CO2	GtCO2	0	0	0	0	0	0	0	0
<input checked="" type="checkbox"/> Total Net CO2	GtCO2	43.45	41.32	36.47	31.52	28.56	26.68	25.16	24.12
<input checked="" type="checkbox"/> Cumulative CO2	GtCO2	43	255	450	620	770	908	1038	1161
CO2 - Atmosphere Calculations									
<input checked="" type="checkbox"/> CO2 To Atmosph	GtCO2	19.45	17.75	13.02	8.68	6.42	5.17	4.27	3.76
<input checked="" type="checkbox"/> PPM Added/Yr	PPM	2.49	2.27	1.67	1.11	0.82	0.66	0.55	0.48
<input checked="" type="checkbox"/> CO2 PPM (Scenario)	PPM	422	434	443	450	454	458	461	464
<input checked="" type="checkbox"/> CO2 PPM	PPM	422	434	444	451	455	459	462	465
<input checked="" type="checkbox"/> Ocean & Land Sink	GtCO2	24.00	23.57	23.45	22.84	22.14	21.51	20.89	20.36
<input checked="" type="checkbox"/> Airborne Fraction	Percent	45	43	36	28	22	19	17	16

Figure 7

- b. "CO2 PPM to Temp Increase (for the AR6 scenarios, which were used to develop formulas to project the "CO2 RF" based on" CO2 PPM" and the ratio of the temperature increase to the total radiative forcing)

Figure 8 is a screenshot showing the Emulator's calculations for "CO2 RF" based on" CO2 PPM", the ratio of the temperature increase to the total radiative forcing, and the corresponding temperature increase.

Select a "CO2 Emissions Only" pathway with the indicated temperature increase: <input type="radio"/> 1.5°C <input checked="" type="radio"/> 2.0°C <input type="radio"/> 2.5°C <input type="radio"/> 3.0°C <input type="radio"/> 3.5°C																						
Validate: <input type="checkbox"/> CO2 to CO2 PPM <input checked="" type="checkbox"/> CO2 PPM to Temp Incr		Show Scenario's: <input checked="" type="checkbox"/> CO2 PPM <input checked="" type="checkbox"/> Temp Incr		Simplified Net-Zero Emission Scenarios																		
IPCC AR6 Scenarios (Average of multiple scenarios with the specified temperature increase)																	Peak Year of CO2 Emissions					
<input type="radio"/> 1.5°C <input checked="" type="radio"/> 2.0°C <input type="radio"/> 2.5°C <input type="radio"/> 3.0°C <input type="radio"/> 3.5°C <input type="radio"/> 4.0°C <input type="radio"/> 4.5°C														# Years			2025	2030	2035	2040	2045	2050
✓	CO2 PPM (Scenario)	PPM	427	439	449	457	463	468	472	473	474	473	472	469	466	462	458	454				
✓	CO2 (Scenario)	W/m-2	2.43	2.57	2.69	2.79	2.86	2.91	2.94	2.96	2.96	2.95	2.93	2.89	2.85	2.80	2.75	2.70				
✓	CO2	W/m-2	2.43	2.57	2.69	2.79	2.86	2.91	2.94	2.96	2.96	2.95	2.92	2.90	2.84	2.79	2.73	2.68				
✓	Rad Frc Coef (ΔT/ΔR)		0.45	0.47	0.48	0.50	0.51	0.52	0.53	0.54	0.54	0.55	0.56	0.56	0.58	0.58	0.59	0.59				
✓	Temp Incr (Scenario)	°C	1.44	1.54	1.66	1.76	1.83	1.90	1.94	1.98	1.99	2.02	2.02	2.03	2.03	2.02	2.02	2.00				
✓	Temp Incr (Initial)	°C	1.43	1.54	1.66	1.75	1.83	1.90	1.93	1.98	1.99	2.02	2.02	2.03	2.02	2.01	2.01	1.99				

Figure 8

9. The "Show Scenario's" checkboxes

- a. "CO2 PPM" – if the scenario includes the CO2 PPM, the corresponding values will be displayed
- b. "Temp Incr" - if the scenario includes the temperature increase, the corresponding values will be displayed
- c.

10. About CO2 pathways

- a. When selecting (or creating) a scenario to explore, keep in mind that, even given the progress in renewable energy, CO2 emissions will not likely decline significantly 15-25 years^{9A-E}. Because there are so many variables, it would probably be best to use a scenario with a CO2 pathway similar to those that major organizations expect. For example, CO2 emissions (from fossil fuels) for the IEA's "Stated Policies" and MIT's "Current Trends" show very little decline even before 2050 (see Figure 9). And the IEA's "Announced Pledges" scenario only shows a modest decrease after 2040. Also, the "Emissions Pathways to 2100" figure produced by Climate Action Tracker^{9F}, which evaluates each country's "nationally determined contribution" shows that emissions might not even change much this century.
- b. When discussing policies needed to limit global warming this century it might be helpful to create three scenarios:
 - i. Emissions unchanged through 2100
 - ii. Emissions reach zero in 2100
 - iii. Emissions remain constant for 15 years and then decrease to zero in 2070
- c. The three scenarios would give policy makers a better understanding of the possible impacts and costs associated with likely climate change

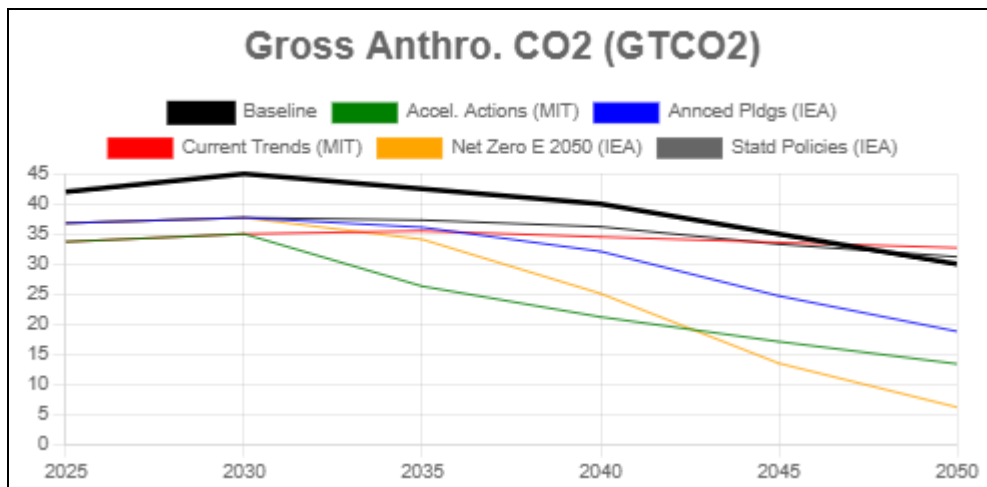


Figure 9.

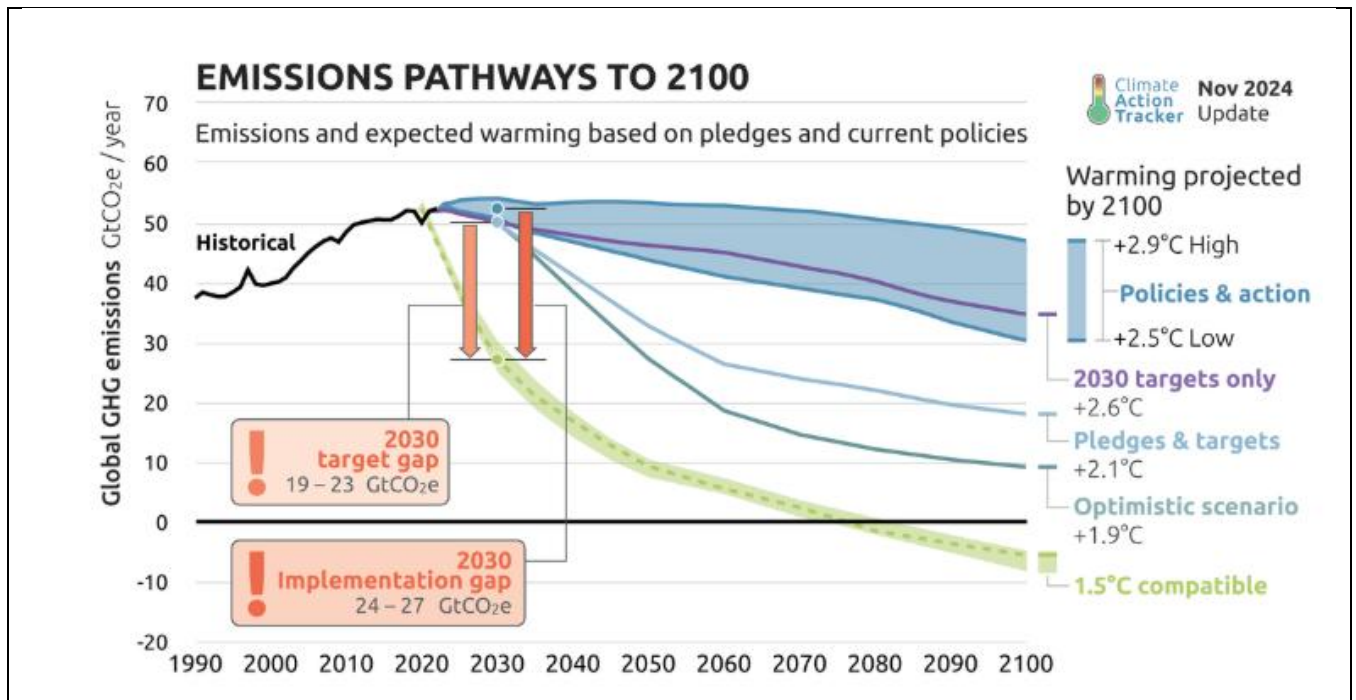


Figure 10.

“What if” Analysis

There are a lot of factors that influence the global temperature increase. This section will explain how the Explorer can be used to analyze the influence of some of the major factors. The heading for each section below indicates which of the “Select the Calculations to be Displayed” was checked.

1. Summary

Displays the data for the net CO₂ emissions, atmospheric CO₂, and expected temperature increase. Click the “Details” checkbox to see the detailed calculations

Item		2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CO₂ - Emissions and Removals																	
✓ Gross Anthro. CO ₂	GtCO ₂	42	42	42	26	21	17	12	7	2	1	1	0	0	0	0	0
✓ Crb Cpt&Str (CCS)	GtCO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
✓ CDR (DAC, etc.)	GtCO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
✓ Carbon Rmvs (Scen)	GtCO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
✓ Cum Carb Rem CO ₂	GtCO ₂	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
✓ CO ₂ Adjustment	GtCO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
✓ Total Anthro CO ₂	GtCO ₂	42.00	42.00	42.00	26.29	21.43	16.57	11.71	6.86	2.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00
✓ Cum Anthro. CO ₂	GtCO ₂	42	252	462	633	752	847	918	964	986	994	999	1001	1001	1001	1001	1001
✓ Carbon Feedbacks	GtCO ₂	2.00	2.54	3.09	3.63	4.18	4.72	5.27	5.81	6.36	6.90	7.45	7.99	8.54	9.08	9.63	10.17
✓ Cum Feedback CO ₂	GtCO ₂	2	13	27	44	64	86	111	139	169	202	238	277	318	362	409	458
✓ Total Net CO ₂	GtCO ₂	44.00	44.54	45.09	29.92	25.61	21.30	16.98	12.67	8.36	7.90	8.45	7.99	8.54	9.08	9.63	10.17
✓ Cumulative CO ₂	GtCO ₂	44	265	489	677	816	933	1029	1103	1155	1196	1237	1278	1319	1363	1410	1460
CO₂ - Atmosphere Calculations																	
✓ CO ₂ To Atmosph	GtCO ₂	27.57	21.33	22.23	7.29	4.07	1.23	-1.24	-3.34	-5.07	-4.99	-4.50	-4.42	-3.93	-3.43	-2.92	-2.41
✓ PPM Added/Yr	PPM	3.53	2.73	2.85	0.93	0.52	0.16	-0.16	-0.43	-0.65	-0.64	-0.58	-0.57	-0.50	-0.44	-0.37	-0.31
✓ CO ₂ PPM	PPM	428	444	458	467	471	473	473	471	468	465	462	459	457	454	452	450
✓ Ocean & Land Sink	GtCO ₂	16.43	23.21	22.86	22.63	21.53	20.07	18.23	16.01	13.43	12.90	12.95	12.42	12.47	12.51	12.55	12.58
✓ Airborne Fraction	Percent	63	48	49	24	16	6	0	0	0	0	0	0	0	0	0	0
Radiative Forcing Coeff (ΔTemperature/ΔRadiative Forcing) and Temperature Increase																	
✓ Rad Frc Coef (ΔT/ΔR)		0.42	0.43	0.44	0.45	0.46	0.47	0.49	0.50	0.51	0.52	0.53	0.54	0.56	0.57	0.58	0.59
✓ Temp Incr	°C	1.31	1.41	1.56	1.64	1.71	1.76	1.78	1.81	1.81	1.85	1.84	1.89	1.88	1.92	1.94	1.97

Figure 11.

2. CO₂

In addition to CO₂, there are two major factors that contribute to net CO₂ emissions – emissions from carbon feedbacks and carbon capture and sequestration where the CO₂ is emitted.

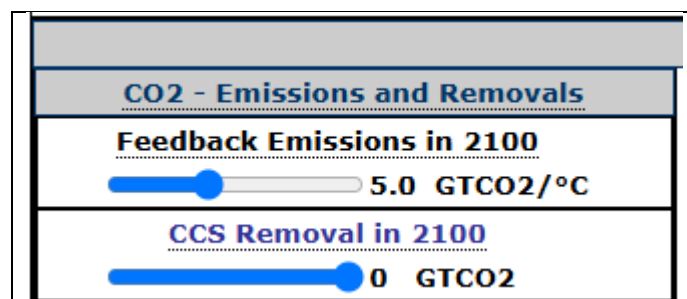


Figure 12.

a. Emissions from Carbon feedbacks

Since carbon feedbacks will increase as the temperature increases, a simple way to estimate carbon feedback emissions is to assume that they will increase by a certain amount per degree of warming. The IPCC AR6 scenarios assume that feedbacks from permafrost will be about half of the total and will be between 0.5 and 1.0 GtCO₂ per degree C¹⁰.

By plotting the actual anthropogenic CO₂ emissions against the amount expected based on the average airborne fraction and recent atmospheric CO₂ concentrations, it appears that carbon feedbacks are now at about 4 GTCO₂/year¹¹ (and this is likely an underestimate).

Carbon feedback emissions in 2100 will likely be between 3 and 10 GTCO₂e per degree C^{12A}.

The current Explorer assumes that carbon feedback emissions were 2 GTCO₂ in 2025 (this may be adjusted in future releases). The default value for carbon feedback emissions in 2100 is 5 GTCO₂/°C. The user can adjust this by using the “Feedback Emissions in 2100” slider. Note that when a value is selected new lines will be added to the two graphs at the top of the Web page to show the “adjusted” temperature increase and costs.

Amazon and Tropical forests have changed from CO₂ sinks to CO₂ sources^{12B}.

b. Carbon capture and storage (CCS)

The AR6 scenarios use up to 20 GTCO₂ of carbon capture and storage for atmospheric removal of CO₂ (see Figure 13). The “CCS Removal in 2100” slider provides an easy way for the user to specify the CCS quantity in 2100. Note that when a value is selected new lines will be added to the two graphs at the top of the Web page (see Figure 14). Note the decrease in the expected temperature increase and the increase in costs (the latter will be discussed in more detail below).

A realistic (and optimistic) estimate for CCS implementation in 2050 is 2-3 GTCO₂/year (perhaps 5 GTCO₂/year in 2100) at a cost of \$60-\$200/ton¹³. CCS is unlikely to be implemented at scale due to a convergence of technical, economic, policy, and societal barriers¹⁴.

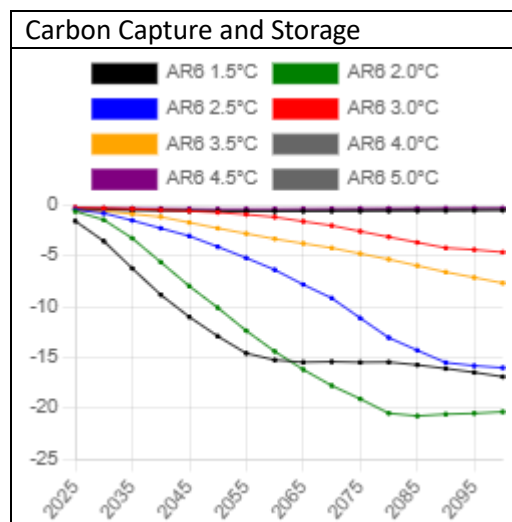


Figure 13.

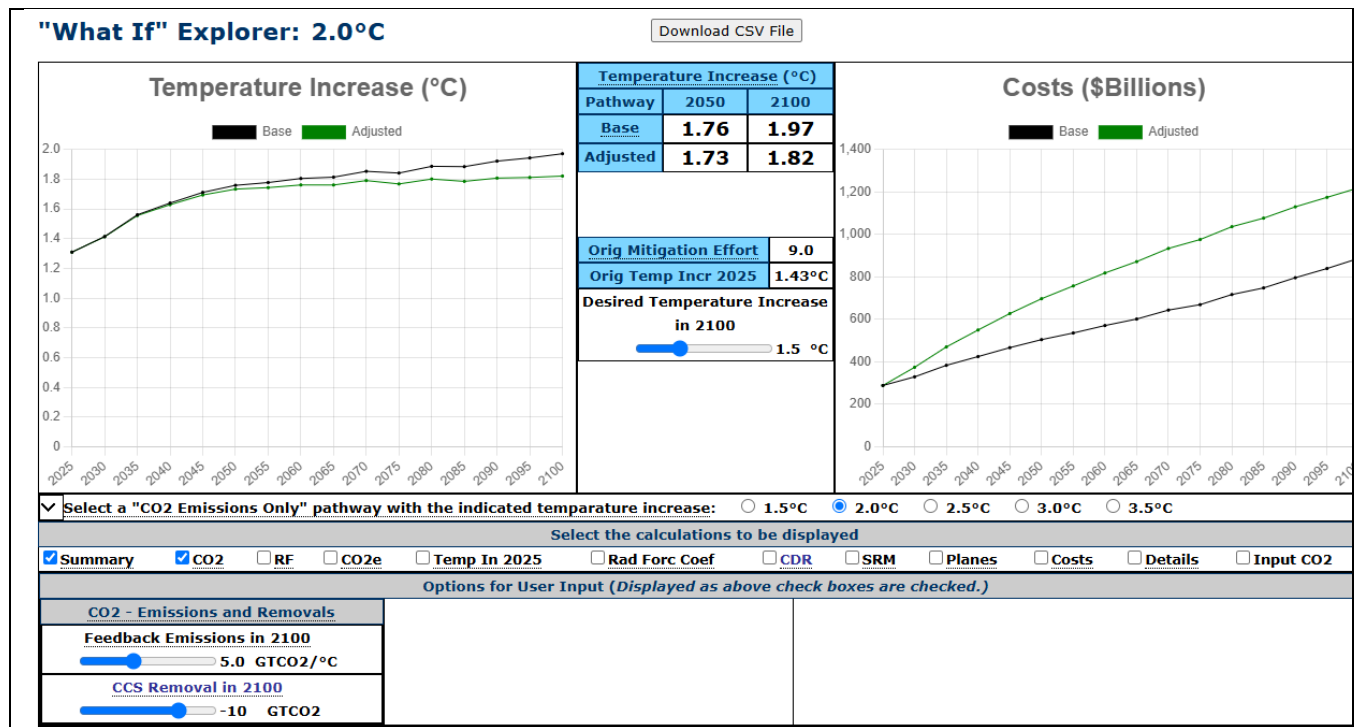


Figure 14.

3. RF

Displays the radiative forcing of the six major categories of radiative forcing (Figure 15) and "sliders" that the user can use to change the mitigation effort and the albedo

✓ CO2	W/m-2	2.38	2.57	2.73	2.83	2.86	2.87	2.85	2.82	2.77	2.71	2.66	2.61	2.55	2.50	2.45	2.40
✓ CH4	W/m-2	0.57	0.56	0.54	0.52	0.51	0.49	0.48	0.47	0.45	0.44	0.44	0.43	0.42	0.41	0.41	0.41
✓ N2O	W/m-2	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.32	0.33	0.33	0.34	0.35	0.36
✓ Other	W/m-2	0.42	0.32	0.33	0.26	0.23	0.19	0.15	0.14	0.10	0.12	0.08	0.11	0.07	0.09	0.10	0.10
✓ Total GHG	W/m-2	3.60	3.69	3.85	3.87	3.88	3.84	3.77	3.72	3.63	3.60	3.49	3.47	3.38	3.35	3.31	3.26
✓ Aerosol	W/m-2	-0.92	-0.83	-0.74	-0.66	-0.59	-0.53	-0.50	-0.46	-0.44	-0.41	-0.39	-0.36	-0.33	-0.31	-0.29	-0.27
✓ Other Non GHGs	W/m-2	0.46	0.44	0.42	0.39	0.37	0.34	0.32	0.29	0.27	0.25	0.22	0.20	0.17	0.15	0.12	0.09
✓ Total RF wo Albedo	W/m-2	3.14	3.30	3.53	3.61	3.66	3.65	3.59	3.54	3.46	3.44	3.32	3.31	3.22	3.19	3.13	3.09

Figure 15

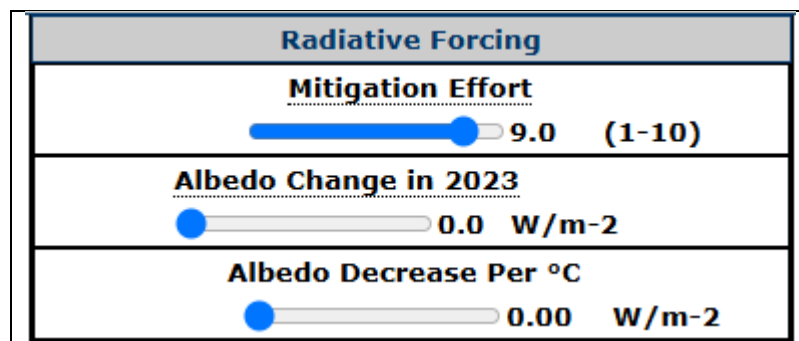


Figure 16.

a. Mitigation Effort

The amount of effort taken to mitigate non-CO2 emissions and aerosols, on a scale of 1 (minimal) to 10 (maximum). The model calculates an appropriate value based on the pathways CO2 radiative forcing value. The model first calculates how close the CO2 radiative forcing value is to those of the AR6 1.5°C

and AR6 4.5°C scenarios. That “closeness” is then used to determine the various non-CO2 radiative forcing pathways for the scenario. For example, if a pathway’s CO2 radiative forcing was 5.7 W/m-2 (halfway between the of AR6 1.5°C and AR6 4.5°C values), the CH4 radiative forcing would also be halfway between the of AR6 1.5°C and AR6 4.5°C values for CH4 or about 0.60 W/m-2 per year

That “closeness” is then used to determine the various non-CO2 radiative forcing pathways for the scenario.

b. Albedo Change in 2023

The global temperature unexpectedly increased significantly in 2023 and again in 2024. Climate scientists have not yet concluded whether this is due to natural variability or to a change to the climate system. Note that the "acceleration" is "permanent" and will be added to every year's temperature increase

c. Albedo Decrease Per °C

The albedo might decrease more rapidly than expected due to changes with cloud reflectivity, thus increasing the equivalent radiative forcing. The value specified here is the additional radiative forcing that might result.

The Earth warmed at a rate of about 0.20°C per decade from 1970-2010¹⁵ and has been warming at a rate of about 0.27°C per decade since. If that rate continues for the next 25 years the temperature increase in 2050 would be about 2.0°C (and a warming rate of 0.36 °C per decade would result in a temperature increase of about 2.2°C in 2050).

4. CO2e

Displays the CO2 equivalent of the greenhouse gases

✓ CO2	GtCO2	44.00	44.54	45.09	29.92	25.61	21.30	16.98	12.67	8.36	7.90	8.45	7.99	8.54	9.08	9.63	10.17
✓ CH4	Total CO2 emissions (listed above but included in this list all the CO2e factors)										24	8.11	7.99	7.85	7.73	7.56	7.42
✓ N2O											63	5.84	5.88	6.08	6.12	6.30	6.55
✓ Total Other CO2e	GtCO2e	7.69	5.84	6.00	4.68	4.27	3.50	2.72	2.48	1.85	2.26	1.38	1.97	1.30	1.73	1.75	1.77
✓ Total GHG	GtCO2e	66.33	64.98	65.63	48.93	44.17	39.05	33.74	29.10	24.08	24.11	23.70	23.89	23.69	24.68	25.30	25.91
✓ Aerosol	GtCO2e	-16.84	-15.21	-13.54	-12.02	-10.80	-9.64	-9.15	-8.50	-7.99	-7.46	-7.10	-6.55	-6.04	-5.65	-5.29	-4.90
✓ Other Non GHG RF	CO2e	8.42	8.05	7.67	7.12	6.73	6.20	5.82	5.27	4.88	4.51	3.97	3.58	3.03	2.66	2.11	1.73
✓ Albedo CO2e	GtCO2e	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
✓ Total	GtCO2e	57.44	60.37	64.88	66.42	67.60	67.79	66.89	66.35	65.17	65.11	63.30	63.48	62.09	62.04	61.48	61.16

Figure 17

5. Temp In 2025

Allows the user to specify the temperature increase for 2025. This defaults to 1.31°C, as that is the expected average temperature increase based on historical data. Note that all of the AR6 and IPCC scenarios have temperature increases above 1.4°C for 2025.

Temperature Increase in 2025

1.31 (°C)

Figure 18

6. Pct. of Runs Meeting Target

The increase in the global temperature depends on the total radiative forcing from greenhouse gases, aerosols, albedo, etc. By examining data from the IPCC's AR6 report, it appears that the ratio of the temperature change in a specific year to the radiative forcing change in the same year ($\Delta T/\Delta RF$) depends on both the total radiative forcing and the probability of limiting global warming to a specific temperature threshold (like 1.5°C or 2°C above pre-industrial levels) - see Table 2. (The Emulator refers to the ratio $\Delta T/\Delta RF$ as the "radiative forcing coefficient" or "RFC".) The "radiative forcing coefficient" is basically an indicator of the "climate sensitivity" in a given year to the total radiative forcing. (Note that only three values can be selected – 50, 67, and 84. These correspond the main three IPCC AR6 alternatives.)

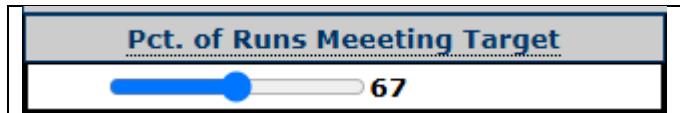


Figure 19

Percent Chance	Total Radiative Forcing in the Year 2100														
	3.50	3.75	4.00	4.25	4.50	4.75	5.00	5.25	5.50	5.75	6.00	6.25	6.50	6.75	7.00
50	0.56	0.55	0.55	0.55	0.55	0.54	0.54	0.54	0.54	0.54	0.53	0.53	0.53	0.53	0.53
67	0.59	0.59	0.58	0.58	0.58	0.58	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56	0.56
84	0.64	0.63	0.63	0.63	0.62	0.62	0.62	0.62	0.61	0.61	0.61	0.60	0.60	0.60	0.60
	"Radiative Forcing Coefficient" (RFC) in 2100														
	1.95	2.08	2.21	2.33	2.46	2.58	2.71	2.83	2.95	3.08	3.20	3.32	3.45	3.57	3.69
50	1.95	2.08	2.21	2.33	2.46	2.58	2.71	2.83	2.95	3.08	3.20	3.32	3.45	3.57	3.69
67	2.07	2.20	2.34	2.47	2.60	2.73	2.86	2.99	3.12	3.25	3.38	3.51	3.64	3.77	3.90
84	2.23	2.38	2.53	2.67	2.81	2.95	3.09	3.23	3.37	3.51	3.64	3.78	3.91	4.05	4.18
Temperature Increase in 2100															

Table 2.

7. CDR

Allows the user to specify the year that carbon dioxide removal (CDR) will start ('Start Year') and peak ('Peak Year'). The model computes the expected "carbon budget" for 2025-2100 based on the temperature increase in 2100 and then subtracts this from the cumulative emissions for 2025-2100 and calculates the "peak amount" of CDR required to meet the "carbon budget".

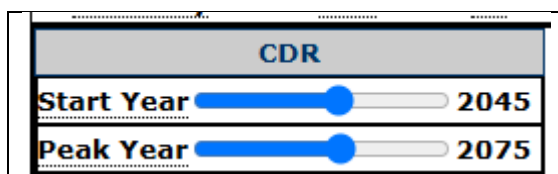


Figure 20

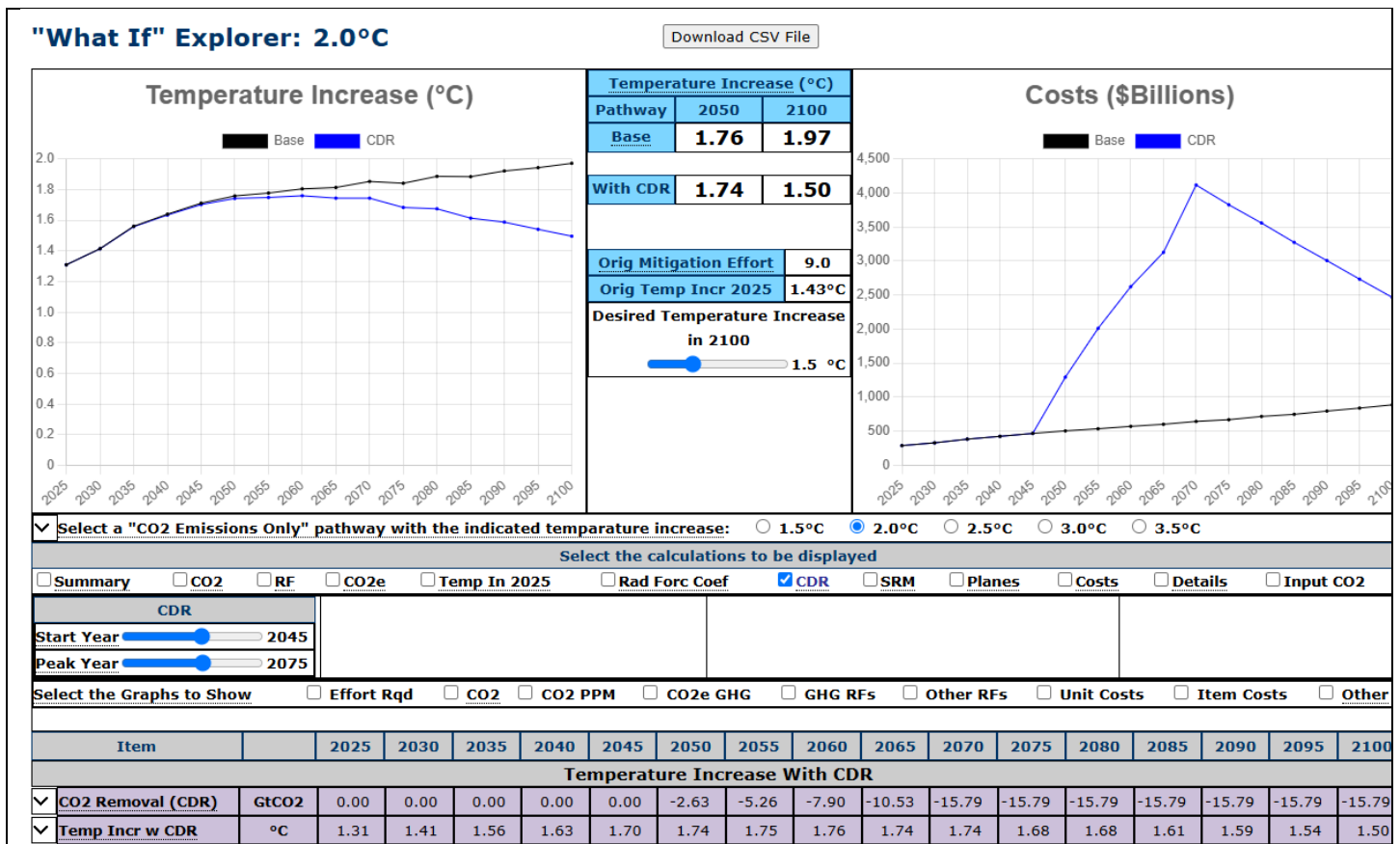


Figure 21

Click the "Effort Required" checkbox to display a graph of the CDR requirement.

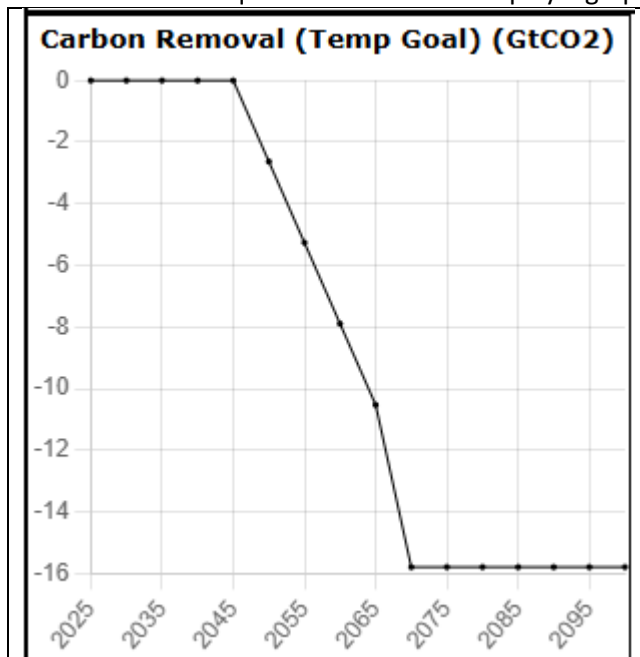


Figure 22

8. **SRM** (Solar Radiation Management)

Use the sliders to specify the year that SRM starts and the amount of radiative forcing being reduced each year.

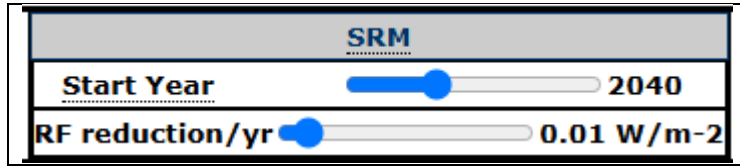


Figure 23

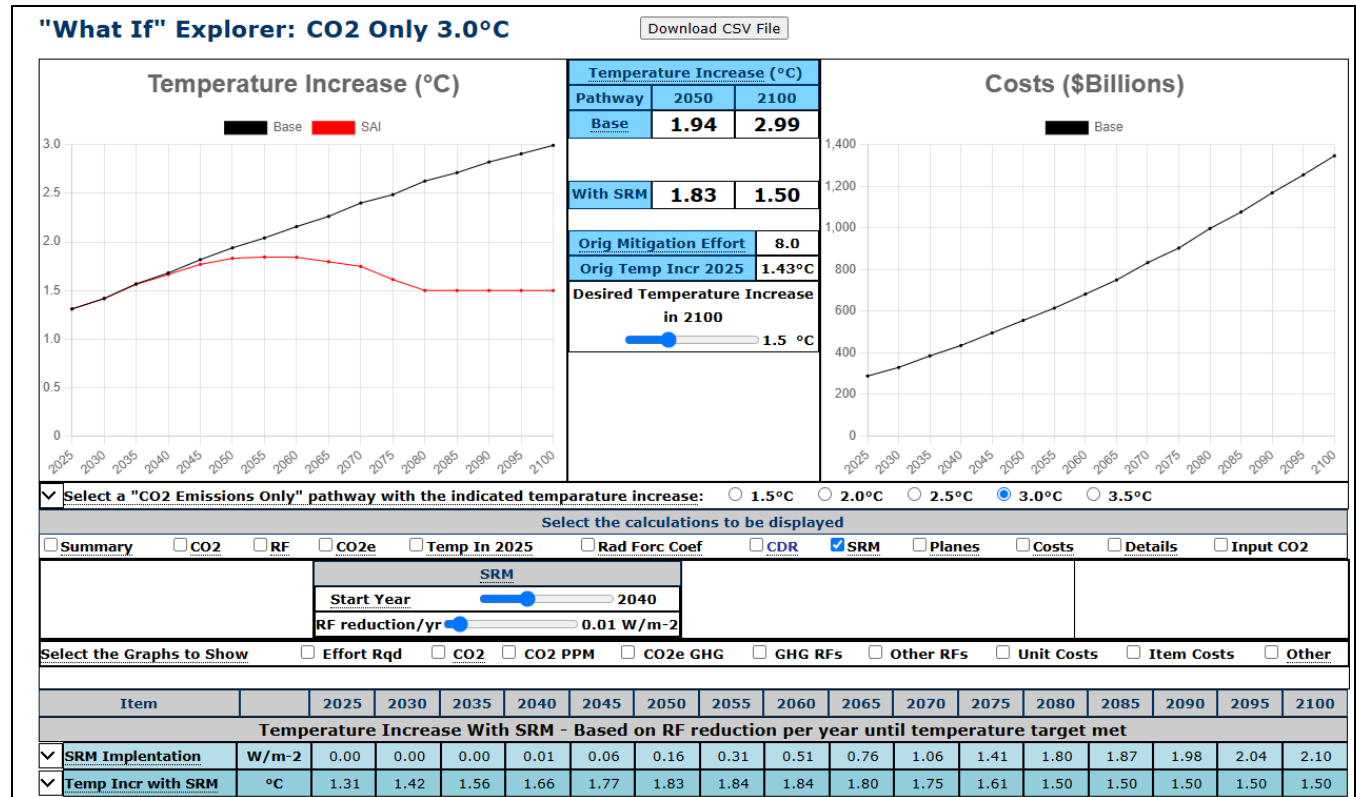


Figure 24

Click the "Effort Required" checkbox to display a graph of the SRM requirement.

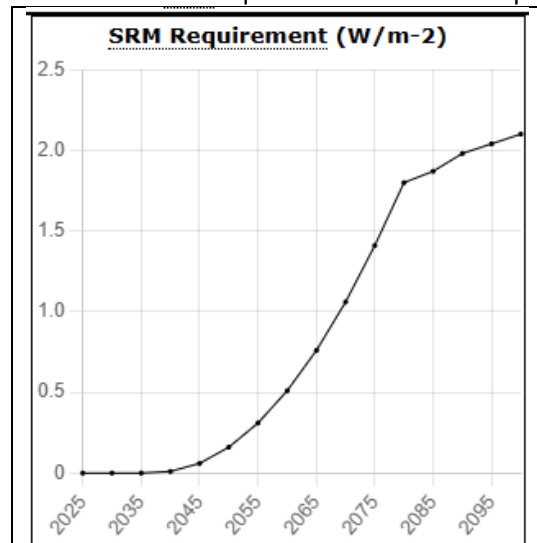


Figure 25

9. Planes

Allows the user to specify when airplanes are first used for stratospheric aerosol injection (SAI) and the number of planes to be added each year to limit the temperature increase to the desired amount. A good value for the cooling per plane is 0.003°C¹⁶.

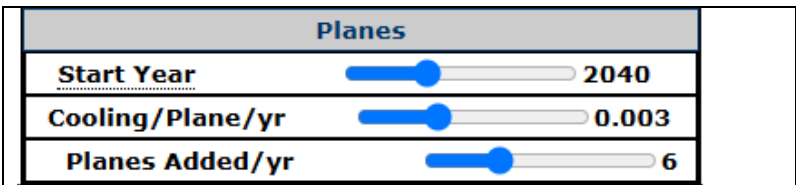


Figure 26

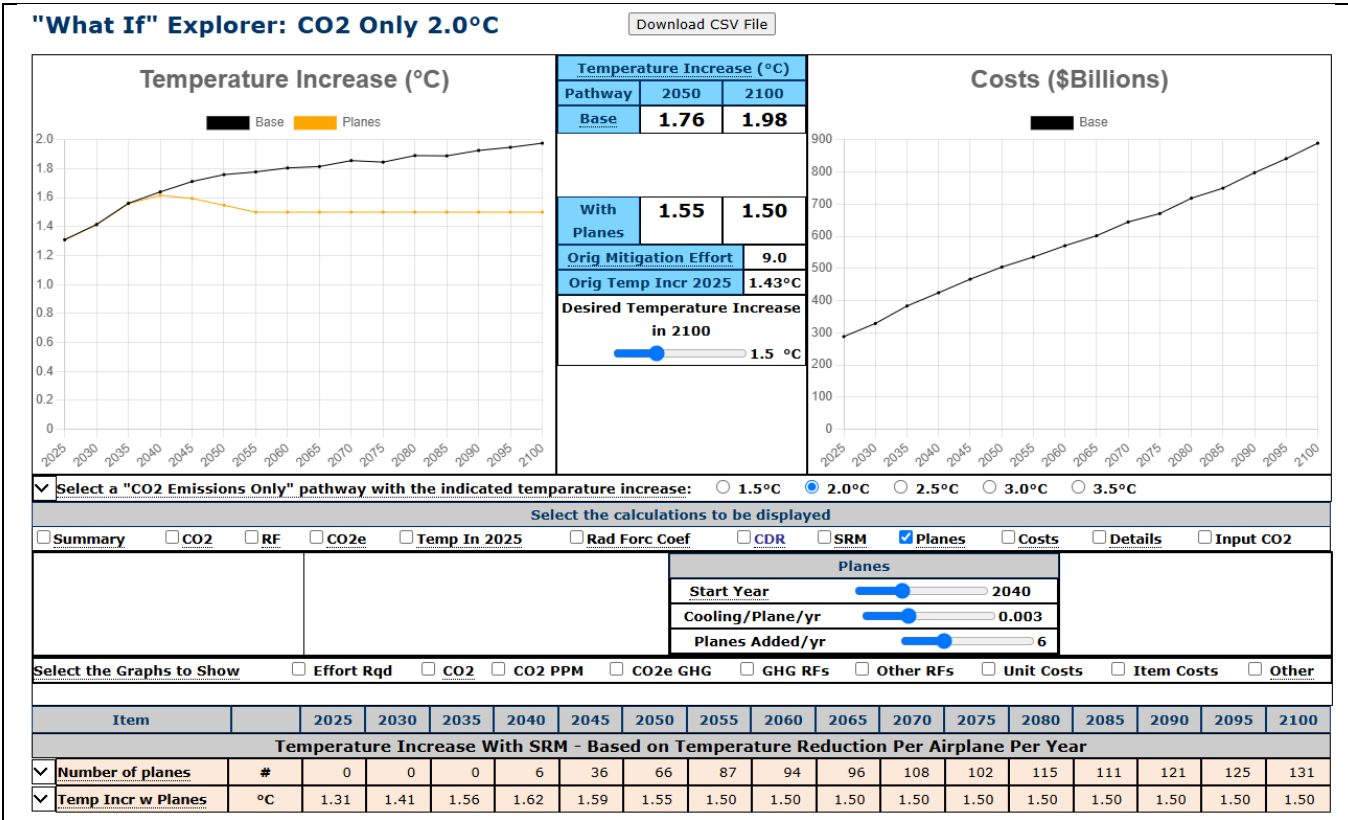


Figure 27

Click the “Effort Required” checkbox to display a graph of the “Number of Planes” requirement.

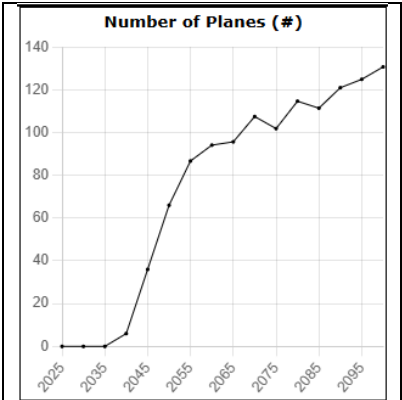


Figure 28

Costs

Use the sliders to specify the “item costs” to be used to calculate the total costs for the scenario. Click on a “Cost Item” to see details for reasonable values.










Costs		
Cost Item	Cost in 2025 (\$B)	Cost in 2100 (\$B)
CCS (\$/Ton)	 70	 40
CDR (\$/Ton)	 400	 100
Disasters (\$B/°C)	 150	 200
SLR (\$B/Foot)	 100	 250
		Sea Level Rise Rise in 2100  1 Feet/°C

Figure 29

For example:

Costs per Item																	
✓ SLR Cost Per Foot	\$B/Ft	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
✓ CCS, BECCS, etc	\$/Ton	70	68	66	64	62	60	58	56	54	52	50	48	46	44	42	40
✓ Carbon Removal	\$/Ton	400	380	360	340	320	300	280	260	240	220	200	180	160	140	120	100
✓ Disaster Costs Per °C	\$B/°C	150	153	157	160	163	167	170	173	177	180	183	187	190	193	197	200
Cost Calculations (With Albedo and CDR)																	
✓ Carbon Rmvl (Total)	GtCO2	0.00	0.00	0.00	0.00	0.00	2.68	5.35	8.03	10.70	16.05	16.05	16.05	16.05	16.05	16.05	16.05
✓ Sea Level Rise Costs	\$B/Yr	92	112	139	162	187	211	234	258	281	311	333	366	391	426	459	495
✓ CCS, BECCS, etc	\$B/Yr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
✓ Carbon Removal	\$B/Yr	0	0	0	0	0	803	1498	2087	2568	3531	3210	2889	2568	2247	1926	1605
✓ Disaster Costs	\$B/Yr	197	217	245	263	280	293	303	313	321	335	339	354	360	373	384	396
✓ Total Costs	\$B/Yr	288	329	383	425	467	1307	2034	2658	3171	4177	3882	3609	3319	3047	2769	2496

Figure 30

10. Details

The “default” is to just display “summary” information. Click on the “Details” checkbox to show/hide the detailed calculations

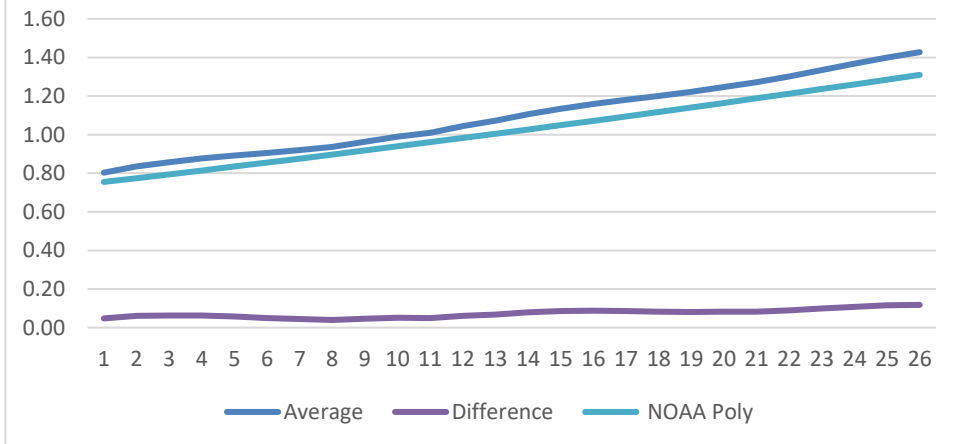
11. Input CO2

Allows the user to adjust the CO2 emissions

Item		2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
✓ Gross Anthro. CO2	GTCO2	42	42	42	26	21	17	12	7	3	2	1					

Figure 31

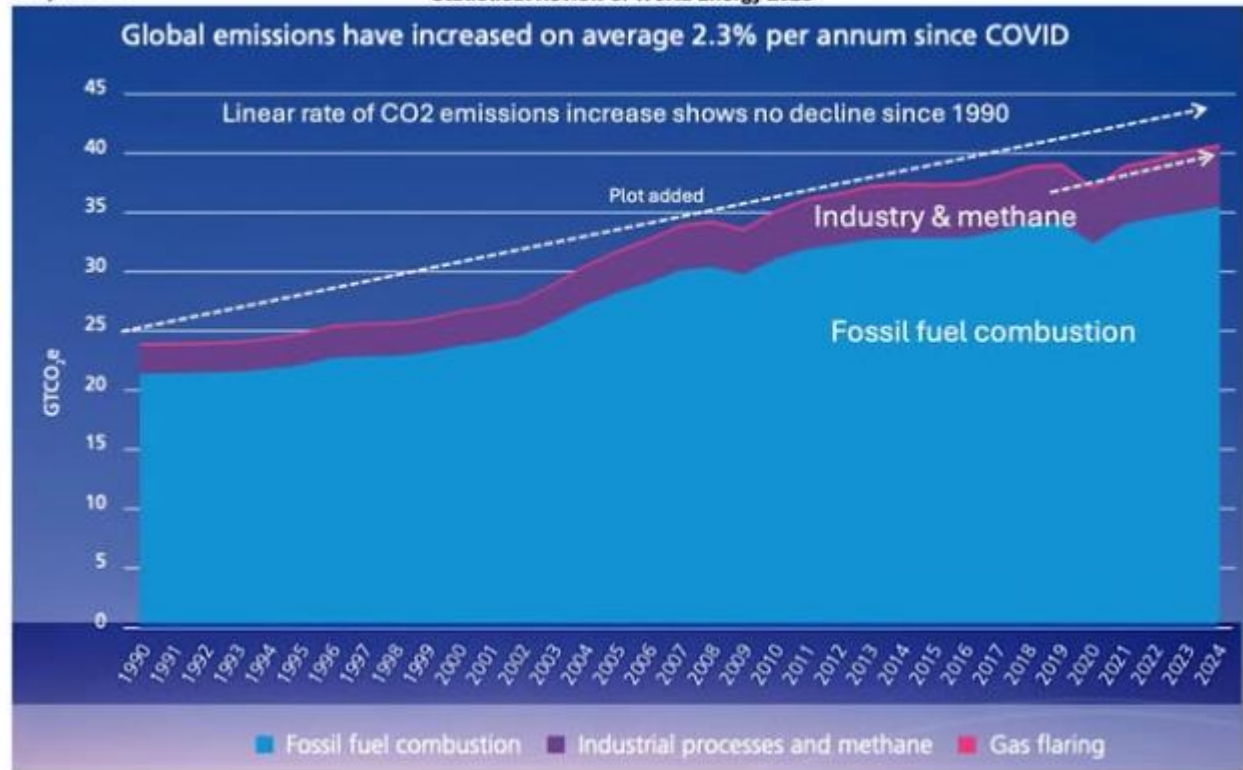
Footnotes

1	AR6 Scenario Explorer and Database hosted by IIASA https://data.ene.iiasa.ac.at/ar6/#/login																																																
2	https://en-roads.climateinteractive.org/scenario.html?v=25.6.0																																																
3	Calculate the expected increase in atmospheric CO2 based on CO2 emissions																																																
4	Calculate the expected radiative forcing from atmospheric CO2																																																
5	Calculate the expected radiative forcing from other greenhouse gas emissions, aerosols, albedo changes, etc.																																																
6	Calculate the temperature increase from the total radiative forcing																																																
7	<table><tr><th colspan="8">Temperature Increase in 2025</th></tr><tr><th>AR6 1.5°C</th><th>AR6 2.0°C</th><th>AR6 2.5°C</th><th>AR6 3.0°C</th><th>AR6 3.5°C</th><th>AR6 4.0°C</th><th>AR6 4.5°C</th><th></th></tr><tr><td>1.4339</td><td>1.4372</td><td>1.4304</td><td>1.4315</td><td>1.4222</td><td>1.4152</td><td>1.424</td><td></td></tr><tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><th>SSP1-19</th><th>SSP1-26</th><th>SSP2-45</th><th>SSP3-Baseline</th><th>SSP4-34</th><th>SSP4-60</th><th>SSP5-34</th><th>SSP5-Baseline</th></tr><tr><td>1.4424</td><td>1.4351</td><td>1.4218</td><td>1.4121</td><td>1.4161</td><td>1.4278</td><td>1.4351</td><td>1.4401</td></tr></table>	Temperature Increase in 2025								AR6 1.5°C	AR6 2.0°C	AR6 2.5°C	AR6 3.0°C	AR6 3.5°C	AR6 4.0°C	AR6 4.5°C		1.4339	1.4372	1.4304	1.4315	1.4222	1.4152	1.424										SSP1-19	SSP1-26	SSP2-45	SSP3-Baseline	SSP4-34	SSP4-60	SSP5-34	SSP5-Baseline	1.4424	1.4351	1.4218	1.4121	1.4161	1.4278	1.4351	1.4401
Temperature Increase in 2025																																																	
AR6 1.5°C	AR6 2.0°C	AR6 2.5°C	AR6 3.0°C	AR6 3.5°C	AR6 4.0°C	AR6 4.5°C																																											
1.4339	1.4372	1.4304	1.4315	1.4222	1.4152	1.424																																											
SSP1-19	SSP1-26	SSP2-45	SSP3-Baseline	SSP4-34	SSP4-60	SSP5-34	SSP5-Baseline																																										
1.4424	1.4351	1.4218	1.4121	1.4161	1.4278	1.4351	1.4401																																										
8	<div><div><div>Temperature Increase and Difference - AR6 and NOAA (from polynomial)</div></div><div>Excel spreadsheets “Formulas and Constants”, worksheet “TempAdj”</div></div>																																																
9A	<div><div>(10) Peter Carter - GHG EMISSIONS FROM ENERGY HAVE NOT SLOWED FROM 1990... Facebook</div><div>GHG EMISSIONS FROM ENERGY HAVE NOT SLOWED FROM 1990</div><div>Statistical Review of World Energy 2025: Energy driven greenhouse gas emissions (CO2e). 2024 Record high energy total GHG emissions, which has not slowed since 1990.</div><div>An extremely high 2.3% annual increase of energy emissions since 2022. From 2010 Fossil fuel CO2 emissions increase was 0.9% a year. Almost all is fossil fuel CO2, but methane emissions from energy is increasing as fast as CO2 (mainly from natural gas industry). Main reason for high increase is government fossil fuel subsidies.</div></div>																																																

Greenhouse Gas Emissions From Energy

Not just CO2

Statistical Review of World Energy 2025



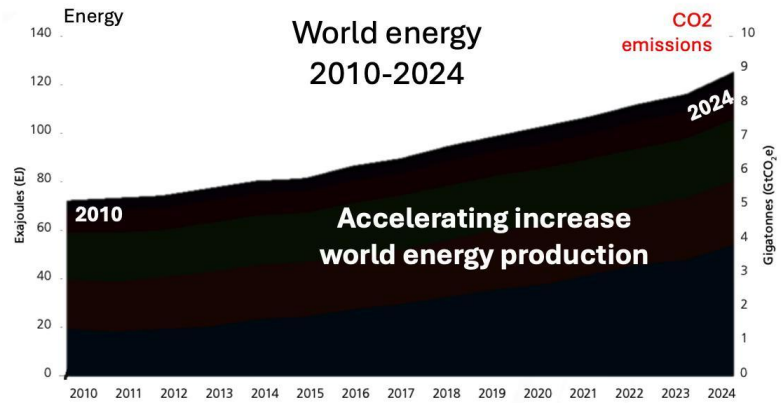
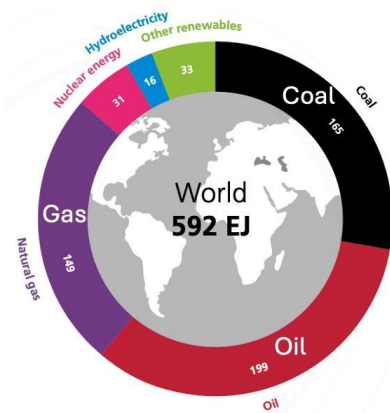
The Energy Institute (EI) Statistical Review of World Energy 2025

Peter Carter, Climate Emergency Institute

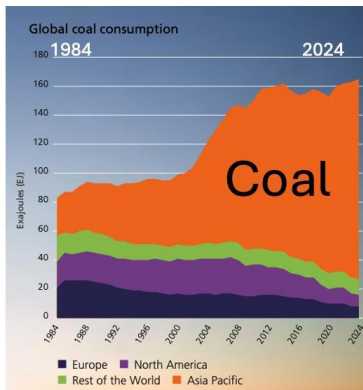
9B

<https://www.facebook.com/photo?fbid=10227885593754342&set=a.3608730145997>

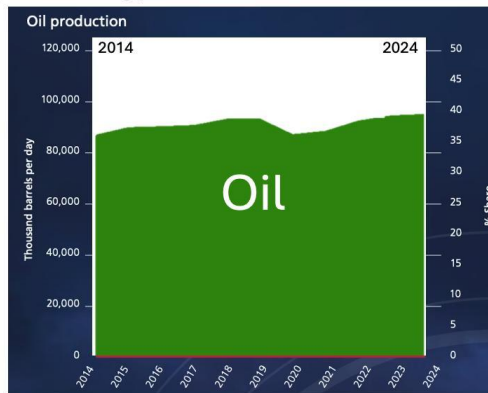
The Energy Institute (EI) Statistical Review of World Energy 2025



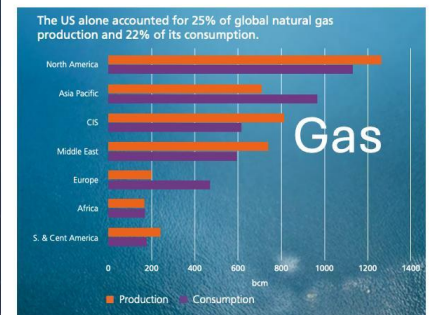
Global coal increased 1% in 2024, and is the second largest source of energy



2024 global oil production rose 0.6%
Oil is the leading energy source at 24%
Leading producer U.S.

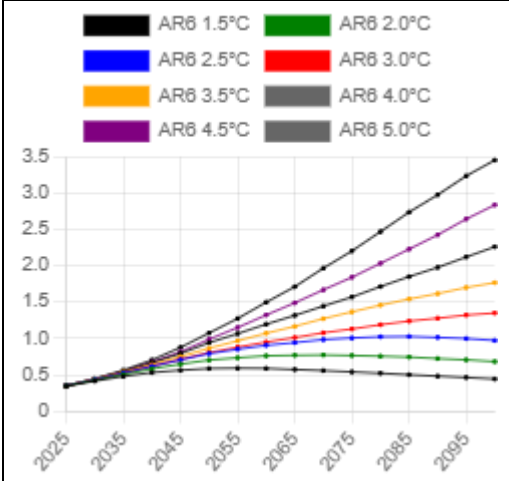


2024, global gas production increased 1.2%
Top producer U.S. 25% Consumption 22%



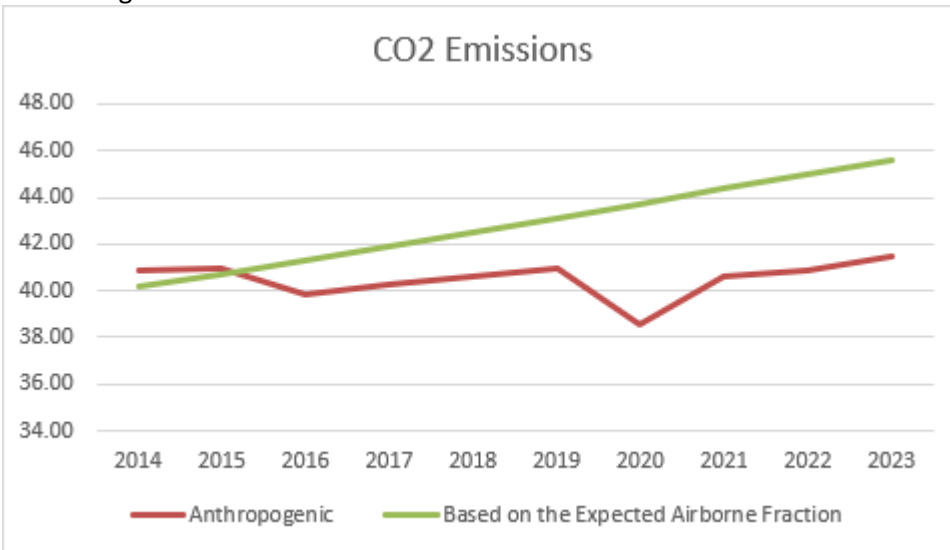
Peter Carter, Climate Emergency Institute

9C	<p>Renewables soar, but fossil fuels continue to rise as global electricity demand hits record levels 26/06/2025 https://www.energyinst.org/exploring-energy/resources/news-centre/media-releases/renewables-soar-but-fossil-fuels-continue-to-rise-as-global-electricity-demand-hits-record-levels</p> <ul style="list-style-type: none"> • Wind and solar combined grew by 16%, reinforcing their role as the fastest growing areas of the energy system. China was responsible for 57% of new additions, with solar almost doubling in just two years. • Wind and solar grew nearly nine times faster than total energy demand, and fossil fuels also grew (just over 1%) in 2024. • The world saw a 2% annual rise in total energy demand, reaching a new high of 592 EJ. • All-time records were reached across ALL forms of energy (coal, oil, gas, renewables, hydro and nuclear). • At 4%, electricity demand growth continued to outpace total energy demand growth, an indicator that the age of electricity is not just emerging but is shaping a new global energy system.
9D	<p>The history of a + 3 °C future: Global and regional drivers of greenhouse gas emissions (1820–2050) July 2025 https://www.sciencedirect.com/science/article/pii/S0959378025000469</p> <p>Meeting climate targets now requires the carbon intensity of GDP to decline 3 times faster than the global best 30-year historical rate (–2.25 % per year), which has not improved over the past five decades. Failing such an unprecedented technological change or a substantial contraction of the global economy, by 2050 global mean surface temperatures will rise more than 3 °C above pre-industrial levels.</p>
9E	<p>Global Banks Increase Fossil-Fuel Funding as Climate Pledges Crumble June 17, 2025 New report shows that banks poured nearly \$900 billion into financing coal, oil and gas projects in 2024 https://www.wsj.com/articles/global-banks-increase-fossil-fuel-funding-as-climate-pledges-crumble-9bbafce4?</p>
9F	<p>https://climateactiontracker.org/global/emissions-pathways/</p>
10	AR6 Feedbacks (GTCO2)



Scenario	Variable Code	2100	Temp	GTCO2/DC	2* GTCO2/DC
AR6 1.5°C	FeedbackCO2	0.24	1.50	0.53	1.06
AR6 2.0°C	FeedbackCO2	0.35	2.00	0.58	1.17
AR6 2.5°C	FeedbackCO2	0.50	2.50	0.66	1.32
AR6 3.0°C	FeedbackCO2	0.68	3.00	0.75	1.50
AR6 3.5°C	FeedbackCO2	0.90	3.50	0.85	1.70
AR6 4.0°C	FeedbackCO2	1.16	4.00	0.95	1.91
AR6 4.5°C	FeedbackCO2	1.40	4.50	1.03	2.06

11 Calculating current carbon feedbacks



Details: <https://www.scenexp.org/downloads/CO2Growth.xlsx>

12A (From Chat GPT)
A reasonable estimate of *annual* emissions from carbon feedbacks per degree Celsius of warming in 2100 is approximately:
3 to 10 GtCO₂-eq per year per °C of warming

📌 What this means:

If the Earth warms by 3°C by 2100, feedbacks could be emitting:

~9 to 30 GtCO₂-eq/year from Earth system processes alone, even in the absence of human emissions.



Breakdown of Estimates:

Feedback Type	Estimated Annual Emissions in 2100	Per °C (if 3°C warming)	Notes
Permafrost thaw	1.0–4.0 GtCO ₂ -eq/yr	~0.3–1.3 Gt/°C	Includes CO ₂ + CH ₄
Boreal/tropical dieback + fires	1.5–3.0 GtCO ₂ -eq/yr	~0.5–1.0 Gt/°C	Amazon, Siberia
Soil carbon loss	1.0–2.0 GtCO ₂ /yr	~0.3–0.7 Gt/°C	Higher in temperate and boreal soils
Ocean carbon feedbacks	0.5–1.5 GtCO ₂ /yr	~0.2–0.5 Gt/°C	Less uptake capacity as ocean warms
Total CO ₂ -eq/yr	4–10 GtCO ₂ -eq/yr	~1.3–3.3 Gt/°C	Conservative estimate
Upper plausible total	10–30 GtCO ₂ -eq/yr	~3–10 Gt/°C	Under high-emissions scenarios (SSP5-8.5)



Key Sources:

- **Comyn-Platt et al. (2018, Nature Geoscience):** 1.5–3 GtCO₂-eq/yr from permafrost thaw alone under RCP8.5 by 2100.
- **MacDougall & Knutti (2016, Nature Geosci):** 0.09–0.27 GtC/yr/°C (~0.3–1 GtCO₂/yr/°C) from permafrost.
- **IPCC AR6 (2021), WGI Ch5 & 9:** feedback emissions range from 1.5–4.5 GtCO₂-eq/year depending on scenario; higher values possible in SSP5-8.5.
- **Arora et al. (2020):** Feedbacks can cause 50–150 GtCO₂ over the century = ~0.5–1.5 Gt/yr average, but increasing over time.



Important Notes:

- These emissions are ***persistent and largely irreversible*** (esp. permafrost).
- Even in net-zero scenarios, these emissions may **require counterbalancing** through **carbon dioxide removal (CDR)**.
- Some emissions are **non-CO₂ GHGs**, particularly **methane** from thawing permafrost, with short-term high warming potential.

12B

THE LAND CARBON SINK HAS WEAKENED

A vivid picture of the state of the global forest carbon sink.

Amazon and Tropical forests are CO₂ emitters. Canadian Boreal sink is weakening from long large fire seasons. Boreal fires are increasing with forest drying and heat.

<https://www.facebook.com/photo/?fbid=10227876421485041&set=a.3608730145997>

Weakening Global Terrestrial Carbon Sink

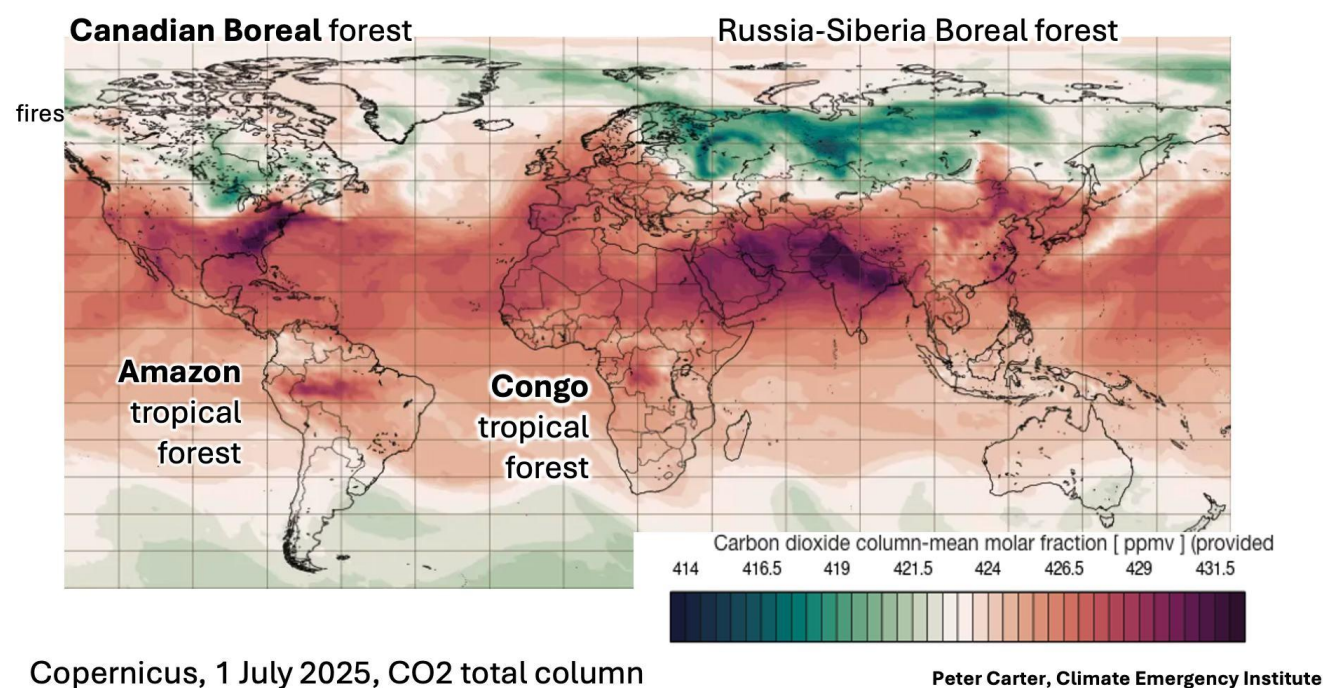
Copernicus CO2, 1 July 2025

The tropical rain forests are not sinking net CO2 - they are a CO2 source

The Boreal great circumpolar forest is the carbon sink now

The Canadian Boreal is weakened, with the Russian Boreal the only large effective land sink

Industrial CO2 emissions are northern hemisphere



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CCS (From Chat GPT)

what are the current best realistic estimates for ccs between now and 2050

ChatGPT said:

If we focus on **realistic** (rather than purely **theoretically necessary**) estimates of **carbon capture and storage (CCS)** deployment between now and 2050, considering **current policy, economics, public acceptance, and project trends**, the numbers are **much lower** than in idealized net-zero scenarios.

Here's a summary of **realistic CCS projections**, based on current and expected deployment capacity, financing trends, and policy momentum:

1. Current Deployment (2023–2024):

- **Actual operating global CCS capacity:** ~50–55 MtCO₂/year (source: Global CCS Institute, 2023)
- **Pipeline (announced + under development):** ~320 MtCO₂/year by early 2030s
- However, **historical project attrition rate** is high — only ~25–35% of announced projects reach operation.

2. Realistic Trajectory to 2050:

Year **Realistic Global CCS Deployment (MtCO₂/year)**

2025 ~80–100 Mt

2030 ~300–500 Mt












2040 ~1.0–1.5 Gt









Notes

Based on active construction and early projects

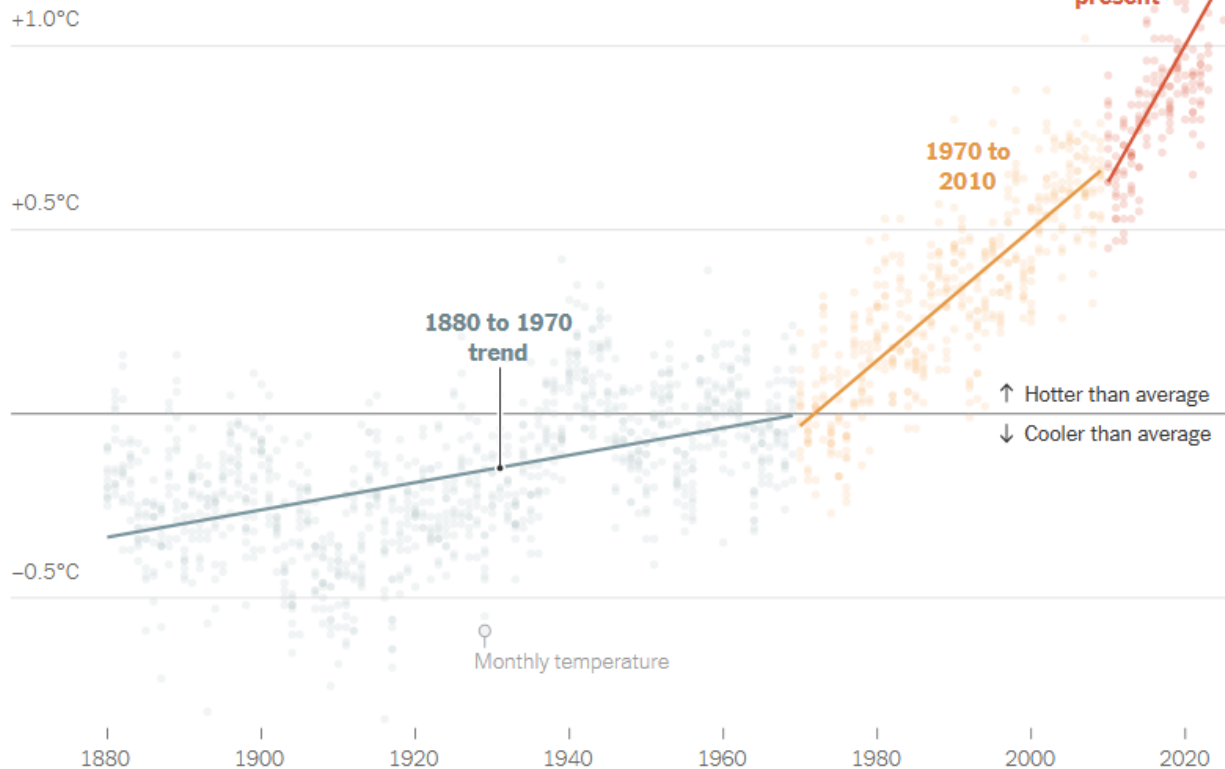
Optimistic if policy incentives hold (IRA, EU CBAM, etc.)

Requires breakthroughs in cost and regulation

	<p>2050 ~2–3 Gt</p> <p>Upper bound realistic under strong but plausible policy acceleration</p> <p>This is significantly lower than the 6–10 Gt seen in IEA or IPCC <i>net-zero-consistent</i> models.</p>
	<p> 3. Key Supporting Sources for Realistic Estimates:</p> <p> Global CCS Institute (2023)</p> <ul style="list-style-type: none"> Projects 280+ facilities by 2030 could provide ~250–300 MtCO₂/year Warns most projects are still in early stages <p> IEA Tracking Clean Energy Progress (2023)</p> <ul style="list-style-type: none"> Notes CCS deployment is not on track with net-zero goals Current policies only support ~10–20% of needed growth <p> BloombergNEF CCS Market Outlook (2024):</p> <ul style="list-style-type: none"> Projects ~2 GtCO₂/year by 2050 under a “real economy” scenario Notes most early deployment will be in the U.S., UK/North Sea, and Gulf countries
	<p> Key Constraints on Realistic CCS Growth:</p> <ol style="list-style-type: none"> Cost: \$60–200+/tCO₂ for industrial or power CCS, more for DAC Lack of Transport & Storage Infrastructure Regulatory Hurdles & Permitting Delays Public Opposition (especially to onshore storage) Competing Priorities (e.g. renewables and electrification receive more focus)
	<p> Bottom Line:</p> <p>Realistically, CCS may reach 2–3 GtCO₂/year by 2050, assuming continued policy support, cost reductions, and successful infrastructure buildout. This is far short of the 5–10 Gt needed in 1.5°C scenarios, meaning CCS will likely play a supplementary role, not a dominant one, in global decarbonization.</p>
14	<p>(From CHAT GPT)</p> <p>Carbon capture and storage (CCS) is unlikely to be implemented at the scale needed (5–10 GtCO₂/year by 2050) for limiting global warming to 1.5–2°C due to a convergence of technical, economic, policy, and societal barriers. Here’s a breakdown of why CCS is falling short of what models say is required:</p>
	<p> 1. High Costs and Poor Economics</p> <ul style="list-style-type: none"> CCS remains expensive: Capture alone costs \$60–150 per tonne of CO₂, and DACCS is even more costly (\$200–600+/tCO₂). Low or uncertain carbon pricing in most regions fails to create a strong economic signal. Most industries lack financial incentives or business models to deploy CCS without large subsidies. <p> Example: The U.S. 45Q tax credit (\$85–180/t) has helped, but uptake is still limited even with this generous support.</p>
	<p> 2. Slow Infrastructure Development</p> <ul style="list-style-type: none"> CCS requires a vast network of pipelines, compressors, and long-term storage reservoirs. Building these safely and legally involves: <ul style="list-style-type: none"> Permitting delays (especially for CO₂ pipelines) Liability uncertainties for leakage Long lead times (10+ years for large-scale systems) <p> By comparison: Renewable energy like wind/solar can be deployed much faster and cheaper, with no transport or storage infrastructure needed.</p>
	<p> 3. High Project Failure Rate</p>

	<ul style="list-style-type: none"> Many CCS projects are announced but never built. Reasons include: <ul style="list-style-type: none"> Financial uncertainty Permitting issues Changes in government or corporate priorities <p> <i>Historical attrition:</i> Up to 70% of proposed projects since the early 2000s have failed to reach operation.</p>
	<p> 4. Lack of Policy Mandates and Global Coordination</p> <ul style="list-style-type: none"> CCS is not required or incentivized at a large scale in most countries. Global climate agreements (e.g., Paris) are technology-neutral; they don't require CCS. Governments often prioritize renewables, efficiency, and electrification, which are more popular and politically safe.
	<p> 5. Public Opposition and Social License</p> <ul style="list-style-type: none"> Communities often resist CCS infrastructure: <ul style="list-style-type: none"> CO₂ pipelines raise safety and land use concerns. Underground storage raises fears of earthquakes or leakage. Unlike wind or solar, CCS has no local benefit—just costs and risk. <p> <i>Not-in-my-backyard (NIMBY)</i> reactions have blocked or delayed key projects in Europe, the U.S., and Australia.</p>
	<p> 6. Misalignment with Broader Energy Transition</p> <ul style="list-style-type: none"> CCS is often used to prolong fossil fuel use, which undermines its climate legitimacy. Climate advocates and funders increasingly favor “fossil-free” paths, not fossil-fueled CCS. Electrification, renewables, and storage are maturing faster and more cheaply than CCS.
	<p> 7. Overreliance in Climate Models</p> <ul style="list-style-type: none"> Models use CCS and CDR to close the gap between emissions and targets when real-world action falls short. But this creates a “moral hazard”: policymakers delay emissions cuts now, assuming CCS will scale later. <p> <i>Result:</i> Circular logic—CCS is assumed to be feasible in models, so real efforts are postponed, but the needed CCS never materializes.</p>
	<p> Conclusion:</p> <p>CCS is unlikely to be deployed at the gigatonne-scale needed by 2050 because it's too expensive, too slow, politically complicated, and socially unpopular. It may still play a limited role in hard-to-abate sectors (cement, steel, DACCS), but the global decarbonization challenge will rely far more on renewables, electrification, efficiency, and behavioral change.</p>
15	<p>The World Is Warming Up. And It's Happening Faster. June 26, 2025</p> <p>“The world is getting hotter, faster. A report published last week found that human-caused global warming is now increasing by 0.27 degrees Celsius per decade. That rate was recorded at 0.2 degrees in the 1970s, and has been growing since.” If that rate continues through 2050 the average temperature in 2050 would be about 2.0°C. If, as Dr. James Hanses has predicted, the warming rates becomes 0.36°C per decade, average temperature in 2050 would be about 2.2°C.</p> <p>https://www.nytimes.com/2025/06/26/climate/climate-heat-intensity.html?unlocked_article_code=1.SE8.b1Yc.8Xt-fK_QkrCZ&smid=url-share</p>

Global average temperature compared with the middle of the 20th century



Source: NASA Goddard Institute for Space Studies - Note: Data available through May 2025. Anomalies relative to the average temperature between 1951 and 1980. - The New York Times

16 Stratospheric aerosol injection tactics and costs in the first 15 years of deployment Temperature Incr.

Wake Smith and Gernot Wagner

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In 2047

95 planes

Total payload 1.5 MT

Total SO₂ disbursed 3MT

Cooling 0.3°C

Cooling per plane: 0.003°C

4. SAI lofter (SAIL)

Given the apparent inadequacy of existing technologies, especially of previously assumed-to-be-adequate modifications to existing aircraft (McClellan et al 2010, 2012), we propose a novel aircraft with disproportionately large wings relative to its narrow fuselage. We also describe the aircraft fleet requirements, and we calculate development and deployment costs from conception through year 15 of the hypothetical program.

More specifically, the preliminary design for SAIL calls for a length of ~46 m, a wingspan of ~55 m, and a wing area of ~250 m², with an aspect ratio of ~12:1. The maximum structural payload would be ~25 t,

SAIL is designed for a service ceiling of ~20 km, with a maximum altitude of up to ~19.8 km in a typical mission. Each mission would last ~5 h, with ~2 h of ascent and descent time each, plus ~1 h on station. The ~2 h for ascent and descent time situates SAIL reasonably between the performance rates of the Global Hawk and U2/ER2. That assumes a ~25 t payload and a conversion of S to SO₂ at ~0.5 t S per minute.

4.2. Fleet

We calculate that in year 1 of the deployment program (assumed to be 2033), the SAIL fleet would require 8 new aircraft including one flight-ready spare plane at each of the two initial bases. This assumes that one spare does not substantially influence our cost estimates. Table 3 summarizes SAIL fleet and activity in the first 15 years of deployment.

Table 3. Total fleet and flight activity by hypothesized deployment year.

Year	New aircraft ^a	Total aircraft ^a	Total payload (Mt S) ^b	Flights/year	Bases	Monthly flight hours/aircraft ^c	Flights/base/
2033	8	8	0.1	4007	2	278	5
2034	6	14	0.2	8015	2	278	11
2035	8	22	0.3	12 022	4	278	8
2036	6	28	0.4	16 029	4	278	11
2037	6	34	0.5	20 036	4	278	14
2038	6	40	0.6	24 044	4	278	16
2039	7	47	0.7	28 051	4	272	19
2040	6	53	0.8	32 058	4	273	22
2041	6	59	0.9	36 065	4	273	25
2042	6	65	1.0	40 073	4	274	27
2043	6	71	1.1	44 080	4	274	30
2044	6	77	1.2	48 087	4	274	33
2045	6	83	1.3	52 095	4	275	36
2046	6	89	1.4	56 102	4	275	38
2047	6	95	1.5	60 109	4	275	41

^aIncludes one spare aircraft per base. ^bS burned *in situ* to disperse 2× SO₂ (see table 1). ^cExcludes spare aircraft.