Model for Calculating the CDR Requirement in 2100

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Calculating the amount of CO2 that will need to be removed from the atmosphere in 2100 for a specific temperature increase is fraught with uncertainty but is essential to crafting the response to global warming. A simple model, based on the data from the IPCC's 1.5°C report, was developed to allow people to explore the CO2 removal requirement for a variety of possible values for the major climate "variables" – cumulative emissions from 2020 through 2100, non-CO2 radiative forcing in 2100, climate sensitivity, and temperature increase. Table 1 shows an example of a CDR removal requirement calculation using the model (the green rows are for user input, orange rows indicate standard climate modeling formulas, the purple rows indicate formulas derived from examining scenario data from the IPCC 1.5 Degree Celsius report, and the blue rows indicate simple math). The "**Step by Step Description of the Model"** section below explains each data source or calculation. The "**Details"** section below provides some additional information for each step and suggestions for reasonable "user input" values.

(Click here to download the IPCC 1.5°C report data that was used to develop the two formulas that are used by the model.)

	Scenario	1
1	Equilibrium Climate Sensitivity	4.0
2	Temperature Increase (°C) in 2100	0.6
3	Equilibrium Climate Sensitivity derived from IPCC models	3.0
4	Percent of ECS Realized	95
5	"2100" Climate Sensitivity (based on percent realized)	3.8
6	Radiative forcing for temperature increase (W/m-2)	0.58
7	"2100" Non-CO2 Radiative Forcing (W/m-2)	0.35
8	"2100" CO2 Radiative Forcing (W/m-2) in 2100	0.23
9	"2100" CO2 PPM	290
10	Cumulative Emissions For Temperature Goal	-982
11	Cumulative Emissions (2020-2100 - GT CO2)	1000
12	Cumulative Emissions from natural feedbacks (2020-2100 - GT CO2e)	1000
13	CO2 removal requirement (GT CO2)	2982
14	CO2 Removal Cost ($/Ton, average)	100
15	Total CO2 Removal cost ($Trillion)	298

Table 1. Example of a CDR Removal Calculation Using the Model

Step by Step Description of the Model

(Detailed description for each step is included in the "Details" section below)

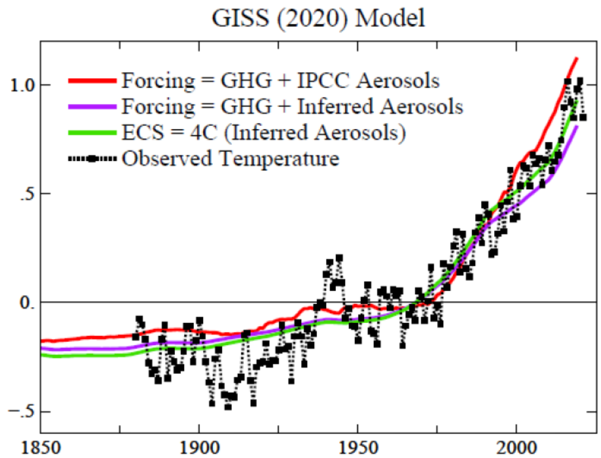
#	How Value Obtained	Step Name
1	User input	**Equilibrium Climate Sensitivity** James Hansen, in his December 2022 "Global Warming in the Pipeline" Paper (https://arxiv.org/pdf/2212.04474.pdf), explained his use of the latest climate models to re-analyze the temperature increase for known values for global temperature, greenhouse gas concentrations, and the Earth's energy imbalance to determine the "best fit" among the "knowns" and the three major "unknowns" of

		climate sensitivity, aerosols, and ocean mixing. He concluded that best value for equilibrium climate sensitivity (ECS) was 4.0°C Equilibrium Climate Sensitivity (ECS) is the expected value for the temperature increase for a doubling of CO2 (or CO2e) over centuries. ECS includes changes to clouds, water vapor, snow cover, and sea ice (these change rapidly in response to a temperature change). The IPCC estimated the range to be from 2-5°C, with a best estimate of 3. 0°C
2	User Input	**Temperature Increase (°C) in 2100** In is paper (see #1 above), Hansen's concluded that "due to warming in the pipeline we need to return to the Holocene-level global temperature". He did not provide an estimate of what temperature increase should be, but a reasonable value might be 0.6°C. The model is probably most "accurate" for values between 1 and 2°C (where we are likely aiming)
3	User Input	**Equilibrium Climate Sensitivity derived from IPCC models** The IPCC scenario data used to derive formulas for this model were obtained by using the MAGICC6 climate model. One of the variables needed to determine the percentage of ECS realized (see #4 below) is the ECS "assumed" by the MAGICC6 climate model. I could not find this demented so I used the value of 3°C. Reasonable values are probably in the range 2.5°C to 3.5°C.
4	Formula from IPCC data	**Percent of ECS Realized** The temperature increase "specified" by equilibrium climate sensitivity will not be reached for several centuries. Since we are concerned with the temperature increase in 2100, a formula for the percent of the ECS that is realized in 2100 was derived by using the IPCC 1.5 Report data.
5	Simple Calculation	**"2100" Climate Sensitivity (based on percent realized)** "2100" Climate Sensitivity = Equilibrium Climate Sensitivity (#1) * Percent of ECS Realized (#4)
6	Standard Climate Formula	**Radiative forcing for temperature increase (W/m-2)** Radiative Forcing = 3.708581727 * Equilibrium Temperature / Climate Sensitivity
7	User Input	**"2100" Non-CO2 Radiative Forcing (W/m-2)** An estimate of the radiative forcing for aerosols and all of greenhouse gases except CO2. The median for IPCC 1.5 scenarios where the temperature increase was between 1.4 amd1.6°C was 0.35 W/m-2 For the IPCC RCP2.5 scenario the value was 0.08 (perhaps because of significant masking by aerosols?)
8	Simple Calculation	**"2100" CO2 Radiative Forcing (W/m-2) in 2100** CO2 Radiative Forcing = Radiative forcing for temperature increase (#6) - Non-CO2 Radiative Forcing (#7)
9	Standard Climate Formula	**"2100" CO2 PPM** "2100" CO2 PPM =278 * $e^{(\text{CO2e Radiative Forcing}/5.35)}$
10	Formula from IPCC data	**Cumulative Emissions For Temperature Goal** The IPCC 1.5 Report data shows a very good correlation between cumulative CO2 emissions and atmospheric CO2 concentration in 2100

11	User Input	**Cumulative Emissions 2020-2100 (GT CO2)** Estimating cumulative CO2 emissions from 2020 through 2100 is a very fraught endeavor. On one hand are the net-zero in 2050 goals, and another hand are the business as usual projections of the IEA and EIA, which have CO2 emissions continuing at that the current through 2050. 1,000 GTCO2 is a reasonable value based on the IEA data.
12	Simple Calculation	**Cumulative Emissions from natural feedbacks (2020-2100 - GT CO2e)** CO2 removal requirement = Cumulative Emissions (2020-2100) (#11) - Cumulative Emissions For Temperature Goal (#10)
13	Simple Calculation	**CO2 removal requirement (GT CO2)** CO2 removal requirement = Cumulative Emissions (2020-2100) (#11) + Cumulative Emissions from natural feedbacks (#12) **-** Cumulative Emissions For Temperature Goal (#10)
14	User Input	**CO2 Removal Cost ($/Ton, average)**
15	Simple Calculation	**Total CO2 Removal cost ($Trillion)** Total CO2 Removal cost = CO2 removal requirement (#13) * CO2 Removal Cost /1000 (#14)

Details

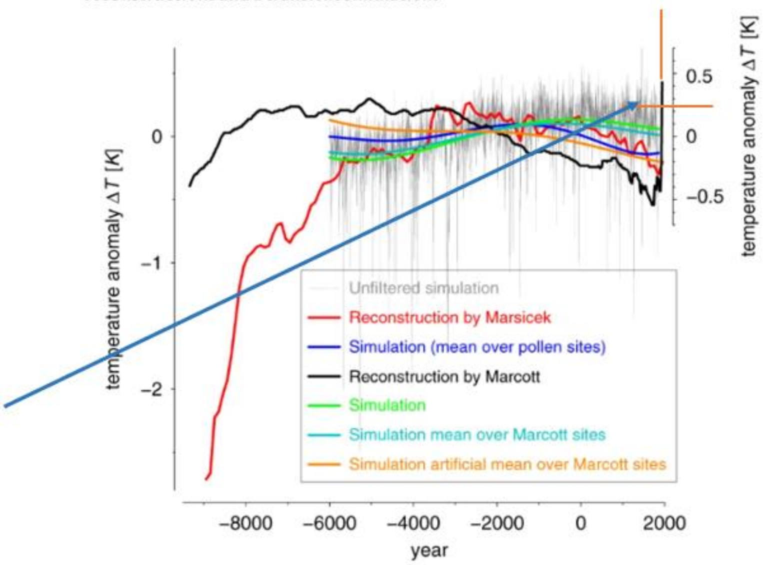
1 **Equilibrium Climate Sensitivity**



(from Hanen's paper)

2 **Temperature Increase (°C) in 2100**

Fig. 1: Annual global-mean temperature anomaly during the Holocene based on reconstructions and a transient simulation.



https://www.nature.com/articles/s41467-020-18478-6

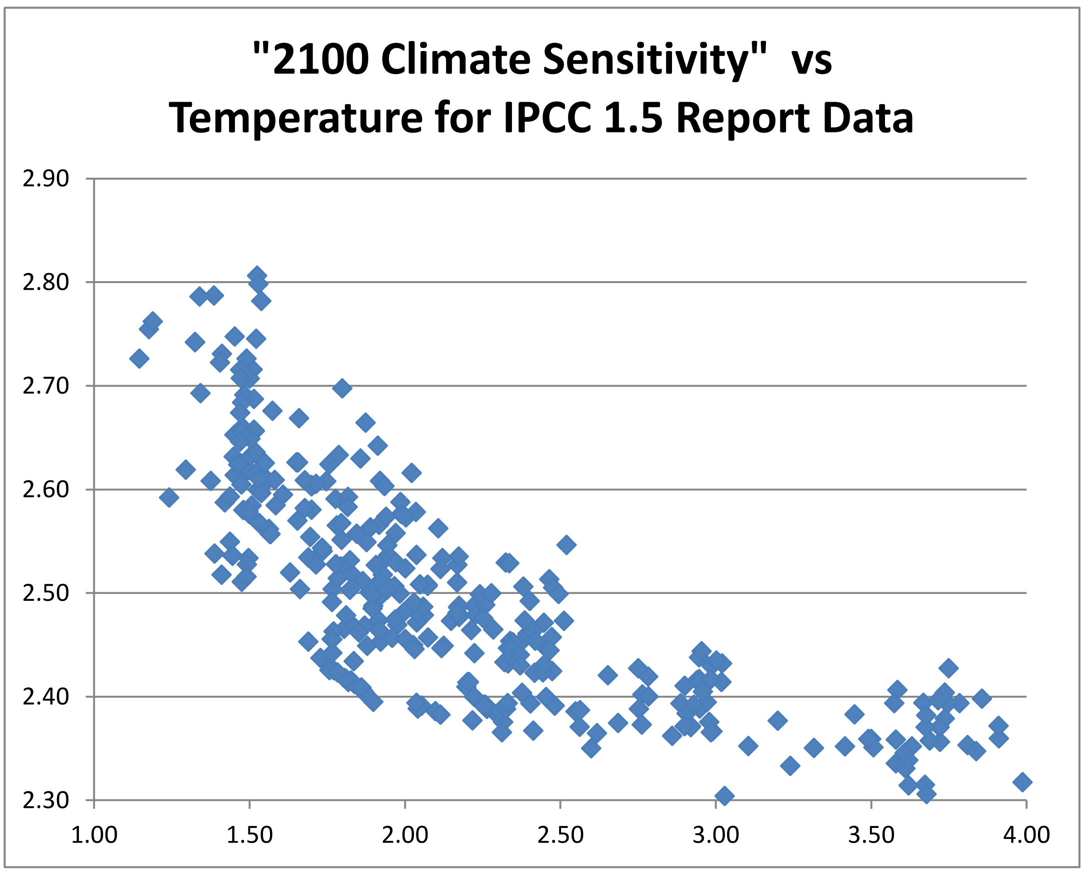
1. The temperature varied about 1° C over the Holocene
2. It reached it lowest value about 150 years ago (about 0.2° C below pre-industrial times)
3. Since then the temperature has increased about 1.4°C (to about 1.2° C above pre-industrial times)
4. The current temperature increase seems to be about 0.6° C above the average value reached about 5,000 years ago, which is about 0.6° C above pre-industrial times
5. A possible target temperature increase could be about 0.6° C below the current value (and about 0.6° C above the pre-industrial average)
6. Given the increase in damages from natural weather disasters in the last 30 years this is a good aspirational goal (and results in the temperature increase reached in 1990)

3	**Equilibrium Climate Sensitivity derived from IPCC models** The IPCC estimated the range to be from 2-5°C, with a best estimate of 3. 0°C
4A	**Percent of ECS Realized** Sample data used to derive the formula

Model	Scenario	P66 Temp Increase	Total Forcing	Realized CS	Possible ECS		
					2.75	3.00	3.25
AIM/CGE 2.0	**ADVANCE_2020_1.5C-2100**	1.42	2.04	2.59	94	86	80
AIM/CGE 2.0	**ADVANCE_2020_Med2C**	2.22	3.46	2.38	86	79	73
AIM/CGE 2.0	**ADVANCE_2020_WB2C**	1.77	2.68	2.44	89	81	75
AIM/CGE 2.0	**ADVANCE_2030_Med2C**	2.41	3.78	2.37	86	79	73
AIM/CGE 2.0	**ADVANCE_2030_Price1.5C**	1.84	2.80	2.43	89	81	75
AIM/CGE 2.0	**ADVANCE_2030_WB2C**	1.92	2.91	2.45	89	82	75
AIM/CGE 2.0	**ADVANCE_INDC**	2.99	4.69	2.37	86	79	73
					% of ECS Realized		

Realized Climate Sensitivity = 3.708 * Temperature in 2100 / CO2e Radiative Forcing

4B The following "scatter plot" is based on the data for scenarios where the temperature increase was less than 4° C



4C **Coefficients for the formula**

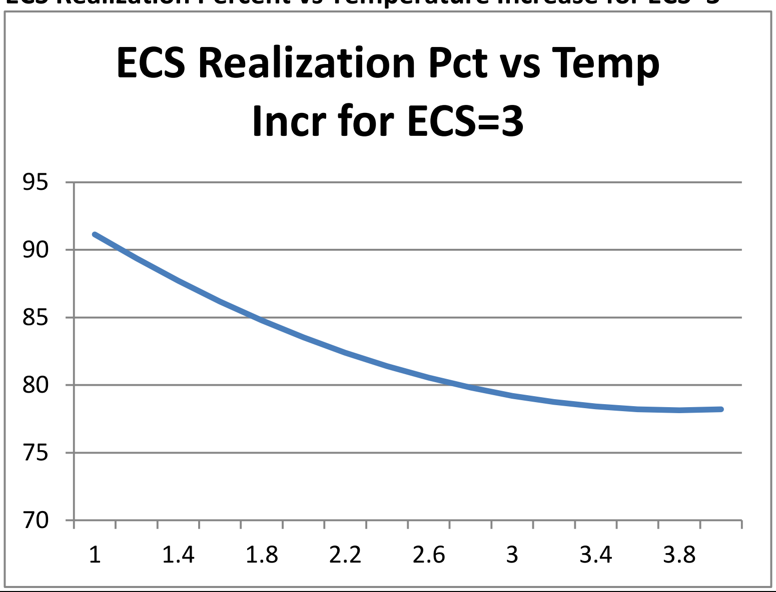
ECS	Coefficients for Percent of ECS Realized from a Temperature Increase for Three Values of ECS		
	A	B	C
2.75	1.80402412	-13.72561463	111.355053
3.00	1.653688777	-12.58181341	102.0754653
3.25	1.526481948	-11.61398161	94.22350642

Percent of ECS Realized = A *ECS * ESC + B*ECS + C

Coefficients	Coefficients for Coefficients of ECS Realized from a Temperature Increase for Three Values of ECS		
	AA	BB	CC
A	0.185028115	-1.665253034	4.984194846
B	-1.407755346	12.66979812	-37.92140965
C	11.42103108	-102.7892797	307.6540247

A = AA *ECS * ESC + BB*ECS + CC

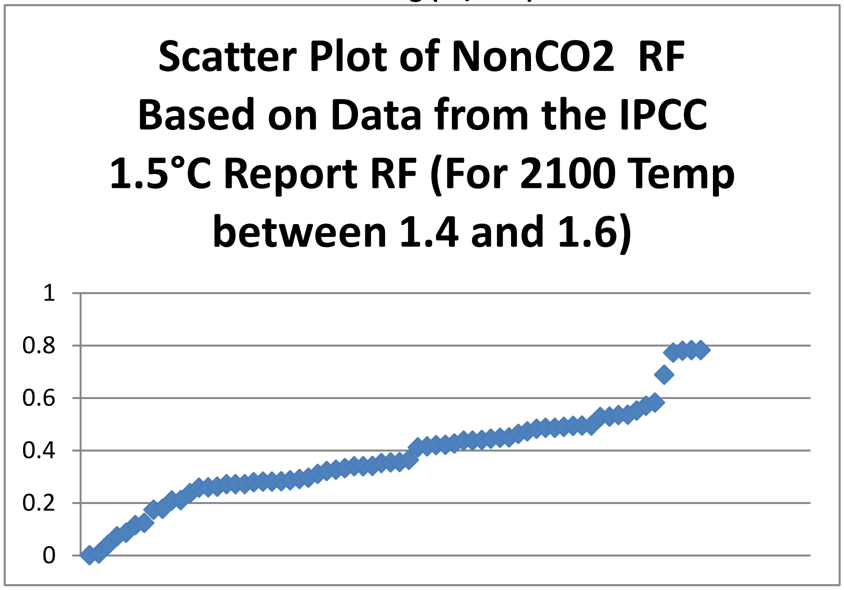
4D **ECS Realization Percent vs Temperature Increase for ECS=3**



5 **"2100" Climate Sensitivity (based on percent realized)**

6 **Radiative forcing for temperature increase (W/m-2)**

7 **"2100" Non-CO2 Radiative Forcing (W/m-2)**



A value between 0.2 W/m-2 and 0.6 W/m-2 seems likely

A value of 0.35 or 0.4 W/m-2 seems like a reasonable value for planning purposes

8 **"2100" CO2 Radiative Forcing (W/m-2) in 2100**

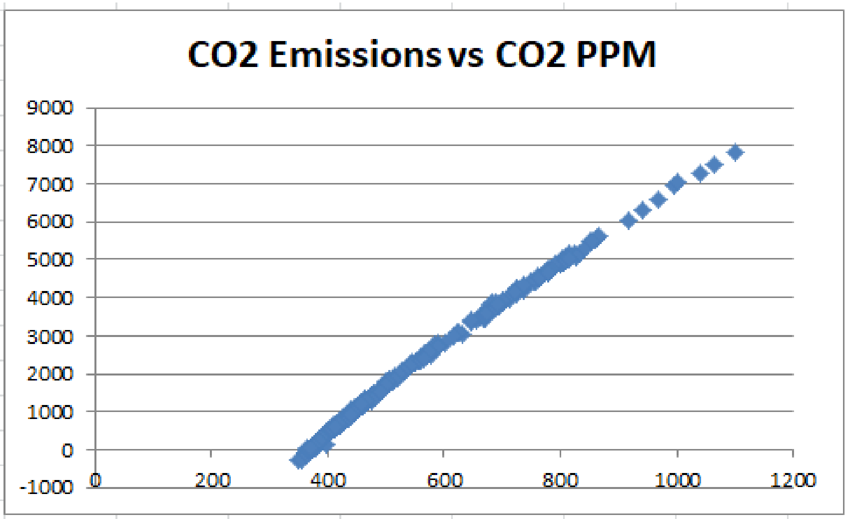
CO2 Radiative Forcing = Radiative forcing for temperature increase (#6) - Non-CO2 Radiative Forcing (#7)

9 **"2100" CO2 PPM**

"2100" CO2 PPM =278 * $e^{(CO2e\ Radiative\ Forcing/5.35)}$

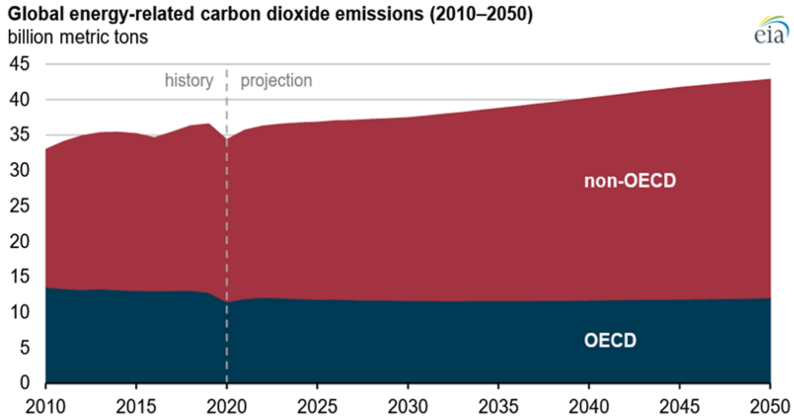
10 **Cumulative Emissions For Temperature Goal**

(Based on IPCC 1.5C Report data)



Coefficients for Cumulative CO2 from a Specific CO2 PPM		
A	B	C
-0.00327668	15.22136	-5127.04

11A **Cumulative Emissions (2020-2100 - GT CO2)**



https://www.eia.gov/energyexplained/energy-and-the-environment/outlook-for-future-emissions.php

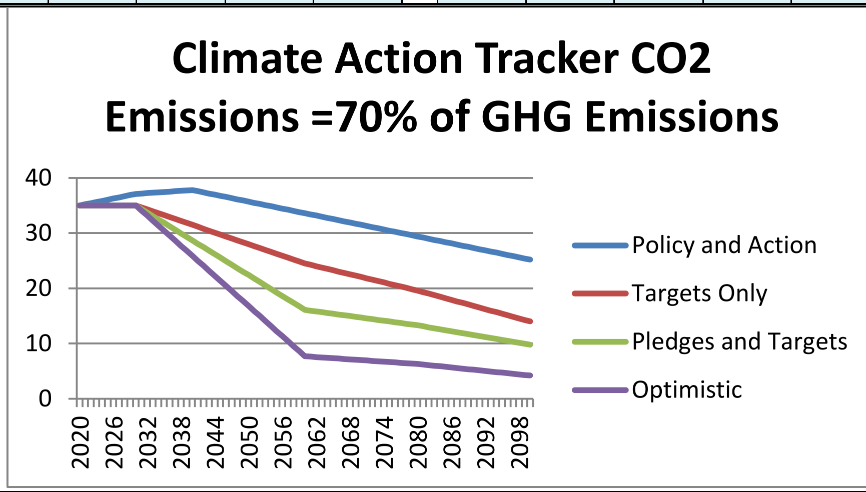
If CO2 emissions continue at that the current rate (about 40 GTCO2/year if emissions from cement and land-use changes are included) through 2030 and then decline to zero by 2060 then cumulative emissions from 2020 to 2100 would then be about 1,000 GTCO2

11B

Peak Year	2030	2035	2040	2045	2050		2030	2035	2040	2045	2050
Zero Year	2060	2065	2070	2075	2080		2070	2075	2080	2085	2090
Cum Emissions 2020-2100	1000	1200	1400	1600	1800		1200	1400	1600	1800	2000

11C

Cumulative Emissions (GTCO2)	
Policy and Action	2655
Targets Only	2044
Pledges and Targets	1664
Optimistic	1255



12 Cumulative Emissions from natural feedbacks (2020-2100 - GT CO2e)

	GTCO2e	Description (For 2020 – 2100)
1	200	Albedo change due to Arctic Ocean ice melt – Ice free in the summer (20% of complete disappearance)
2	200	Albedo change due change in Northern Hemisphere snow extent (roughly the same as albedo change due to Arctic Ocean ice melt)
3	200	Reduction of land carbon stores of about 5% for 40 years (50 GTCO2/year)
4	50	If the Amazon rainforest turns to a savannah
5	400	GTCO2 emission from permafrost
6	???	Several others

13 CO2 removal requirement (GT CO2)

CO2 removal requirement = Cumulative Emissions (2020-2100) (#11) + Cumulative Emissions from natural feedbacks (#12) - Cumulative Emissions For Temperature Goal (#10)

14 CO2 Removal Cost ($/Ton, average)

15 Total CO2 Removal cost ($Trillion)

Total CO2 Removal cost =

	CO2 removal requirement (#13) * CO2 Removal Cost /1000 (#14)