A Simple Formula for Calculating Carbon Budgets

Estimate CO2 emission budgets using only climate sensitivity, annual methane emissions, cumulative N2O emissions, and the desired temperature increase.

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Objectives

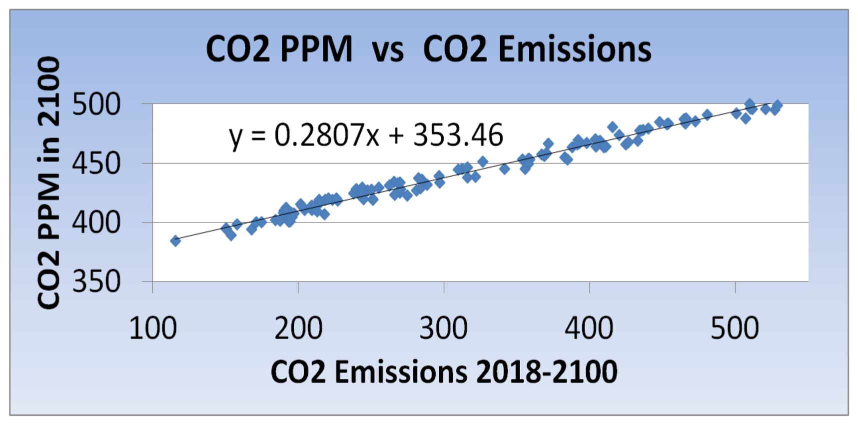
Use the output of sophisticated climate models to develop simple formulas for estimating CO2 emission budgets

Use the formulas to create:

- "Lookup tables" for CO2 emission budgets
- Equivalence table for climate factors
- Worksheets for adjusting existing CO2 emission budgets

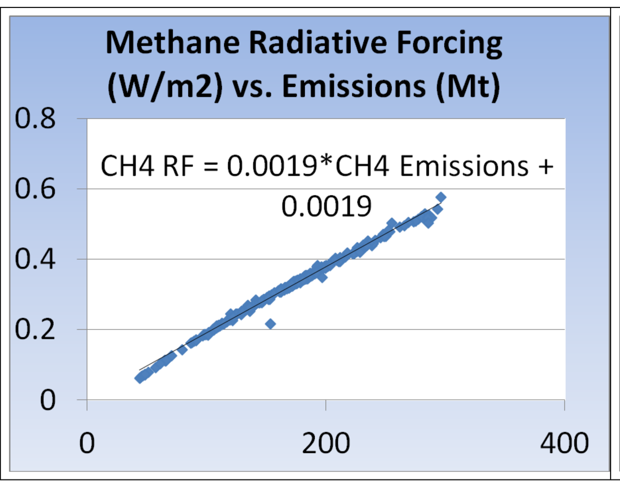
Climate Model Output

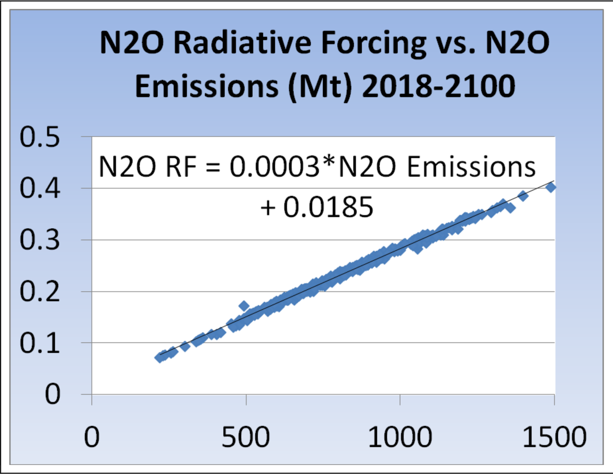
A. Relate CO2 Atmospheric PPM to CO2 Emissions



Combine with two standard climate formulas to create a formula for CO2 emissions budgets.

B. Relating Other Greenhouse Gas Emissions To Their Radiative Forcings in 2100





A value of -0.05 W/m2 for all the radiative forcing elements other than CO2, CH2, and N2O provides a relatively close estimate for many of the climate scenarios.

Non-CO2 RF = 0.0019 * CH4Emissions + 0.0003 * N2OEmissions - 0.03

CO2 Budget For Non-CO2 RF

C. CO2 Budget Formula For Non-CO2 Radiative Forcing

$$\text{CO2 Budget} = 3.5007 * \text{CO2OrigPPM} * (1 + \text{ET} / \text{CS}) * e^{(-\text{Non-CO2RF}/5.35)} - 1232.1$$

The formula calculates CO2 emission budgets within 10% for 95% of the 182 FAIR scenarios where the P66 temperature increase is >= 1.4 and CO2 emissions > 60GTC and atmospheric CO2 in 2100 < 500 PPM.

D. CO2 Budget "Lookup Table" Based on Non-CO2 RF

		Temp Increase: 1.5 °C							
		Climate Sensitivity							
		2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4
Non-CO2 RF (W/m2)	0.3	378	315	263	219	181	148	119	94
	0.4	348	287	235	192	155	122	94	69
	0.5	319	259	208	166	129	97	70	45
	0.6	290	231	182	140	104	73	46	22
	0.7	262	204	155	114	79	49	22	-2
		CO2 Budget 2018-2100 (Emissions - GTC)							

E. Equivalences Based on the CO2 Budget Formula

Equivalences for a climate sensitivity of 2.8 and a temperature increase of 1.75°C:

		Clim. Sens	Temp Incr	Rad Forc	Atm CO2	Cum CO2 Emis	Ann CH4 Emis	Cum N2O Emis	$100/ Ton CO2
Climate Factor	Amt		°C	W/m2	PPM	GTC	MT	MT	$Billion
Climate Sensitivity	0.1		0.063	0.074	5.685	19.9	39.3	248.8	7,303
°C	0.1	0.156		0.117	8.941	31.3	61.8	391.3	11,487
W/m2	0.1	0.135	0.085		7.713	27.0	53.3	337.5	9,909
PPM CO2	1.0	0.017	0.011	0.013		3.5	6.9	43.8	1,285
CO2 Emissions (GTC)	10	0.050	0.031	0.037	2.857	10.0	19.7	125.0	3,670
CH4 Ann. Emissions (MT)	10	0.025	0.016	0.019	1.457	5.1		63.8	1,872
N2O Emissions (MT)	100	0.040	0.025	0.030	2.285	8.0	15.8		2,936

It could cost about $11 Trillion to decrease the global temperature by 0.1°C. by removing 31.3 GTC of CO2 from the atmosphere.

(Assuming capture and sequestration costs were $100/Ton CO2 ($367/Ton C))

CO2 Budget For CH4 and N2O

F. CO2 Budget Formula Using CH4 and N2O Emissions

$$\text{CO2 budget} = 3.5007 * \text{CO2OrigPPM} * (1 + \text{ET} / \text{CS}) * e^{(-\text{Non-CO2RF}/5.35)} - 1232.1$$

where Non-CO2RF =(0.0019*CH4Emissions+0.0003* N2OEmissions -0.03)

How well the calculation compares with the scenario values:

FAIR scenarios where the P66 temperature increase is >= 1.4 and CO2 emissions > 60GTC and atmospheric CO2 in 2100 < 500 PPM					
Number of Scenarios	Percentage of Difference Between Scenario CO2 Emissions and Emissions Calculated Based on CH2 and N2O				
	<5%	<10%	<15%	<20%	<25%
182	29	58	80	92	95
135*	40	76	88	96	97
45*+	44	71	84	91	91
30*#	50	96	100	100	100
	Percentage of scenarios where the calculated emissions differ from the scenario emissions by less than a given percent				
*"Other radiative forcing" between -0.18 and 0.1 W/m2					
+ P66 Temperature increase between 1.45 and 1.55					
# 30 of 35 scenarios which used the 'AIM/CGE 2.0' model					

(The IPCC emissions for the 67 percentile for 1.5°C were 115 GTC - 10% of this is 11 GTC)

G. CO2 Budget "Lookup Table" Based on CH4 and N2O

		Climate Sensitivity:2.6									
		Temp Increase: 1.5 °C									
		Cumulative N2O Emissions (Mt)									
		500	550	600	650	700	750	800	850	900	950
CH4 Emissions 2100 (MT)	150	200	196	192	188	184	180	176	172	168	164
	250	150	146	142	138	134	130	127	123	119	115
	350	101	98	94	90	87	83	79	75	72	68
	450	55	51	48	44	41	37	33	30	26	23
	550	10	6	3	0	-4	-7	-11	-14	-18	-21
	650	-33	-37	-40	-43	-47	-50	-53	-57	-60	-63
	750	-75	-78	-82	-85	-88	-91	-94	-98	-101	-104
		CO2 budget from 2018-2100 (Based on CH4 and N2O - GTC)									

(The range shown above roughly includes the emissions range in the RCP scenarios)

H. CO2 Emissions Budget Adjustments

- Freshwaters emit at least 103 megatons (Mt) of CH4 per year
- Older climate models likely underestimated the radiative forcing of methane by 25%

Adjusting a budget where the climate sensitivity is 2.8 and the temperature increase is 1.75°C:

CO2 Cumulative Emissions	GTC	115	Initial CO2 emissions budget
CH4 2100 Emissions	Mt	250	
N2O Cumulative Emissions	Mt	950	
IPCC 1.5°C report feedbacks	GTC	-30	
CH4 - 25% additional forcing	GTC	-32	=(5.1 GTC/10 Mt CH4) * 250 * 0.25
CH4 - Additional emissions	GTC	-64	=(5.1 GTC/10 Mt CH4) * 100 * 1.25
Adjusted CO2 Emiss. Budget	GTC	-11	(Adjusted anthropogenic CO2 budget)

With adjustments likely needed for climate sensitivity, CH4, and natural emissions, we should plan on there being no remaining anthropogenic CO2 emissions budget.

CO2 Budget Formula Variables

I. Temperature Target

- IPCC goal: hold the increase to well below 2°C and pursue efforts to limit the temperature increase to 1.5°C
- The temperature increase will almost certainly exceed 1.5°C by mid-century (and possibly by 2028) and will very likely exceed 2.0° C well before 2100.

By capturing and sequestering enough CO2 any temperature target can be met.

J. Anthropogenic Greenhouse Gas Emissions

- Greenhouse gas emissions will increase about 1% per year through 2030 under current policies (latest UN "Emissions Gap Report")
- Entrenched interests (fossil fuels, etc.) are interested in maintaining the status quo
- Our society has not taken any really serious steps to reduce greenhouse gas emissions

Estimating 2018-2100 CO2 emissions based on a peak year and percent change per year:

	Peak Yr:	2020			2030			2050		
Pct Chg to Peak Yr:		0	1	2	0	1	2	0	1	2
Annual % Change After Peak Yr	0	858	900	943	858	982	1123	858	1133	1509
	-1	609	638	668	661	753	858	751	981	1294
	-2	457	478	500	534	605	686	672	870	1137
	-3	360	377	394	449	507	572	615	788	1022

With a lot of inertia in our energy system, reducing emission quickly is not likely.

K. CH4 and N2O Emissions

For CH4, the difference between RCP 2.6 and RCP 8.5 is equivalent to about 290 GTC of CO2, so our emphasis also needs to be on ways to reduce CH4 emissions.

It would be very helpful to have some detailed scenarios on possible emission pathways for CH4 and N2O in order to help understand what the tradeoffs are.

L. Climate Sensitivity

- The "IPCC 1.5°C Report" uses "transient climate response" (TCR): the amount of warming that might occur at the time when CO2 doubles, having increased gradually by 1% each year.
- The average value of the calculated TCR for 45 scenarios where the temperature increase was between 1.45°C and 1.55°C is 2.46.
- Newer global climate models indicate that our climate is more sensitive to GHG emissions.

In the "IPCC 1.5°C Report" the average year when the models predict that 1.5°C will be exceeded is 2033. A recent analysis shows this happening 2.5 years earlier.

M. Natural Emissions

Feedbacks - GHGs	Carbon Store (GTC)	Possible emissions through 2100 (GTCe)
IPCC 1.5° Report		27
Permafrost	1,600	120
Soils		55
Peat	270 to 370	100
Surface waters	CH4 - 100Tg/yr	60
Forests		Forests will likely turn from sinks to sources (as is currently happening in the Arctic)
Methyl Hydrates	5,000 to 20,000	
Amazon	86	The Amazon could transition to a savannah

Observations

N. Carbon Capture and Sequestration (and Costs)

- Significant carbon capture and sequestration will be required to meet even a 2° C budget
- There are many way to capture and sequester carbon: carbon capture and storage (CCS), direct air capture (DAC), iron ocean fertilization, reforestation, rebuilding soils, etc.
- Average carbon capture and sequestration costs are hard to come by. An average cost of $100/ton CO2 seems like a good estimate for the period 2018-2050.

If our global society is not willing to fund very significant carbon capture and sequestration (due to high costs at the scale needed) there is a good chance that we could end up with a "hothouse Earth" that is incompatible with life as we know it.

(With BAU, CO2e could be over 750 PPM in 2100. With a temperature increase over 5°C there could be quite significant CH4 emissions from methyl hydrates.)

O. What is a "Fair" Carbon Budget for the US?

- The global carbon budget for 1800 to 2100 is approximately 3,270 GTCO2e (for the 50th percentile of model runs for a 1.75° temperature increase: 1940 + 290 + 1040)
- Historical US CO2 emissions have been about 17% of this budget (and 25% of historical CO2 emissions)
- The US has about 4% of the world's population; as seen by other countries, what is the US's "fair share" of the 3,270 GTCO2 global carbon budget?

If future US CO2 emissions are 100 GTCCO2 and average capture and sequestration costs are $100/Ton CO2, then the US would need to spend at least $10 Trillion (about 1/2 of the total US debt) in the next 40 years to capture future CO2 emissions.

(If US CO2 emissions decline from the current 5.3 GTCO2/year by 2.6% of current emissions per year until emissions reach zero in 2057, cumulative emissions will be about 100 GTCO2.)