What are the Expected CDR costs to Reach a Temperature Target by 2100?

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http://ccdatacenter.org/documents/CDRCostExpectations.pdf

- Even if climate geoengineering techniques [,which includes carbon dioxide removal,]were ever actively pursued, and eventually worked as envisioned on global scales, they would very unlikely be implementable prior to the second half of the century[1]
- If politicians and advisers think it is acceptable to emit carbon now and claw it back later, they might take more risks and obstruct mitigation in the real world[2]

The total temperature increase expected at the end of this century will be due to five major factors: (1) the net quantity of CO2 emissions this century (anthropogenic emissions plus natural emissions minus CO2 removed), (2) the amount of this CO2 that is absorbed by the oceans and biosphere, (3) the total non-CO2 radiative forcing (which is influenced by the quantity of anthropogenic and natural methane emissions in the last decade of this century) , (4) how much the albedo changes in the Arctic region, and (5) how the clouds change in response to global warming (note that the latter two usually included as components of climate sensitivity). Of these, humans only can affect the first and third, as the others represent a natural response to global warming .

Carbon dioxide removal costs can then be estimated by selecting a temperature target, estimating a carbon emissions budget for the temperature target, and estimating anthropogenic and natural emissions from now until 2100. The difference between the latter two is the amount of CO2 that needs to be removed from the atmosphere and the CDR costs can be estimated by multiplying this value by the estimated cost per ton to remove CO2 from the atmosphere and sequester it. Since there are many climate factors involved, the estimated costs will vary considerably and can best be presented a series of tables.

The following information can be used to create the tables:

- Anthropogenic emissions are expected to peak by 2030 and then decline. The tables in Appendix 1A specify the amount of emissions from 2018 to 2100 for various peak years and emission change percents after the peak year.
- Natural emissions between now and 2100 will be significant, perhaps 100 GTC (See Appendix 1B)
- An estimate of the amount of this CO2 that is absorbed by the oceans and biosphere(#2 above) for a given amount of CO2 emissions can be obtained by developing a formula based on the results of climate models. This formula can then be used to calculate a CO2 budget bases on non-CO2 radiative forcing, climate sensitivity, and equilibrium temperature (see Appendix 2).
- Non-CO2 radiative forcing is now about 1.1 W/m-2 and is expected to decline by 2100. A reasonable range of values is 0.3 to 1.2 W/m-2 (see Appendix 3)
- A value for the future climate sensitivity is very difficult to predict, primarily due to how much the albedo changes in the Arctic region, and how the clouds change in response to global warming. A reasonable range of values is 2.4 to 4.0 (see Appendix 4)

These tables can then be use to estimate CDR costs. For example, If the climate sensitivity is 3.0 and we can limit the non-CO2 radiative forcing to 0.75 W/m-2 and anthropogenic emissions are 450 GTC (which is relatively aggressive), then the equilibrium temperature will be about 3.0° C. It will then cost about $50 trillion to limit the temperature increase to 2° C and about $80 trillion to limit the temperature increase to 1.5° C.

Based on the above, the following tables can be created:

		Climate Sensitivity																			
		2.4					3.0					3.4					3.8				
		Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)				
		0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25
Equil Temp	0.0	-400	-447	-491	-534	-575	-400	-447	-491	-534	-575	-400	-447	-491	-534	-575	-400	-447	-491	-534	-575
	0.5	-186	-243	-297	-348	-398	-229	-284	-336	-385	-433	-249	-303	-354	-403	-450	-265	-318	-369	-417	-463
	1.0	28	-39	-102	-163	-220	-58	-120	-180	-237	-291	-98	-159	-217	-272	-325	-130	-189	-246	-299	-351
	1.5	241	165	92	23	-43	113	43	-24	-88	-149	53	-15	-79	-141	-199	5	-60	-123	-182	-239
	2.0	455	369	287	209	134	284	206	131	60	-8	203	129	58	-10	-74	140	68	0	-65	-127
	2.5	669	573	482	395	312	455	369	287	209	134	354	273	196	122	51	275	197	123	52	-15
	3.0	882	777	676	580	489	626	532	443	358	276	505	417	333	253	176	410	326	246	170	97
	3.5	1096	981	871	766	666	797	695	599	506	418	656	561	470	384	301	545	455	369	287	209
	4.0	1310	1185	1066	952	843	968	859	754	655	560	807	705	608	515	426	680	584	492	404	321
		Anthropogenic CO2 Budget (GTC)																			
		=CO2 Budget -100 (Natural emissions)																			

Table 1. Anthropogenic CO2 Budget for an equilibrium temperature, climate sensitivity, and non-CO2 radiative forcing for a 100 GTC of natural emissions

For an "aggressive" CO2 emissions reduction scenario (2 percent per year after 2025), about 400 GTC of CO2 will be emitted (see Appendix 1A). The following tables show the CDR requirements and costs for $100/ton C for CDR. Note that a cost of $200/ton is more likely, but $100/ton was used to allow easy calculations for other estimated costs.

		Climate Sensitivity																			
		2.4					3.0					3.4					3.8				
		Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)				
		0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25
Equil Temp	0.0	800	847	891	934	975	800	847	891	934	975	800	847	891	934	975	800	847	891	934	975
	0.5	586	643	697	748	798	629	684	736	785	833	649	703	754	803	850	665	718	769	817	863
	1.0	372	439	502	563	620	458	520	580	637	691	498	559	617	672	725	530	589	646	699	751
	1.5	159	235	308	377	443	287	357	424	488	549	347	415	479	541	599	395	460	523	582	639
	2.0	-55	31	113	191	266	116	194	269	340	408	197	271	342	410	474	260	332	400	465	527
	2.5	-269	-173	-82	5	88	-55	31	113	191	266	46	127	204	278	349	125	203	277	348	415
	3.0	-482	-377	-276	-180	-89	-226	-132	-43	42	124	-105	-17	67	147	224	-10	74	154	230	303
	3.5	-696	-581	-471	-366	-266	-397	-295	-199	-106	-18	-256	-161	-70	16	99	-145	-55	31	113	191
	4.0	-910	-785	-666	-552	-443	-568	-459	-354	-255	-160	-407	-305	-208	-115	-26	-280	-184	-92	-4	79
		CDR Requirements (GTC) for 400 GTC of Anthropogenic Emissions																			
		=(0 - Anthropogenic CO2 Budget -400)																			

Table 2. CDR Requirements for 400 GTC of Anthropogenic Emissions

		Climate Sensitivity																			
		2.4					3.0					3.4					3.8				
		Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)					Non-CO2 RF (W/m-2)				
		0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25	0.25	0.50	0.75	1.00	1.25
Equil Temp	0.0	80	85	89	93	97	80	85	89	93	97	80	85	89	93	97	80	85	89	93	97
	0.5	59	64	70	75	80	63	68	74	79	83	65	70	75	80	85	66	72	77	82	86
	1.0	37	44	50	56	62	46	52	58	64	69	50	56	62	67	72	53	59	65	70	75
	1.5	16	23	31	38	44	29	36	42	49	55	35	41	48	54	60	39	46	52	58	64
	2.0	-5	3	11	19	27	12	19	27	34	41	20	27	34	41	47	26	33	40	46	53
	2.5	-27	-17	-8	1	9	-5	3	11	19	27	5	13	20	28	35	13	20	28	35	41
	3.0	-48	-38	-28	-18	-9	-23	-13	-4	4	12	-11	-2	7	15	22	-1	7	15	23	30
	3.5	-70	-58	-47	-37	-27	-40	-30	-20	-11	-2	-26	-16	-7	2	10	-14	-5	3	11	19
	4.0	-91	-78	-67	-55	-44	-57	-46	-35	-25	-16	-41	-30	-21	-11	-3	-28	-18	-9	0	8
		CDR Costs ($Trillions) for400 GTC of Anthro Emissions and $100 /Ton C for CDR																			
		0.1 * (0 - Anthropogenic CO2 Budget - 400)																			

Table 3. CDR Costs for 400 GTC of Anthropogenic Emissions and an average CDR cost of $100/ton C

The spreadsheet http://ccdatacenter.org/documents/CalcCDRCosts.xlsxcan be use to produce tables for other values of anthropogenic emissions, natural emissions, and CDR cost/ton C.

Appendix 1A - Anthropogenic Emissions from 2018 to 2100

Anthropogenic emissions from 2018 to 2100 based on peak year

9.86	2015 Fossil Fuel Emissions (GTC)
1.6	2015 land use emissions (GTC)
2070	Year when land use emissoins reach zero
0.029091	Land use decline/year (GTC)

	Peak Yr:	2020			2025			2030		
	Pct Chg to	0	1	2	0	1	2	0	1	2
Annual	0	846	888	931	846	929	1019	846	969	1111
Pct	-1	526	552	578	565	633	709	601	712	840
Change	-2	299	312	327	348	393	444	397	478	579
of Peak	-3	216	226	236	266	297	333	315	373	445
Yr After	-4	175	183	191	225	250	278	274	320	377
		Emissions 2018-2100			Emissions 2018-2100			Emissions 2018-2100		

	Peak Yr:	2020			2025			2030		
	Pct Chg to	0	1	2	0	1	2	0	1	2
Annual	0	881	923	966	881	964	1055	881	1005	1146
Pct	-1	632	661	691	659	718	783	684	776	881
Change	-2	480	501	523	519	564	613	557	628	709
After	-3	383	400	417	428	464	502	472	530	595
Peak Yr	-4	320	333	347	367	397	428	414	462	517
		Emissions 2018-2100			Emissions 2018-2100			Emissions 2018-2100		

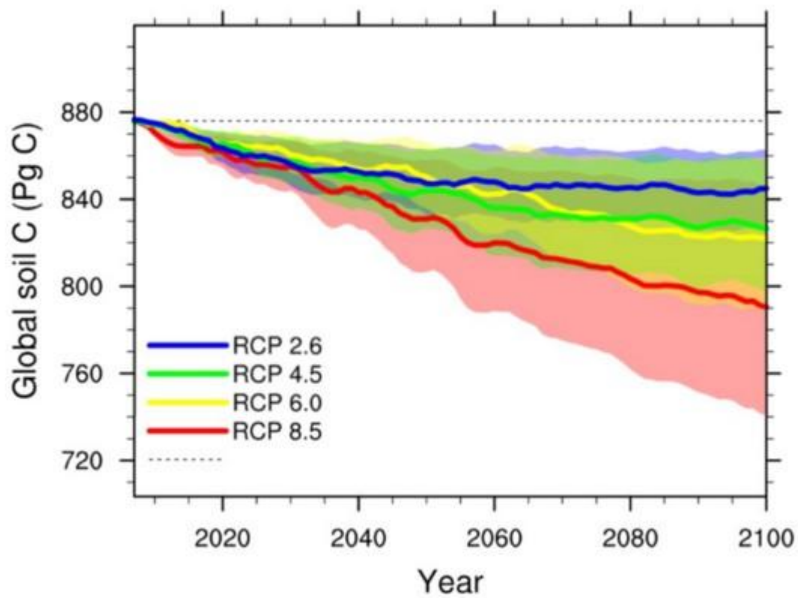
Table 4. Anthropogenic Emissions

(see http://ccdatacenter.org/documents/CalcCDRCosts.xlsx for details)

Appendix 1B - Natural Emissions from 2018 to 2100

Emissions from natural feedbacks will come from permafrost, wetlands, surface waters, soils, etc. A "good working number" is perhaps 100 GTC.

- Emissions from permafrost and wetlands will "likely" be about 200 GTCO2 (https://www.carbonbrief.org/permafrost-wetland-emissions-could-cut-1-5c-carbon-budget-five-years)
- "[G]lobally, lakes and manmade "impoundments" like reservoirs emit about one-fifth the amount of greenhouse gases emitted by the burning of fossil fuels" "[S]cientists have found that this surge in aquatic plant growth could double the methane being emitted from lakes [(to 40% of current fossil fuel emissions)] ... over the next 50 years." https://climatecrocks.com/2018/05/17/in-lakes-cat-tails-and-algal-blooms-could-be-a-toxic-methane-feedback/
- We found that about 55 trillion kg of carbon could be lost by 2050. This value is equivalent to an extra 17% on top of current expected emissions over that time. These losses are like having another huge carbon emitting country on the planet, accelerating the rate of climate change.



https://medium.com/@Alex_Verbeek/another-reason-to-be-worried-about-climate-change-1bf1e21e78e#.bzhqdsrsz

Appendix 2 - CO2 Uptake Formula

(see http://ccdatacenter.org/documents/CO2UptakeExpectations.pdf for details)

- The ocean and biosphere currently absorb about 55% of anthropogenic CO2 emissions[1]
- The amount absorbed varies greatly from year to year and will likely decrease later this century[2,3,4]
- For the case where the CO2 removed by CDR does not exceed the CO2 emissions, the relationship between total CO2 emitted from 2015 to 2100 and atmospheric CO2 in 2100 is close to linear in both the MAGICC and C-ROADS models:

  "2100 CO2 PPM" = 0.2586 * CO2 Emissions 2016-2100 + 342.87

- This allows a CO2 "budget" to be specified for an equilibrium temperature, climate sensitivity, and amount of non-radiative forcing in 2100[5,6,7] by using the formula:

  CO2 Budget = (278 * e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35) - 342.87)/ 0.2586

- If we can limit net emissions to about 250 GTC, the ocean and biosphere will absorb all of the emitted CO_2 and atmospheric CO_2 will eventually return to the current level[5,6,7]

Net CO2 Emission (GTC)	200	250	300	350	400	450	500	550	600	650	700	750
2100 CO2 PPM	395	408	420	433	446	459	472	485	498	511	524	537
Added To Atmosphere	-20	7	35	62	90	117	145	172	199	227	254	282
Net Removed from Atmosphere	220	243	265	288	310	333	355	378	401	423	446	468
Percent Added to Atmosphere	-10	3		18	22	26	29	31	33	35	36	38

Table 5. "implications" of Net CO2 Emissions

Appendix 3 - Non CO2 RF

			IPCC Radiative Forcing Estimates				
Greenhouse Gas	Chemical Formula	Residency Time	2011	2100 - RCP 2.6	2100 - RCP 4.5	2100 - RCP 6.0	2100 - RCP 8.5
Carbon dioxide	CO_2	5-200	1.68	2.22	3.54	4.7	6.49
Nitrous oxide	N_2O	114	0.17	0.23	0.32	0.41	0.49
CFCs		45-85	0.337	0.1	0.1	0.1	0.1
Methane	CH_4	12	0.97	0.27	0.41	0.44	1.08
Other Climate Factors			-0.867	-0.22	0.13	0.35	0.34
Total			2.29	2.6	4.5	6	8.5

Table 6. IPCC Radiative Forcings

Appendix 4 - Climate Sensitivity

Footnotes

1	**Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals** Abstract Current mitigation efforts and existing future commitments are inadequate to accomplish the Paris Agreement temperature goals. In light of this, research and debate are intensifying on the possibilities of additionally employing proposed climate geoengineering technologies, either through atmospheric carbon dioxide removal or farther-reaching interventions altering the Earth's radiative energy budget. Although research indicates that several techniques may eventually have the physical potential to contribute to limiting climate change, all are in early stages of development, involve substantial uncertainties and risks, and raise ethical and governance dilemmas. Based on present knowledge, climate geoengineering techniques cannot be relied on to significantly contribute to meeting the Paris Agreement temperature goals. Closing paragraph: "....based on the current knowledge reviewed here, proposed climate geoengineering techniques cannot be relied on to be able to make significant contributions, e.g., at the levels of CDRref or RFGref, towards counteracting climate change in the context of the Paris Agreement. Even if climate geoengineering techniques were ever actively pursued, and eventually worked as envisioned on global scales, they would very unlikely be implementable prior to the second half of the century15. Given the rather modest degree of intended global mitigation efforts currently reflected in the NDCs (Fig. 2 and Supplementary Table 1), this would very likely be too late to sufficiently counteract the warming due to increasing levels of CO_2 and other climate forcers to stay within the 1.5 °C temperature limit—and probably even the 2 °C limit—especially if mitigation efforts after 2030 do not substantially exceed the planned efforts of the next decade. Thus at present, the only reliable way to attain a high probability of achieving the Paris Agreement goals requires considerably increasing mitigation

	efforts beyond the current plans, including starting extensive emissions reductions much sooner than in the current NDCs." https://www.nature.com/articles/s41467-018-05938-3#article-info
2	**Don't deploy negative emissions technologies without ethical analysis** - " A lack of transparency and ethical discussion has three consequences. First, policymakers have false expectations. This is the 'moral hazard' worry: if politicians and advisers think it is acceptable to emit carbon now and claw it back later, they might take more risks and obstruct mitigation in the real world. For example, in IPCC scenarios with CO_2 retrieval, emissions from fossil fuels and industry can remain as high as 32 gigatonnes of CO_2 in 2030 (see 'Three-fold folly', top panel). Without CO_2 removal, emissions would have to be reduced to 23 gigatonnes of CO_2 by 2030 — a difference almost equivalent to China's emissions each year since 2008". https://www.nature.com/articles/d41586-018-06695-5
	Company captures carbon dioxide from the air in quest to avoid CO_2 shortages 23 July 2018 (Climeworks) The 18-turbine plant is able to supply around 900 tons of CO_2 annually - or the approximate level released from 200 cars but at a heavily subsidised rate. The farm is paying market rates of approximately 100 to 200 Swiss Francs (£77 to £153) but it costs about 600 Swiss Francs (£461) to extract it from the air. Chief executive and co-founder Jan Wurzbacher told Sky News he hopes to overcome the cost with scale and improvements in the technology. https://news.sky.com/story/company-captures-carbon-dioxide-from-the-air-in-quest-to-avoid-co2-shortages-11446011