Carbon Dioxide Removal - U.S. Cost Expectations

Bruce Parker August 25, 2018

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

Climate scientists have known for many years that we will not be able to meet the Paris temperature target ("well below 2.0°) without capturing and sequestering vast amounts of carbon dioxide by either natural and/or mechanical means. And if affordable carbon capture methods can be implemented then almost any temperature increase target can eventually met by removing sufficient carbon dioxide from the atmosphere. Because the quantity of additional emissions from natural feedbacks is dependent on the temperature increase (with a 1.5°C increase often being seen as threshold where the natural emissions become significant), some people are advocating for removing many tens of gigatons of CO2 in the near term in order to avoid the need to also remove the natural emissions. However, if natural emissions are expected to amount to about 100 GTC[1] and anthropogenic emissions are expected to be at least 700 GTC (which is likely given the power of vested interests), then delaying most of the CO2 removal until the removal process becomes much more affordable might make economic sense.

Assuming that there is, at most, only a small "carbon budget" left[2,3] , we need to eventually capture and sequester almost all of the CO2 emitted after this year in order to prevent the effects of climate change from becoming very disruptive to our civilization. Using Hansen's $450/tC as a rough estimate[4], we, in the U.S., should be spending about $1,900 per person per year (about $700 billion total) for the next 30-50 years to capture and sequester carbon (note that as U.S. emissions are reduced the annual amount of CO2 we would need to remove would remain essentially the same in order to account for historical cumulative U.S. emissions). The cost per ton of removing carbon dioxide will almost certainly drop in the next 30-50 years but the average annual CDR costs would likely be over $500 billion per year for the U.S. to capture and sequester its share of future CO2 emissions (for a total of about $25 trillion). Looking the U.S. share of global CO2 removal costs this century yields a similar cost estimate: if global CO2 anthropogenic emissions are in the 600 GTC range between now and 2100[3] and the average "removal" cost over the century (BECCS, CCS, DAC, soil restoration, reforestation, oceanic sequestration, etc.) might be about $250/tC (partly due to the need to "front load" the removals) then the total global removal costs would then be about $175 trillion. The U.S. share of this might be about 15% due to historical and future emissions, or about $25 trillion. (Note that mitigation costs are not included in either estimate.)

Meeting the Paris temperature target then comes down to a funding issue. We can certainly *afford* to remove the required CO2 from the atmosphere as it's only about 2.5% of our GDP. But will politicians (and their donors) be willing to *fund* the costs by agreeing to a massive tax increase to pay for the carbon dioxide removal? Given vested interests (both fossil fuel companies and oligarchs who want even more tax cuts), our current national debt, the public being unaware of the magnitude of the problem and the needed sacrifice, and the fact that most of the money spent on carbon capture will produce no tangible benefits (other than reducing the costs of future natural disasters), it's hard to imagine that, unless the costs of CDR drop substantially, that politicians will be willing to budget the necessary funds or that private industry will be willing to contribute much. (Note that a price on carbon should include the cost of capturing and sequestering CO2 from the atmosphere as that cost must eventually be incurred to remove the emitted CO2 from the atmosphere. Any rebated carbon tax would need to be in addition to the capture and sequestration cost.)

Our climate strategy for the next 20-30 years will likely remain pretty much the same as it is today - work hard to mitigate greenhouse gas emissions where it makes economic sense and fund R&D to reduce carbon dioxide removal cost. In other words, let the "free market" determine how much CO2 is emitted, with governments providing some incentives to reduce emissions (e.g., tax credits, renewable portfolio standards, carbon taxes, carbon caps, electric vehicle mandates, CAFE standards, power plant emission regulations, etc.) . But this will likely not be anywhere near sufficient to limit the temperature increase to 3.0 °C (let alone "well under 2.0 °C") because the necessary funding for carbon dioxide removal will almost certainly be missing.

Summary and Assumptions

- Realistically (for a climate sensitivity over 3 and non-CO2 radiative forcing over 0.6 W/m-2) there is, at most, only a small "carbon budget" left[2,3] that will allow meeting the Paris temperature target of "well below 2.0°C"
- Cumulative natural emissions will be at least 100 GTC before 2100[1]
- Cumulative anthropogenic emissions will be at least 600 GTC before 2100[3]
- Meeting the Paris temperature target requires capturing and sequestering vast amounts of CO2 (likely more that 700 GTC)
- Average carbon dioxide removal costs are currently about $450/ton C[4]
- Average carbon dioxide removal costs between now and 2050 will likely be greater than $250/ton C
- Cumulative global CDR costs would likely be over $175 trillion ($25 trillion for the U.S.) by 2100 if the Paris temperature target is to be met
- Governments are unlikely to fund significant CDR unless CDR costs can be reduced significantly (perhaps by an order of magnitude)
- Climate scientists and environmental groups have not done a good job of informing the public as to what needs to be done
- We are likely on a path to a "hot house" Earth with very little chance of avoiding 4°C by 2100 by only relying on mitigation and carbon dioxide removal techniques.

Other observations and items of interest

- The temperature increase will likely be around 1.5°C by 2030, 2°C by 2050, and at least 4°C" by 2100[5]
- A 2017 study found that a 4.0°C average temperature increase is expected based on progress towards decarbonizing the economy[6] (and the study likely did not include significant emissions from natural feedbacks)
- Future temperature increases are likely to be much more than the current models have predicted[3,5]
- It is important to use high-end climate sensitivity because some studies have suggested that climate models have underestimated three major positive climate feedbacks. This would result in a temperature increase of about 5.5-5.7°C by 2100 for the IPCC's 2.0°C carbon budget.[5]
- "Warming of 4°C or more could reduce the global human population by 80% or 90%,35 and the World Bank reports “there is no certainty that adaptation to a 4°C world is possible”"[7]
- "Many researchers are concluding that ecological systems around the planet will not be able to tolerate temperature rise much beyond 1.5°C."[8]
- Global warming is shifting many forests from carbon sinks to carbon sources, thus increasing natural emissions and reducing the CO2 uptake in the biosphere[1]
- The biggest danger to our civilization is that weather patterns will likely shift in response to global warming, potentially disrupting food production and causing widespread famines.
- We should expect an equilibrium sea level rise of about 30 feet if the Earth's average temperature increases 1°C and about 60 feet for 2°C, although it will likely take a thousand years or so to reach equilibrium[9]
- We could have between one and two meters of sea level rise by 2100, but the sea level will continue to rise well after 2100 before reaching equilibrium[9]
- Flood losses in major coastal cities around the world may exceed $1 trillion dollars per year as a consequence of sea level rise by 2050[9]
- By 2050, live corals could become rare in tropical and sub-tropical reefs due to the combined effects of warmer water and increased ocean acidity[10].
- Oceans could lose up to $1 trillion in annual value by 2100 due to acidification[10]
- The "cost of action" ($25 trillion for the U.S.) is much more than the "cost of inaction"(which would need to be roughly 3 Hurricane Katrinas per year to match the "cost of action")

End notes

1 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

Global warming is shifting many forests from carbon sinks to carbon sources, thus increasing natural emissions and reducing the CO2 uptake in the biosphere
From **What Lies Beneath** (download PDF from https://www.breakthroughonline.org.au/) (Page 25)

2 Current climate models can be used to develop a formula which provides a rough estimate of the atmospheric CO2 in 2100 based on CO2 emissions from 2016-2100. For the case where the CO2 removed by CDR exceeds the CO2 emissions, results from the MAGICC model were used to create a polynomial equation that provides such an estimate:

"2100 CO2 PPM" = 0.0000522 * Emissions * Emissions + 0.20778 * Emissions + 347.0537
(where Emissions = CO2 Emissions 2016-2100)

The following table shows the estimated CO2 PPM values for a range of emissions:

PPM Calculations based on Emissions (polynomial equation)										
Emissions	-250	-200	-150	-100	-50	0	50	100	150	200
CO2 PPM	298	308	317	327	337	347	358	368	379	391
CO2 Removed	475	405	335	264	193	121	49			

Note that net-zero emissions results in an atmospheric concentration of CO2 of about 350 PPM , the value recommended by Dr James Hansen

http://ccdatacenter.org/documents/CO2UptakeExpectations.pdf

3 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 . The following table shows an estimated anthropogenic carbon budget for various equilibrium temperatures, climate sensitivities, and non-CO2 radiative forcing for 100 GTC of natural emissions using a formula for oceanic and biosphere uptake based on the MAGICC and C-ROADS climate models.

		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 (cells marked in "yellow" bracket the anthropogenic emissions budget for "well below 2° C" for a realistic range of non-CO2 radiative forcing)

1. **Natural Emissions** from 2018 to 2100 will likely exceed 100 GTC (see Footnote 1 above)

2. **Non-CO2 RF in 2100** may be in the range 0.5-1.0 W/m-2 based on IPCC estimates. The actual value will depend on how quickly methane emissions and fossil fuel emissions can be reduced (the latter being responsible for most the aerosols that mask 0.5-1.1° C of warming). Note that for RCP 4.5 the estimate for non-CO2 RF is about 1 W/m-2

			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	CO2	5-200	1.68	2.22	3.54	4.7	6.49
Nitrous oxide	N2O	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	CH4	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 Forcing

3. **Climate Sensitivity**

- Climate sensitivity which includes "long term" feedbacks (Earth System Sensitivity - ESS) is likely between 4–6° C [1]
- The rate of change in energy forcing is now so great that “long-term” feedbacks have already begun to operate within short time frames[2]

- Recently it has been demonstrated the models that best capture current conditions have a mean value of 3.7°C compared to 3.1°C by the raw model projections[3]
- The authors conclude that in warmer periods climate sensitivity averages around 4.88°C[2]
- It is important to use high-end climate sensitivity because some studies have suggested that climate models have underestimated three major positive climate feedbacks[2]

(See http://ccdatacenter.org/documents/ClimateSensitivityExpectations.pdf for footnotes for the above)

Based on the above, a good "planning range" for climate sensitivity for estimating the temperature increase in2100 is 3.4 to 3.8. Even for a climate sensitivity of 3.0, the anthropogenic CO2 emissions budget has already been exceeded for an equilibrium temperature increase of 1.5°C and non-CO2 radiative forcing over about 0.6 W/m-2.

4. **Anthropogenic CO2 Emissions**

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
0.029	Land use decline/year (GTC)
22	Anthropogenic Emissions 2016-2017

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

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

Conclusion

Based on the above, any remaining anthropogenic carbon budget which results in an equilibrium temperature "well below 2.0 °C" is quite small (see cells marked in "yellow" in Table 1 above) relative to expected anthropogenic emissions of greater than 600 GTC.

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

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Cost of Carbon Capture: Can Young People Bear the Burden?

James Hansen[a,b] and Pushker Kharecha[a]

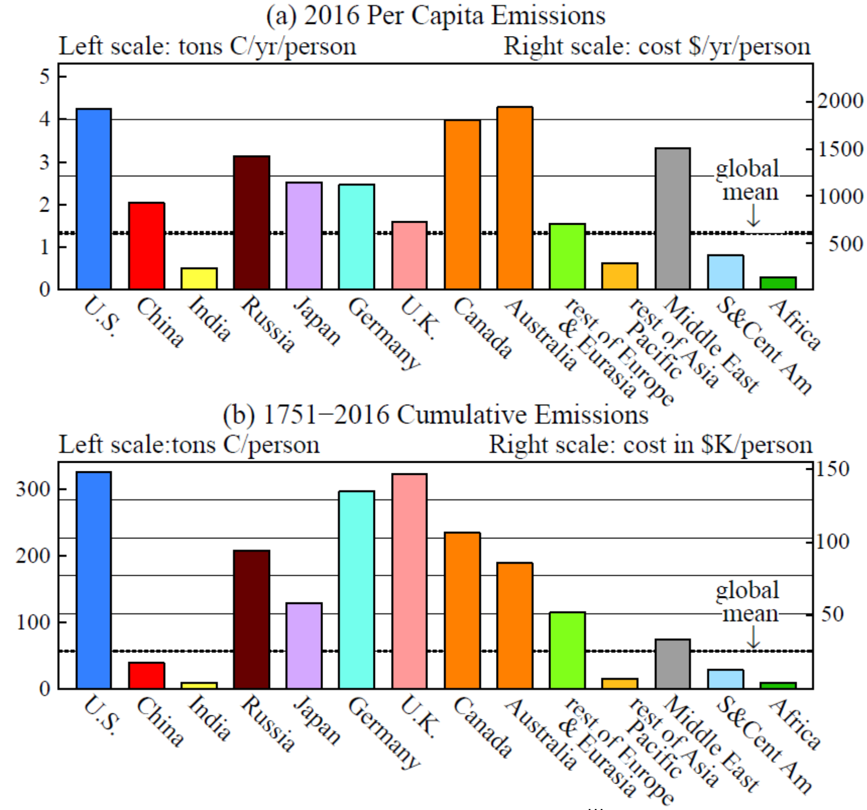

Figure 2. Update of Figure 6 of Hansen and Sato[10]. Per capita cost for extraction of the emitted CO_2 (right scale) assumes an extraction cost of \$124/tCO_2 [(\$450/tC)]

https://www.sciencedirect.com/science/article/pii/S2542435118303465

Figure 1. Carbon Capture Cost Estimate *(per capita emissions are for all greenhouse gasses)*

5 http://ccdatacenter.org/documents/TempIncreaseExpectations.pdf

6 "Our Climate Progress Dashboard monitors 12 indicators to show the progress being made towards decarbonising the global economy. It compares projections made by international organisations to estimate the temperature change implied by the progress in each area. Together, they suggest we are heading for a rise closer to 4° than the 2° commitment global leaders made in Paris in 2015." https://www.schroders.com/en/about-us/corporate-responsibility/sustainability/climate-progress-dashboard/

7 From **What Lies Beneath** (download PDF from https://www.breakthroughonline.org.au/) (Page 14)

8 http://advances.sciencemag.org/content/4/8/eaau9981

9 http://ccdatacenter.org/documents/SeaLevelRiseExpectations.pdf

10 http://ccdatacenter.org/documents/OceanAcidificationExpectations.pdf