**A “Planning Number” for the $CO_2$ Removal Requirement from 2020 Through 2100 (DRAFT)**

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I’ve been “puzzling” through what to expect for global warming for over twenty years and finally reached the conclusion that one’s optimism or pessimism on “solving climate change” depends primarily on whether one expects (or does not expect) our society to be willing to pay the costs associated with limiting the temperature increase to a specific amount. Since it is not politically feasible to reduce greenhouse gas emissions quickly enough to limit the temperature increase to 1.5°C (or even 2.0°C), there will be significant costs associated with removing $CO_2$ from both industrial processes (e.g., CCS for power pants) and the atmosphere (CDR) to meet the temperature goal 1.5°C (or even 2.0°C). So one’s optimism or pessimism on “solving climate change” can depend on what one’s assumptions are for estimating both the $CO_2$ removal requirement and the $CO_2$ removal cost. Note that assumptions can primarily be explicit (e.g., the world will come close to meeting the “net-zero $CO_2$ emissions in 2050 goal”) or implicit (e.g., the IPCC $CO_2$ budgets assume that anthropogenic methane emissions will decrease by 50% from 2020 values by 2050). There are roughly eight major assumptions:

| # | Assumption For | My Estimate |
|---|---|---|
| 1 | 2100 Temperature increase target (with post-2019 $CO_2$ budget of 400 GT $CO_2$) | 1.5°C |
| 2 | US responsibility for global CCS and CDR costs needed to reach a specific temperature increase target | 20-25% |
| 3 | Annual funding to help developing countries to either mitigate GHG emissions or for CDR in order to reach “net-zero $CO_2$ emissions” (not likely to happen) | $1Trillion |
| 4 | Cumulative gross anthropogenic $CO_2$ emissions 2020 through 2100 (excludes CCS and CDR) | 2000 |
| 5 | Cumulative $CO_2e$ emissions from natural feedbacks 2020 through 2100 (above that which was used to calculate the IPCC $CO_2$ budgets) | 500 |
| 6 | $CO_2e$ from non-$CO_2$ radiative forcing ($CH_4$, $N_2O$, aerosols, albedo, deforestation, etc.) above that which was used to calculate the IPCC $CO_2$ budgets | 500 |
| 7 | Equilibrium climate sensitivity (ECS) | 4.0 |
| 8 | Average CCS and CDR costs in 2050 (and how steep - or shallow - the “cost learning curves” will be) | $100 |

Based on the above assumptions, the total “carbon dioxide removal requirement” is likely to be between 1,500 and 3,000 GT$CO_2$ at a cost of between $150 and $300 Trillion (of which the US would be responsible for $30-60 Trillion). Although “affordable”, I would think that those costs are too high for the World’s politicians to be willing to actually spend the needed monies.

Some details for the above assumptions (see “Notes” below for additional background information)

1. The temperature increase target should be 1.5°C since a temperature increase above 1.5°C in 2100 will result in ecosystems collapse, an increase in natural disasters, etc.
    a. The global temperature is currently increasing by at least 0.27°C per decade and will likely continue to do so through at least 2040 (see Note 1 below)
    b. The global temperature increase will likely exceed 1.5°C by 2030 and 2.0°C by 2050
    c. The global post-2019 $CO_2$ budget for a 66% chance of limiting the temperature increase to 1.5°C is 400 GT $CO_2$

2. The US responsibility for the global CCS and CDR costs needed to reach a specific temperature increase target could be between 20% and 25% due to both historical emissions and wealth

3. Developed countries will not provide anywhere near enough funding to help developing countries to either mitigate GHG emissions or for CDR (see Note 3 below)
    a. The US should probably be donating at least $200 Billion/year to this effort (20% of the $1Trillion needed). Not doing this will cost the US significantly more in the long run because it is much cheaper to mitigate emissions today than it will be to remove the $CO_2$ from the atmosphere in several decades

4. Anthropogenic $CO_2$ emissions will not decline before 2030 (based on NDCs, IEA, and EIA), so the goal of reducing $CO_2$ emissions by 50% by 2030 will not even be close to being met (see Note 4 below)
    a. GHG emissions for non-OECD counties will not decline before 2040 and will not likely decline before 2050 (based on IEA, and EIA), partly because they want to "grow their economies" and have no incentive to reduce emissions beyond "BAU" (and will certainly not pay for CDR)
        i. Yes, the world is making progress on "climate solutions", but I defer to the "expert judgement" of CAT, EIA, and IEA when it comes to projecting future emissions
    b. After 2050, an optimistic projection of future anthropogenic $CO_2$ emissions (a linear reduction to net-zero $CO_2$ emissions in 2080) will result in cumulative emissions of about 2,000 GT $CO_2$
    c. Some of these emissions could be eliminated with CCS, but since only developed countries are apt to deploy CCS, a reasonable assumption for emissions reduction in 2050 from CCS might be 5%, or 2 GT $CO_2$/year. Given all of the uncertainties, this number is small enough to be ignored.

5. Cumulative $CO_2e$ emissions from natural feedbacks 2020 through 2100
    a. Even if the temperature increase in 2100 is 1.5°C, the extended "overshoot" of 1.5°C will result in significant $CO_2e$ emissions from natural feedbacks and the collapse of ecosystems (at least 500 GT$CO_2$ beyond what is included in the IPCC budget calculations??)

6. $CO_2e$ from non-$CO_2$ radiative forcing
    a. The global pledges to reduce both methane emissions and emissions from deforestation will likely not be met, perhaps increasing the "$CO_2$ removal requirement" by at least another 500 GT$CO_2$ (see Note 6 below)

4,5,6:

- Cumulative $CO_2$ emissions from all sources from 2020 to 2100 will likely be between 2,000 GT$CO_2$ and 3,000 GT $CO_2$
- Based on the IPCC $CO_2$ budgets for a 66% chance of limiting the temperature increase, without mitigation the temperature increase in 2100 will likely be between 2.6°C and 3.2°C
- Based on the IPCC $CO_2$ budgets for a 66% chance of limiting the temperature increase to 1.5°C, the $CO_2$ removal requirement will likely be between 1,600 GT $CO_2$ and 2,600 GT $CO_2$
- If the $CO_2$ is to be removed over a period of 50 years, the average annual CDR amount to limit the temperature increase to 1.5°C will be between 30 and 50 GT$CO_2$

7. If equilibrium climate sensitivity (ECS) is closer to 4.0°C (see Hansen), the "$CO_2$ removal requirement" for a specific temperature increase would likely be at least an additional 500 GT$CO_2$
    a. If equilibrium climate sensitivity (ECS) is closer to 4.0°C, the temperature increase in 2100 could be closer to 4.0°C
    b. If equilibrium climate sensitivity (ECS) is closer to 4.0°C, the $CO_2$ removal requirement will likely be between 2,100 GT $CO_2$ and 3,300 GT $CO_2$
    c. If equilibrium climate sensitivity (ECS) is closer to 4.0°C and the $CO_2$ is to be removed over a period of 50 years, the average annual CDR amount to limit the temperature increase to 1.5°C will be between 40 and 60 GT$CO_2$

8. If average CCS and CDR costs are $100/ton, the global mitigation and removal costs will likely be between $3 and 6 Trillion/year (ramping to that amount from essentially zero to day to $3 and 6 Trillion/year in 2050)
    a. It will likely cost $10-15 Trillion to reduce the global temperature by 0.1°C (see Note 8 below)
    b. If the US is responsible for 20% of the costs (since developing nations will not pay) then the US should expect to pay $0.6 and 1.8 Trillion per year
    c. I believe that most people in the US assume the that the US responsibility for dealing with climate change will be satisfied it the US gets net-zero $CO_2$ in 2050. Unfortunately this is not the case. The cost

of meeting the US's DAC responsibility will be significantly greater than the cost of reaching net-zero $CO_2$ in 2050

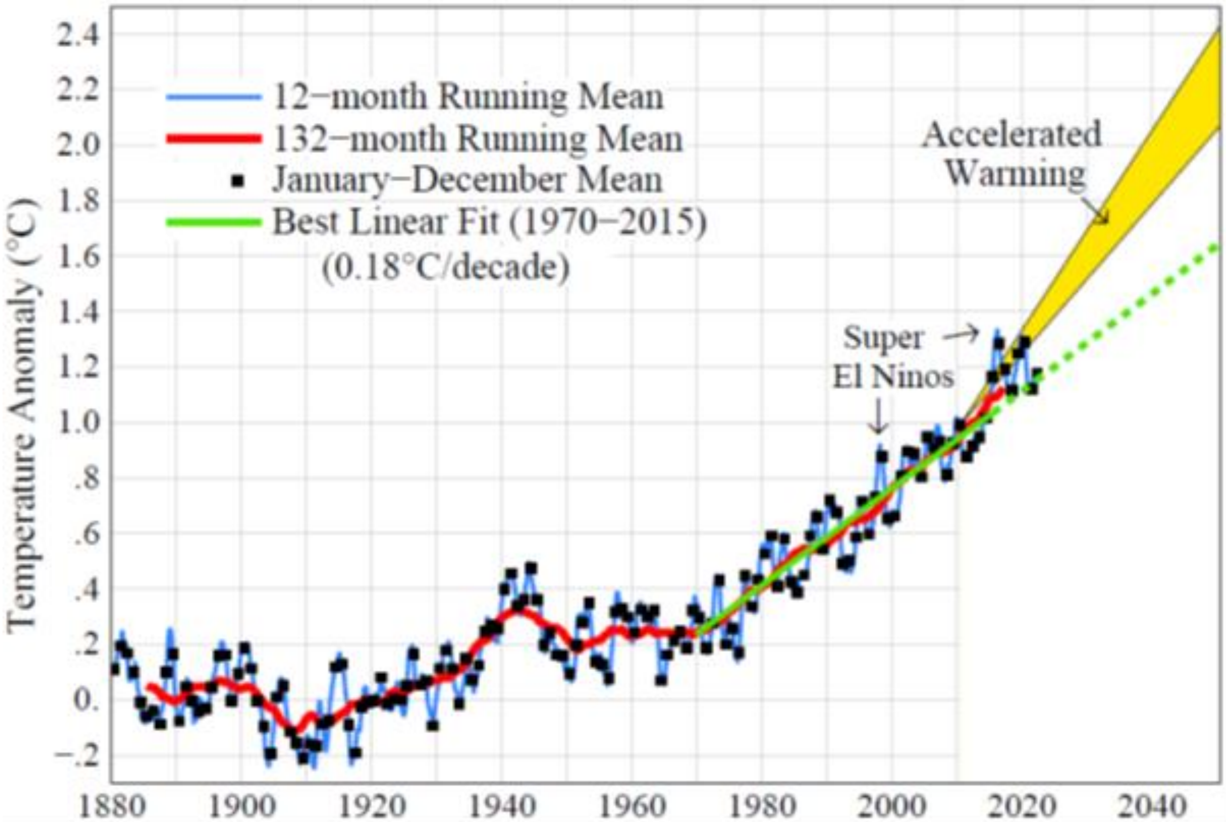
In order to improve on the above assumptions and estimates, it would be very helpful to have

1. For the IPCC budgets, implied values for ECS, emissions from natural feedbacks, 2100 RF for methane and aerosols, and albedo changes in the Arctic
2. Impact on the $CO_2$ budget for values of ECS ranging from 2.6 to 4.0°C
3. Estimates of specific emissions from natural feedbacks for anthropogenic emission pathways for cumulative $CO_2$ emissions ranging from 500 GT $CO_2$ to 3,000 GT$CO_2$
4. Reasonable "cost learning curves" for CDR (CCS, DAC, etc.)

Notes:

1. Global temperature increase

Expected temperature increase (Hansen - https://arxiv.org/pdf/2212.04474.pdf)




3. Developing countries are key to climate action

   How much money do developing countries need for climate change?

   Recent granular assessments of climate finance needs suggest that emerging markets and developing countries other than China will need to increase climate spending to around $2.4 trillion per year by 2030—more than four times the current level—of which $1 trillion would need to come from external sources. This is an order of magnitude greater than the initial commitment made by advanced economies in Copenhagen in 2009 to provide $100 billion in additional climate finance to developing countries by 2020, a pledge that has still not been met. Our volume's bottom-up case studies corroborate the major gaps in the global financial architecture, and a gap in the process of coordinating finance from different sources.

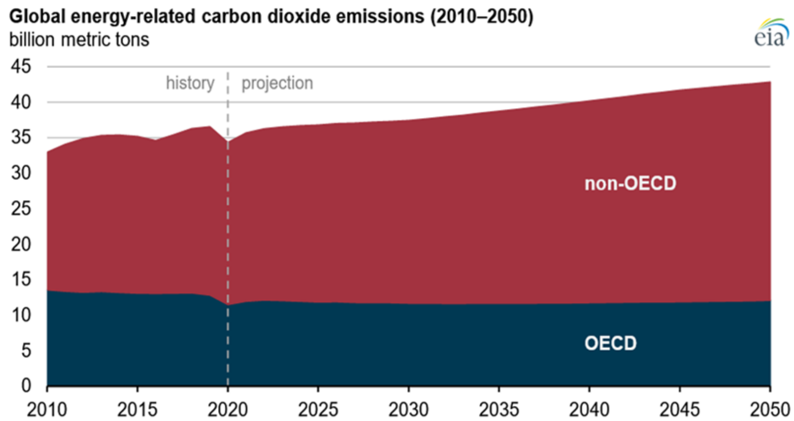
   https://www.brookings.edu/blog/future-development/2023/03/03/developing-countries-are-key-to-climate-action/#:

4. EIA - If CO2 emissions increase by 0.8% per year from the current rate (about 40 GTCO2/year if emissions from cement and land-use changes are included) through 2050 and then decline to zero by 2080 then cumulative emissions from 2020 to 2100 would then be about 2,000 GTCO2

**World CO2 emissions are projected to increase**

EIA's International Energy Outlook 2021 (IEO2021) Reference case projects that if current policy and technology trends continue, global energy consumption and energy-related CO2 emissions will increase from 2020 through 2050 as a result of population and economic growth. However, projected future growth in energy-related CO2 emissions is not evenly distributed across the world, and the majority of the projected future growth in energy-related CO2 emissions is among the group of countries outside the Organization for Economic Cooperation and Development (OECD).

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

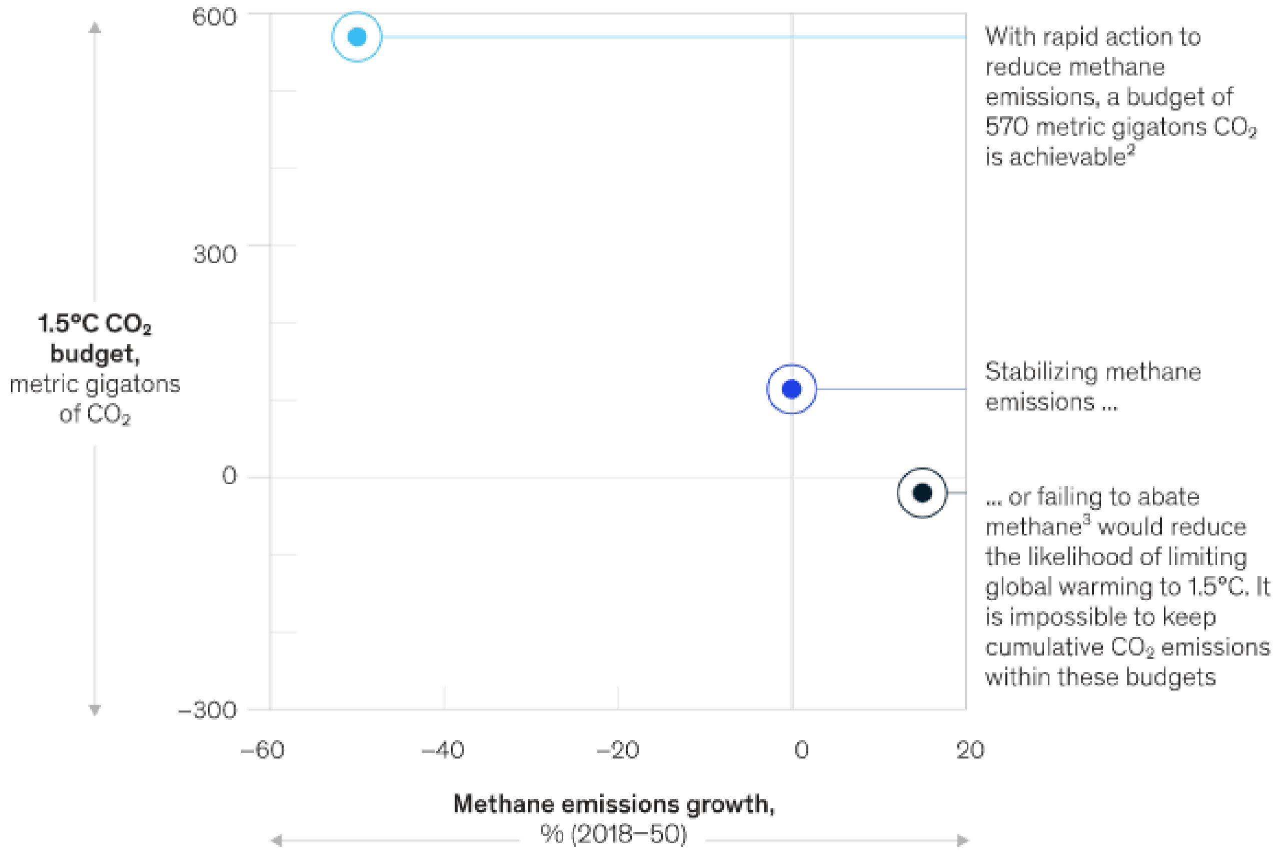



https://www.eia.gov/energyexplained/energy-and-the-environment/outlook-for-future-emissions.php

6. Methane emissions vs CO2 Budget

## The trajectory of methane emissions has a significant impact on the remaining 1.5°C budget for $CO_2$ emissions.

Impact of methane emissions scenarios on the remaining 1.5°C $CO_2$ budget[1]




1. The 1.5°C $CO_2$ budget is a limit on cumulative $CO_2$ emissions from 2018 onward, established as 570 metric gigatons $CO_2$ (66% chance of keeping warming below 1.5°C) in the Intergovernmental Panel on Climate Change's (IPCC's) *Special report: Global warming of 1.5°C* (2018). Impact on the carbon budget was calculated using the global warming potential* (GWP*) formula published in Cain et al (2019).
2. Assuming non-$CO_2$ gases are reduced according to the average of 1.5°C no-overshoot scenarios published in the IPCC SR1.5 report, including a 73 percent reduction of nitrous oxide emissions and 55 percent reduction of methane emissions by 2050.
3. Current trajectory of methane emissions according to energy and population projections from McKinsey's Global Energy Perspective and agricultural projects from the Food and Agriculture Organization (FAO) of the United Nations.

Source: Michelle Cain et al., "Improved calculation of warming-equivalent emissions for short-lived climate pollutants," *Climate and Atmospheric Science*, September 2019, Volume 2, Number 29, nature.com; E.G. Nisbet et al., "Very strong atmospheric methane growth in the 4 years 2014–2017: Implications for the Paris Agreement," *Global Biogeochemical Cycles*, February 5, 2019, Volume 33, Number 3, agupubs.onlinelibrary.wiley.com; J. Rogelj et al., *Special report: Global warming of 1.5°C*, Intergovernmental Panel on Climate Change, 2018, ipcc.ch; McKinsey analysis

https://www.mckinsey.com/capabilities/sustainability/our-insights/curbing-methane-emissions-how-five-industries-can-counter-a-major-climate-threat

8. Cost to reduce the global temperature by 0.1°C
   a. According to the IPCC AR6, emissions of 750 GT CO2 will increase the global temperature from 1.5°C to 2.0°C (for a 66% chance – 400 GT CO2 to 1150 GT CO2 - see https://fairallocation.org/IPCCAR6Budget.aspx
   b. So if takes about 150 GTCO2 to increase the temperature by 0.1°C, about the same amount will be needed to be removed to reduce the temperature by 0.1°C
   c. At $100/ton to remove CO2 – "the holy grail" and DOE "Carbon Negative Shot" – of which $10/ton is for compression and storage - then $90 ton for capture and total of $15 trillion
   d. Reduce $90 by a third and the cost is $10.5 trillion
   e. Reduce $90 by a half and the cost is $8.25 trillion