Climate Change - When Time Runs Out

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1. Introduction

This is last of three posts regarding climate change. The first two are described and linked below.

The first of these three papers on climate change, on increases in the temperature predicted by a number of recent major climate models, is linked below.

https://www.energycentral.com/c/ec/accelerated-warming

The second part (linked below) described the apparent cause of recent major disasters.

https://www.energycentral.com/c/ec/emerging-negative-effects-climate-change

This paper lays out the case of why we are probably out of time to simply stop emitting greenhouse gases (not that this is easy), and probably need to start removing greenhouse gases (GHG) from the atmosphere, mainly carbon dioxide (CO_2), in addition to stopping the emission of GHG by 2050.

2. Out of Time?

Last year the referenced IPCC Report projected: *"Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (high confidence)"*[1] Since this report was written, much has happened to suggest that the above projection is overly optimistic. Some of these events are described by the first report in this series (linked above), and my earlier post linked below:

https://www.energycentral.com/c/ec/methane-growth

A recent major publication on negative emissions technology (referenced at the end of this paragraph) indicated: *"Meeting a 2°C target is becoming exceedingly challenging; the global mean temperature has already risen about 1°C over the 20th century. Most climate and integrated assessment models project that the concentration of atmospheric carbon dioxide (CO_2) would have to stop increasing (and perhaps start decreasing) by the second half of the century for there to be a reasonable chance of limiting warming and the associated dangerous climate impacts.*[2]

"The focus of climate mitigation is to reduce energy sector emissions by 80-100 percent, requiring massive deployment of low-carbon technologies between now and 2050. …negative emissions technologies (NETs)…remove carbon from the atmosphere and sequester it. Under the present conditions, where fossil CO_2 is continuously added to the atmosphere, removing CO_2 from the atmosphere and storing it has exactly the same impact on the atmosphere and climate as simultaneously preventing emission of an equal amount of CO_2."

And from the 2018 UN Emissions Gap Report: *"Even if the nations of the world live up to their current commitments, that will likely result in global warming of around 3°C by the*

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[1] Intergovernmental Panel on Climate Change, "Global Warming of 1.5°C", Oct 2018, https://www.ipcc.ch/sr15/

[2] The National Academies Press, "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda", 2019, https://www.nap.edu/read/25259/chapter/1

end of the century. That's a number that would be catastrophic – and fatal for many small island states and coastal areas. The fact is that we are already seeing climate change play out in front of us. From the Caribbean superstorms to droughts in the Horn of Africa, or record temperatures and wildfires, our planet is already changing."[3]

And by the way, I don't see any sign of "… *nations of the world [living] up to their current commitments*…", and time has REALLY run out.

3. Primary Source

As I'm writing this paper, and trying mightily to keep it under 3,000 words, I have discovered that reference 2 above has many more relevant details than I can include and come close to this goal. Thus all I will provide below is a brief summary of each method involved. If the reader is interested in the whole story for any of these technologies, please go through the above link in reference 2, and read the corresponding section.

Reference 2 is a consensus study report (see quote from this source below) from the National Academies of Sciences, Engineering, and Medicine, and is about 500 pages long. I have attempted to use similar section-titles as this source. Thus it should be easy to find the related chapters.

"Consensus Study Reports published by the National Academies of Sciences, Engineering, and Medicine document the evidence-based consensus on the study's statement of task by an authoring committee of experts. Reports typically include findings, conclusions, and recommendations based on information gathered by the committee and the committee's deliberations. Each report has been subjected to a rigorous and independent peer-review process and it represents the position of the National Academies on the statement of task."

4. Natural Climate Solutions

We will start with these removal methods, because they are the easiest (read: least expensive). They are also being practiced as part offsets used the California and other cap and trade programs.

Note that this section corresponds to chapters 2 (Coastal Blue Carbon) and 3 (Terrestrial Carbon Removal and Sequestration) in reference 2.

But first we must briefly review some unit simplifications that I will make in this paper. I will use the term "tonne" to represent 1,000 kilograms = 2,205 pounds or about 1.1 U.S. tons. Another term that is used for this metric is megagram. I will use the term Gigaton to represent 1 Billion tonnes (10^9 tonnes) or 1 Petagram (10^{15} grams). These terms are frequently used to describe quantities of greenhouse gases that must be removed from the atmosphere.

The title to this section and an excellent paper is referenced here.[4] The paper was written in 2017, but it is still very useful. So what are natural climate solutions? They are *"…20 conservation, restoration, and/or improved land management actions that increase*

[3] United Nations Environment Program. Emissions Gap Report – 2018, Nov 2018, http://wedocs.unep.org/bitstream/handle/20.500.11822/26895/EGR2018_FullReport_EN.pdf?isAllowed=y&sequence=1

[4] Bronson W. Griscom, et al, Proceedings of the National Academy of Sciences of the United States of America (PNAS), "Natural climate solutions", October 31, 2017, https://www.pnas.org/content/114/44/11645

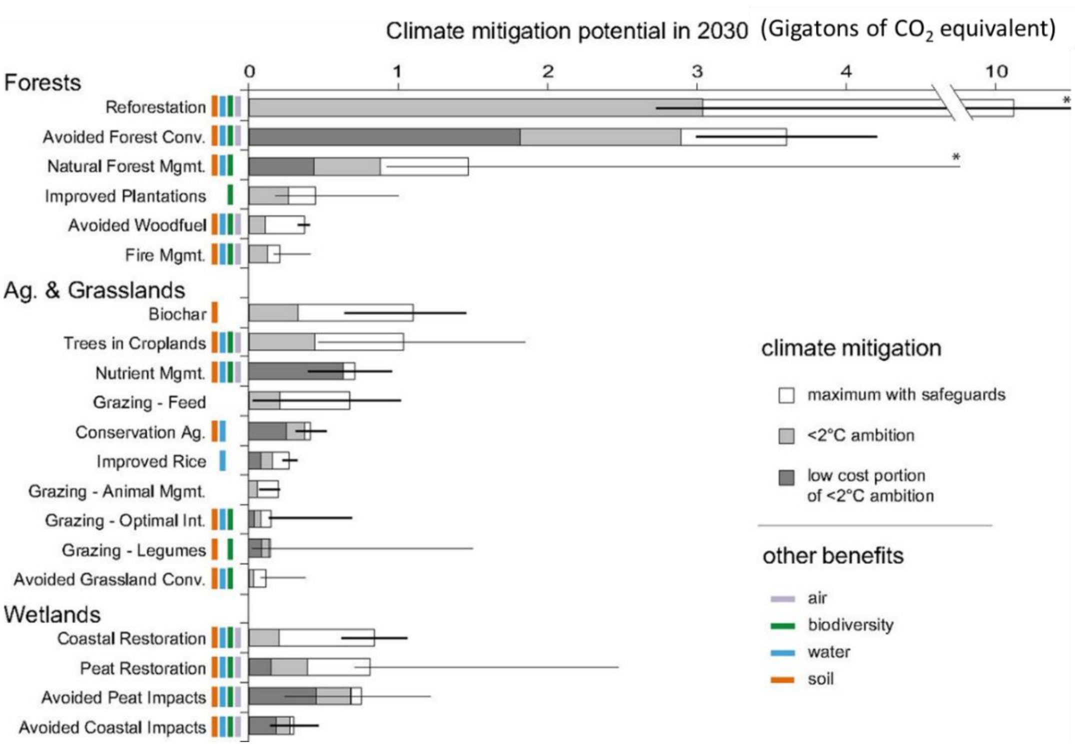
carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands."

How much do they cost? This is answer is bit more complicated. For instance, some of the measures are improved agricultural and wildland management practices. In the former case, in addition to sequestering more carbon, they may actually improve crop yields. In the latter case they improve diversity and resilience. In both cases, they may have a positive payback (negative cost).

With others the cost may be minimal to slightly positive or slightly negative. For instance, replacing marginal cropland that was created from previously cleared forests with new forests definitely has a cost. However once these forests reach a stage of maturity sufficient for sustained-yield harvesting, is the net financial yield greater or less than the net yield from cropland? Also, what is the cost of money for the maturation time, and what is the comparative cost of maintaining a healthy forest compared to the marginal cropland? A cost per tonne of CO_2 equivalent will be given from reference 2 et al for each technique described below. Note that these costs assume technological-maturity required to minimize the costs of each method while maximizing the co-benefits.

The third question is how much GHG can we mitigate using natural climate solutions? The reference 1 paper estimates that, while constraining these efforts to maintain food production at a high enough level to feed the future earth's population and maintaining enough fiber production for clothing and other reasonable use, and biodiversity conservation—is 23.8 Gigatons of CO_2 equivalent. About half of this is considered cost effective. Reference 1 says that this *"…can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C."* Keep in mind this is from a 2017 perspective. Although I believe that it is now too late to restrain warming to 2%, this will give readers will give an idea of the scale of these solutions.

Reference 1 included a chart (below) detailing the potential mitigation of these solutions.



4.1. Wetlands: Coastal Blue Carbon

From Reference 2: *"Coastal carbon sequestration … refers to carbon dioxide (CO_2) removal from the atmosphere in conjunction with plant growth and the accumulation and burial of plant organic carbon residue in the soil of tidal wetland and seagrass ecosystems. Tidal wetlands, including salt marshes and mangroves, thrive in soft-sediment, shallow regions of estuaries between high and mean sea level, while seagrasses inhabit adjacent soft-sediment estuarine bottoms with adequate light penetration."* These are sometimes called "blue carbon" even though they are primarily coastal and not in the open ocean.

The cost of this capture and sequestration technique (again per reference 2) is zero to $20 per tonne of CO_2. This has strong other benefits in preventing coastal erosion, mitigating storm-surge from coastal storms and promoting biodiversity.

4.2. Terrestrial Carbon Removal and Sequestration – Afforestation / Reforestation / Forest Management

This technique is using forest management techniques to increase the amount of CO_2 stored in a given forested area. There are potentially three ways of doing this: (1) use of long lived trees with minimal harvesting only used to promote forest health, (2) harvest the trees and use them for long-lived structures, furniture, and other products with multidecadal life spans, combined with sustainable forest practices such as to maximize the total amount of CO_2 storage, and (3) manage the forest soils to store the maximum amount of CO_2 consistent with (1) and/or (2).

The cost of (again per reference 2) is estimated at zero to $20 per tonne of CO_2. However, I have seen other estimates as high as $150 per tonne of CO_2 if scaled up to remove 500 Million tonnes of CO_2 per year. I would guess that both estimates assume the lands used have minimal value for other uses.

4.3. Terrestrial Carbon Removal and Sequestration – Agricultural Enhancement of Soil CO_2 Storage

This is modifying existing agricultural practices to enhance CO_2 storage. Some of these (like adding bio-char to soils and low-till no-till techniques) can have a positive effect on agricultural production.

Reference 2 estimates that the cost of this techniques ranges from zero to $100 per tonne of CO_2. These techniques should only be used so as to maintain or increase food and fiber production.

5. Bioenergy with Carbon Capture and Storage (BECCS)

I covered these in (mainly) sections 3 and 4 of the earlier post linked below, and I will not cover most of that same ground herein.

https://www.energycentral.com/c/cp/nuts

From reference 2: *"The International Energy Agency climate change models suggest that at least 2 Gigatons CO_2 per year removal by BECCS should be implemented by 2050 to keep global temperature rise below 2°C. To put this in perspective, 1 Gigaton of dry biomass is roughly equivalent to 1.4 Gigaton of CO_2 and 3.9 Million GWh primary energy, and the United States annually emits about 6.5 Gigatons of CO_2 and consumes slightly more than 28 GWh of primary energy."* Note: I converted the units in this quote.

The basic concept of BECCS is that biomass would be used to fuel (more or less) conventional thermal generation except the CO_2 from combustion would be captured and sequestered. There are currently two carbon-capture methods that can used for directly combusted biomass: Petra Nova System for post-combustion CO_2 capture and integrated-gasification combined-cycle (IGCC) for pre-combustion carbon capture. For additional information on these, go through the above link.

Additional methods include conversion of biomass to combustible gases. For instance, biomethane produced by fermentation, and then separated into hydrogen and CO_2. The former would be combusted, producing mainly water vapor, and the latter would be sequestered. The link below is to an earlier paper where techniques for this process (reformation), possible future improvements and cost goals are reviewed in section 2.2.

https://www.energycentral.com/c/cp/hydrogen-futures

The most efficient and cost-effective process for producing power from hydrogen would be Combined Cycle. The largest advantage of the above techniques would be that transportation of biomethane could use existing natural gas pipelines, and existing combined-cycle plants could be converted to use hydrogen fuel.

6. CO_2 Capture Directly from the Atmosphere

Direct Air Capture has one significant problem. From reference 2: *"…thermodynamics sets a lower bound on the energy required to separate a mixture of gases. Dilute streams are more difficult to separate and require more energy than more concentrated mixtures. The direct air capture approaches described in this chapter are technically feasible, but because CO_2 in air is ~300 times more dilute than in flue gas from a* [fossil] *fired power plant, the separation process for the same end CO_2 purity will likely be more expensive than capture from* [these] *power plants.*

"The cost of carbon capture for direct air capture systems has been a contentious issue. The estimates found in the literature span an order of magnitude, from $100 to $1,000 per tonne of CO_2. These estimates represent the costs of CO_2 captured, and not the costs of net CO_2 removed from the atmosphere, with these costs tending to render direct air capture among the most expensive atmospheric CO_2 removal approaches. One challenge to comparing estimates is that earlier reports often used different system boundaries; for example, not all studies accounted for all the steps needed for a complete cycle. Some utilized generic correlations for process operations, while others performed out detailed optimizations of specific systems. As progress continues on pilot and demonstration plants, more accurate costs can be expected to become available.

"Estimates at the high end of the cost spectrum ($1,000 per tonne of CO_2) were not based on a specific technology. Rather, they were based on direct air capture energy requirements and application of second-law efficiencies to the calculation of minimum separation energy based on 75 percent air capture and 95 percent CO_2 product. A range of energy resource costs from wind to natural gas were considered, leading to an approximate upper estimate of $1,000 per tonne of CO_2.

"Estimates of $641-819 per tonne of CO_2 based on a benchmark liquid system were provided in the first report to assess direct air capture, produced by the American Physical Society. Although comprehensive in its analysis, that report's benchmarking system introduced key limitations. This system conceptually adapted the technology for CO_2 capture from flue gas streams to CO_2 capture from air. Because air has much lower concentrations of CO_2, the volume of gas flow per ton of CO_2 captured is much larger and the power requirements to overcome the pressure drop in the …configuration

contribute to significant capital and operating costs [because] *the basic geometry and gas-liquid contact scheme would remain the same. Such designs are now recognized as not broadly applicable to direct air capture systems."*

Reference 2 evaluated various proposal to improve the efficiency of air-capture systems in great detail. The major issue with these proposals is, at best, they have only been demonstrated at laboratory-scale. I would guess that that when you try to scale these up to a size sufficient to absorb a significant amount of CO_2 the extrapolated cost for a "production" unit would not be significantly lower than the above estimates.

Oh yes – one other issue, these will only capture CO_2. For sequestration (and its additional cost) see the next section.

7. Geologic Sequestration

There are basically two stable pathways for sequestering CO_2 permanently:

- **Mineralization:** Combine it with sub-surface minerals in a natural process.
- **Deep sequestration:** Pump liquefied (supercritical) CO_2 into deep geologic formations that are isolated from the surface by higher impermeable geologic layers.

These are covered in the subsections below.

7.1. Mineralization

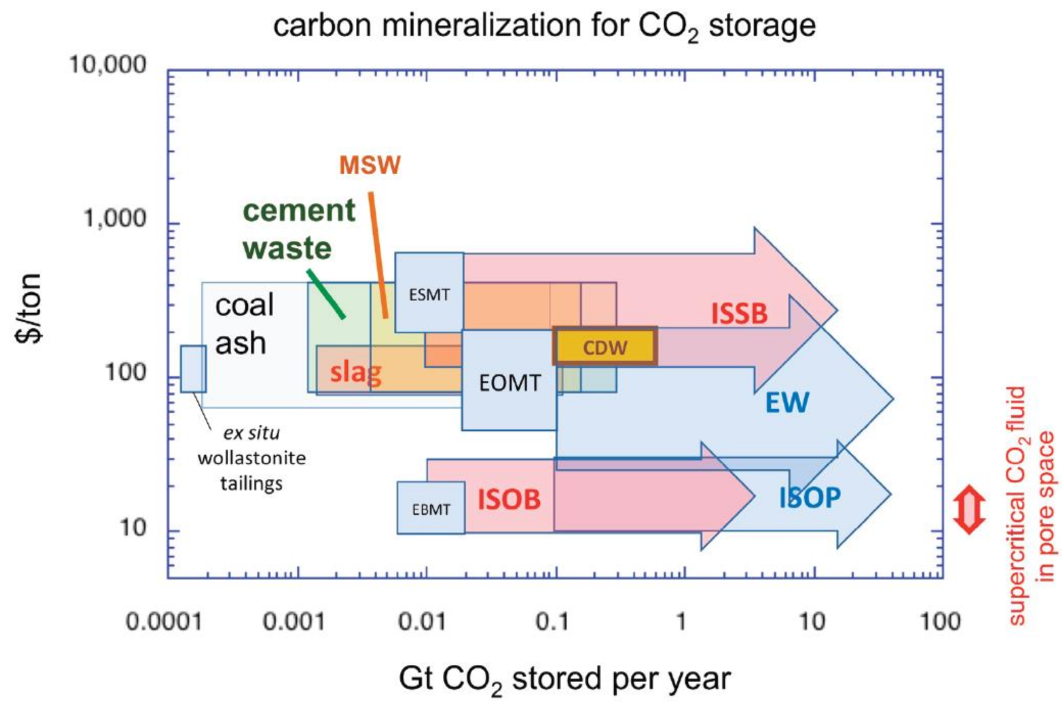
Underground silicate minerals and rocks rich in calcium and magnesium periodically come to the earth's surface. When this happens they undergo a natural weathering process where they absorb CO_2. The most common of these minerals are: wollastonite, olivine, pyroxenes, serpentine polytypes and brucite.

There are also some man-made materials that naturally absorb CO_2 as they weather, *"…including steel slag, construction and demolition wastes, and cement kiln dust, that are rich in metal cations and have relatively low SiO_2 and Al_2O_3 contents. These materials react readily with CO_2 to form carbonate minerals at rates comparable to, or slightly faster than, the fastest reacting natural silicate minerals (i.e., wollastonite and olivine)."*

Also from reference 2: *"Carbon mineralization methods are either aimed at storing CO_2 in carbonate minerals (referred to as solid storage) or both removing CO_2 from air and storing it in carbonate minerals (referred to as combined mineral capture and storage). Solid storage can be accomplished in three ways:*

1. *ex situ carbon mineralization—solid reactants are transported to a site of CO_2 capture, then reacted with fluid or gas rich in CO_2,*
2. *surficial carbon mineralization—CO_2-bearing fluid or gas is reacted with mine tailings, alkaline industrial wastes, or sedimentary formations rich in reactive rock fragments, all with a high proportion of reactive surface area, and*
3. *in situ carbon mineralization—CO_2-bearing fluids are circulated through suitable rock formations at depth."*

Although the above sounds easy, it isn't. Neither is it inexpensive. There is a wide range of costs: from less than 10$ per tonne of CO_2 to several hundred dollars per tonne of CO_2. The reference 2 figure below defines the cost per tonne and potential capacity of various methods:



ESMT: *ex situ* serpentine-rich mine tailings; EOMT: *ex situ* olivine-rich mine tailings; EBMT: *ex situ* brucite-rich mine tailings; ISSB: *in situ* seafloor basalt; ISOB: *in situ* onland basalt; ISOP: *in situ* onland peridotite; EW: enhanced weathering peridotite quarried & ground for mineralization; MSW: municipal solid waste; CDW: construction & demolition waste

From reference 2: *"The cost of carbon mineralization is highly dependent on the path and materials used. Nonetheless, a consistent theme is that the cost for proposed CO_2 storage via ex situ mineralization is about 10 times higher than the cost of storage of injected CO_2 in subsurface pore space beneath an impermeable cap rock* [next subsection]*, even when the long-term cost of monitoring potential leaks is included for storage in pore space."*

And finally from reference 2: "All of these avenues for mitigating CO_2 emissions via carbon mineralization warrant continued, accelerated research programs, including laboratory experiments, numerical modeling, investigation of social and regulatory factors, and pilot projects in the United States."

7.2. Deep Sequestration

You will note from the above quote and figure: (1) deep sequestration ("…storage of injected CO_2 in subsurface pore space beneath an impermeable cap rock…") is one of the least expensive sequestration methods, and (2) it requires monitoring for leaks. If significant leaks are detected, these will probably be mitigated using injection of CO_2 absorbing solutions or slurries (using materials described in the prior subsection). Thus this is a very good reason for developing mineralization techniques. Another good use is in conjunction with bioenergy with carbon capture and storage or other processes that produce CO_2.

From reference 2: *"Geological sequestration is a necessary complement to direct air capture of carbon dioxide (CO_2) (see section 5) and bioenergy with carbon capture and sequestration (section 4). After CO_2 is captured, it is compressed into a supercritical fluid, then injected down a well into a geologic formation that is deep enough for the CO_2*

to remain as a supercritical fluid, typically 1 km or more. Compression of the gas to a supercritical fluid allows more CO_2 to be sequestered. This is due to the high-density of the fluid (~600 kg/m^3) relative to gaseous CO_2 and the reduced buoyancy forces in water-filled geological formations, although the system maintains a strong buoyant drive between CO_2 and brine." Note that I have adjusted the above section references to be correct per this paper.

Note that the above described process is already well developed as it is currently used (with CO_2) for enhanced oil and natural gas recovery. *"However, there are many practical challenges to accessing the storage volume at the needed rates."* The most series of these may be the potential for geological sequestration to drive seismic activity.

Since this process is well developed and studies, its economics are probably as well-understood as any examined in this paper or its references. This cost is given in the table below (from reference 2);

TABLE 7.4 Compilation of All-In Costs for Sequestration in Deep Sedimentary Basins

Study	Low Estimate (2013$/t$CO_2$)	High Estimate (2013$/t$CO_2$)
IPCC, 2005	1	12
ZEP, 2011	2	18
DOE, 2014	7	13
GCCSI, 2011	6	13

NOTE: These estimates do not include the cost of compression. ZEP = Zero Emissions Platform, GCCSI = Global Carbon Capture and Storage Institute

8. Potential Conflicts and Other Issues

One potential source for conflict is the land for photovoltaic generation (PVs) vs. forestation or growing biomass for BECCS. Both are currently large users of land. Although, in the west there are huge amounts of unused or minimally productive range lands and arid unproductive lands (even in California), in other areas this could be an issue.

One potential mitigating factor could be the continually increasing efficiency of PVs, which will allow the land-use of PVs to plateau in a few decades while the net power output continues to increase. Below is a link to a fairly recent paper on PVs. Section 1 has an NREL chart that shows the efficiency growth trajectory and the best current efficiency for research cells. Current best efficiency for commercial cells (mono-crystalline-silicon) is about 22%.

https://www.energycentral.com/c/pip/photovoltaic-technologies-%E2%80%93-past-present-and-future-part-2

Other possible mitigating techniques could facilitate the use of lands in the southwest U.S. that are currently too arid for forestation. These could be used through a combination of genetically modified trees intended to sequester CO_2 for many decades to centuries and solar desalinization to provide irrigation.