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TRANSBOUNDARY WATERS

PRACTITIONER BRIEFING SERIES

Issue 16

Transboundary Carbon – Technology

Transboundary Carbon *Technology*

"The long-standing adversarial dynamic between global north and global south proves practically counterproductive. This division has hindered our ability to unite and leverage our collective strength and robs us of tremendous opportunities. Yet, in the face of a threat that endangers the health of our planet, and our very existence, we must find in collective action a force that neutralizes and transcends these divisions. Climate change does not respect artificial distinctions, traditional boundaries, or old antagonisms. Instead, it should unite us against a shared borderless challenge." *— William Ruto, President of Kenya (COP 28)*

Shared Reductions:

Carbon emissions everywhere cause climate change anywhere. Carbon dioxide removal (CDR) offers an alluring solution to undo pollution of the past. Can it scale to reach Net Zero by 2050, or will it just prolong the inevitable?

Gigatons of carbon are emitted each year through human activity, particularly from the energy, electricity, and transport sectors, primarily from the use of fossil fuel sources. Gigatons of carbon are also removed, by the earth's natural processes on land and at sea, from vegetation uptake in photosynthesis, or the very slow process of mineralization. The Global Carbon Budget illustrates this carbon cycle, which shows the natural flow of this element through the spheres of earth.

The real issue of climate change is one of balance. Excess carbon is emitted by human activity due to our reliance on fossil fuels as an input. To reverse this, then we need only to remove this excess and tip the scales back into balance. With each year of continued emissions, the size of the response required to reach back to this this balance increases. In legacy emissions 1.5 trillion tons—or 1,500 Gigatons (Gt)—of carbon have been emitted since the industrial revolution.

As we covered in our last briefing, while CO2 is not the most potent of GHGs, it is the most abundant and among the longest lasting, making it a particularly impactful gas in terms of radiative forcing long-term. If the world reached Net Zero emissions tomorrow, it would only stop warming further, and still have an atmospheric concentration of CO2 50% higher than before the industrial revolution. And of course the world will not stop polluting tomorrow and is struggling to stop polluting in the coming decades.

Slow moving global cooperation on climate, questions of equity, responsibility, and other difficult issues in a global competitive economy are leading us down a path of ever more carbon in the atmosphere. Even once we have reached Net Zero, as we must, there will still be gigatons of excess carbon in the atmosphere that will need to be removed. This is a key factor in why transboundary carbon technology is not solely about mitigation or decarbonizing a sector, but of scaling up our ability to undo pollution of the past and re-sink these excess emissions in a truly durable way.

It is clear there are currently no credible pathways for staying below +1.5°C and that we will overshoot this target—and may already have—but this cannot mean that efforts falter. In fact, it is all the more reason to speed up, particularly our efforts to reverse emissions and pull excess carbon from the atmosphere and oceans to stabilize temperatures on the right side of 1.5°C.

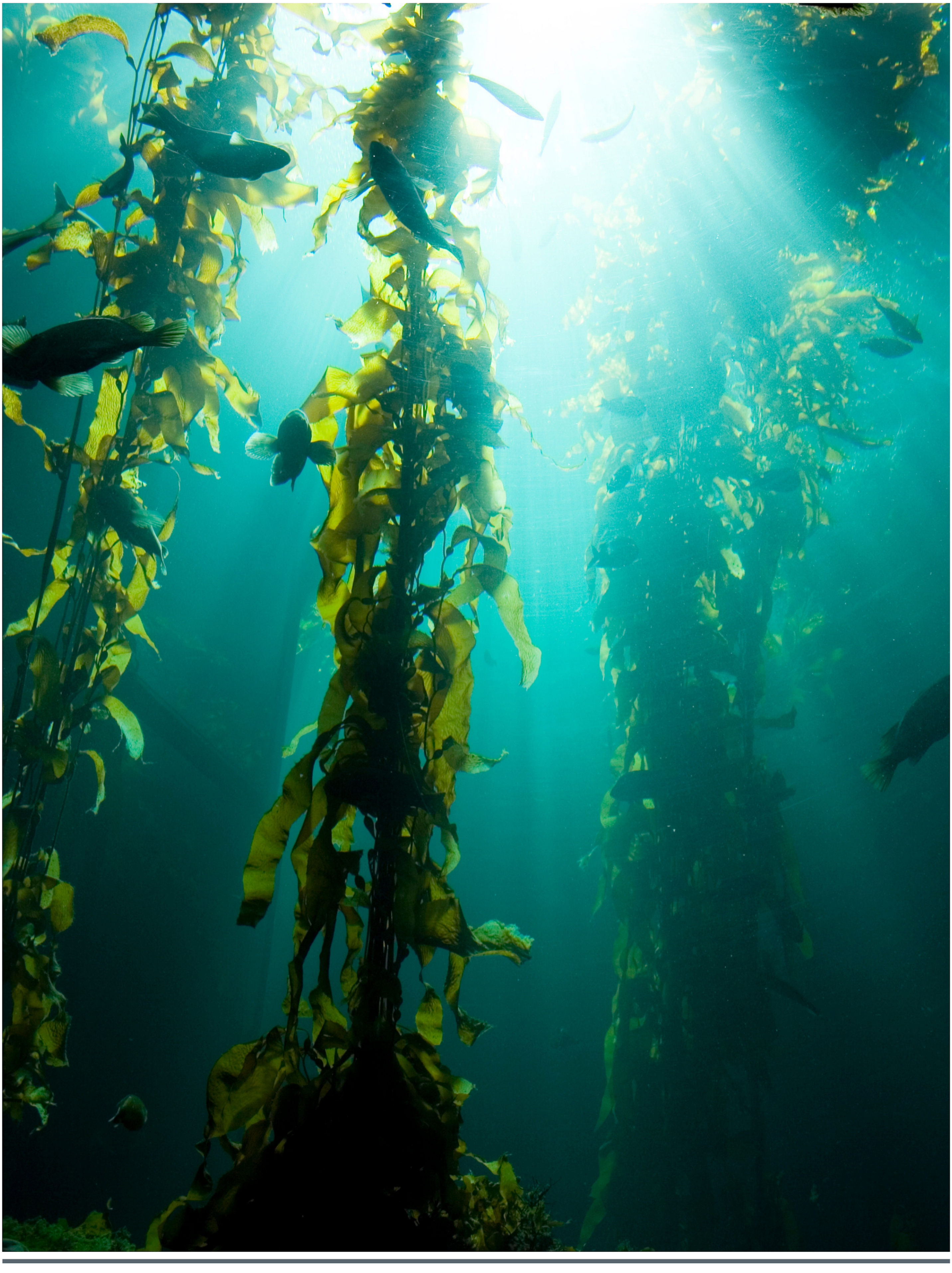
This issue will examine Transboundary Carbon *Technology* and the state of carbon dioxide removal. The following brief will focus on Transboundary Carbon *Valuation*, the economic case for carbon markets and offsets necessary to bring CDR to market.

Practical Summary

- There are currently no viable pathways to meet the 1.5°C or 2.0°C Paris targets, and emissions have not yet peaked. Each year of delay requires more aggressive reductions and furthers the need for scaled up CDR.
- Achieving Net Zero by 2050 requires 10 GtCO2e of CDR per year, from current levels of 2 GtCO2e/yr. Of this, only 0.002 GtCO2/yr comes from novel CDR methods outside of conventional land management.
- CDR will likely be a critical part of the answer to transboundary carbon and climate restoration, but is currently far behind in scale and impact, at a price point that is economically inefficient.
- This emerging carbon sector can be divided between CCS/CCUS and CDR, with the principles of removal and durable storage beyond just emission reductions that prolong fossil fuels.
- There are concerns that investments in CDR will increase the risk of 'moral hazard' of carbon emissions by further delaying fossil fuel phase-outs and diverting potential funds from other carbon mitigation responses.
- With the most optimistic and rapid transition to renewables from fossil fuels, legacy emissions and hard-to-carbonize sectors will remain a contribution to net temperature increases, and delays in CDR investment today will cause more harm in the future by delaying their rollout.
- An everything-everywhere-all-at-once approach is needed to address the greatest transboundary environmental issue of our time.

Source: CCS Knowledge

The first CCS project on a coal fired power plant, first built in 1959 and retrofitted in 2014. Ultimately a failure of CCS deployment, with no permanent storage but CO2 production for EOR, which increased local power prices and did not capture enough CO2. Further planned CCS installments were cancelled in 2018.



Achieving the Paris Targets — The Need for CDR

The conclusion of COP28 in the UAE in December 2023 reached several milestones, including pledged funding for the Loss & Damage fund of COP27 in Egypt (with $726 million), and a landmark statement about the 'just, orderly' transition away from fossil fuels. The final text of the meeting was delayed over the exact wording of this commitment, with many feeling it was insufficient, while others see it as historic progress towards meeting the Paris Agreement commitments.

The Paris temperature targets of +1.5°C and +2.0°C agreed to in 2015 are not just arbitrary markers but seen as the defensive lines for the climate 'tipping points' that will lead to greater damage and potentially irreversible changes. Like many climate targets, the relative data points and their meaning are critical. The average temperature baseline has typically been the 'pre-industrial' period of 1850-1900, before the widespread use of fossil fuels but the earliest period of global temperature records available. Meaning a global average annual temperature in this period of 13.5° Celsius or 56.3° Fahrenheit. From this baseline, every fraction of a degree matters, and it is better to be closer than further away.

"There is nothing magical about the 1.5 number, other than that is an agreed aspirational target. Keeping at 1.4 is better than 1.5, and 1.3 is better than 1.4, and so on... The science does not tell us that if, for example, the temperature increase is 1.51 degrees Celsius, then it would definitely be the end of the world. Similarly, if the temperature would stay at 1.49 degrees increase, it does not mean that we will eliminate all impacts of climate change. What is known: The lower the target for an increase in temperature, the lower the risks of climate impacts." – Sergey Paltsev, MIT

At current emission rates and with present policies, the world will hit +2.7°C above the 1850-1900 average (with a range between 2.2-3.4°C) by the year 2100. Assuming the stated 2030 climate targets are in fact reached, it will still be +2.5°C (range of 2-3°C). Since COP26 in Glasgow two years ago there have been no changes in this current trajectory. With COP28 in Dubai, the first-ever reference to the transition away from fossil fuels left much to be desired by climate experts, as it does not include specific timelines or levels, instead focusing on a transition that is just, orderly, and equitable, and achieves Net Zero by 2050. Similarly, the pledge to phase out coal in Glasgow in 2021, which used stronger language than that used for all fossil fuels in Dubai, has in practice seen coal usage increase in subsequent years due to shifting geopolitical realities.

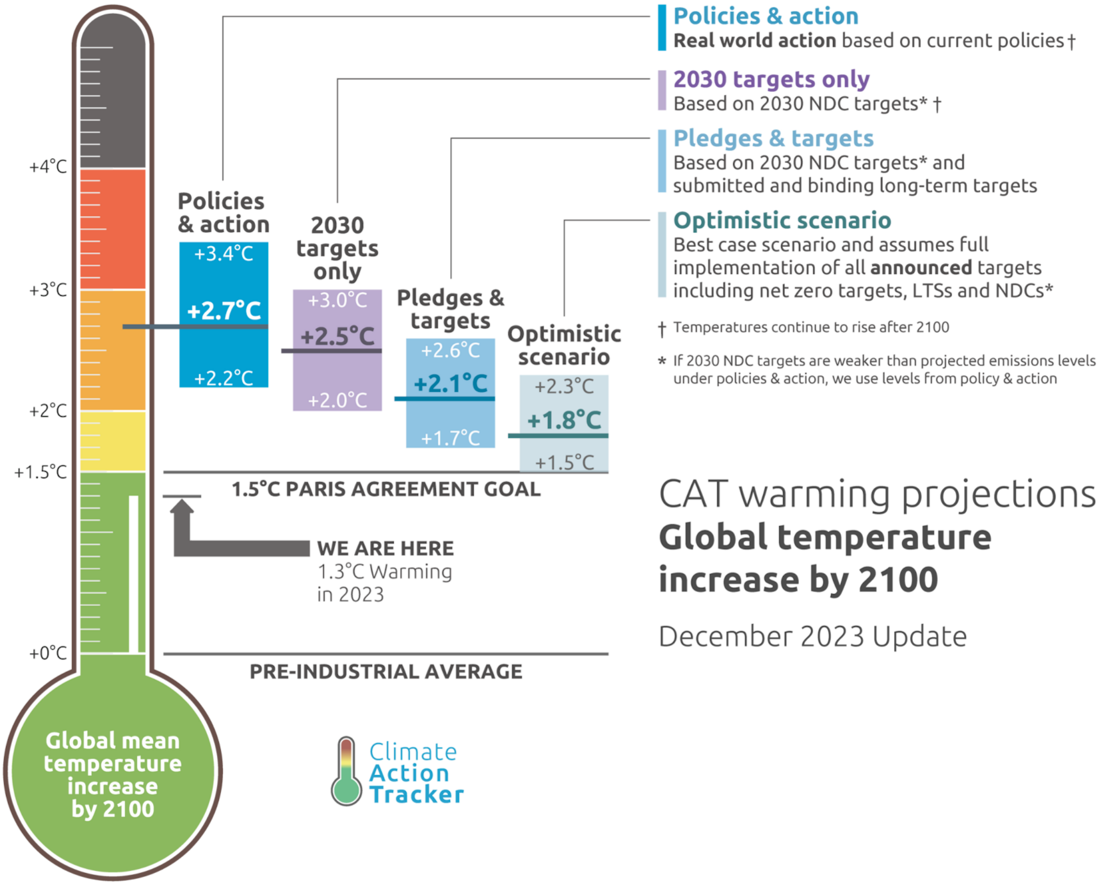
While the end goal remains the same—reaching Net Zero by 2050—how to achieve this will depend on how countries move forward, and at what pace. For example, even building out an entirely new hydrogen economy for heavy industries, while electrifying everything, and increasing renewables well beyond the 3x pledge of COP28, would still require CDR on a massive scale to meet temperature targets.

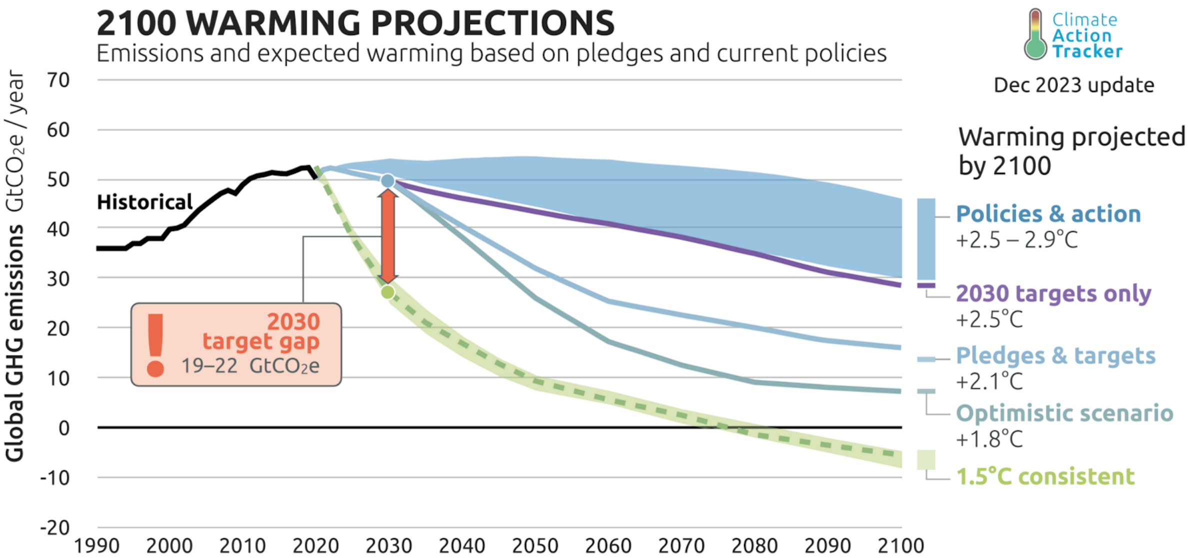
"Once decarbonization options have been expended, CDR could play a vital role in neutralizing residual emissions; therefore, most scenarios aligned with the Paris Agreement project substantial CDR capacities." - McKinsey

Simply stated, the need for CDR is a direct function of policy failures elsewhere. The inability to curb emissions or remove fossil fuels fast enough. This has led to important debates about whether carbon removal could be a distraction from making the necessary transitions and transformations of the global economy as quickly as possible. Organizations such as Climate Action Tracker estimate that every Gt of CCS or CDR used only delays reaching Net Zero and prolongs emissions further into the future, and thus should be capped to limit their use and reliance on them. Caps of 5 GtCO2e would still represent a large scaling up of the CDR industry.

Furthermore, the hard-to-decarbonize sectors ranging from steel to agriculture will require CDR to be able to meet Net Zero at all, and beyond this, the *negative* emissions required to actually bring down atmospheric CO2 levels to their pre-industrial levels. As previously discussed, all of the legacy CO2 in the atmosphere will not disappear for thousands of years, and even reaching Net Zero tomorrow still leaves a highly elevated atmospheric CO2 level without carbon removal technology.

The progress thus far and the lack of commitment to phase-out fossil fuels on any specific and immediate timeline further deepens the need for novel CDR methods. As will be discussed, the scaling up of such methods requires large investment and developing these techniques today.


Policies & action
Real world action based on current policies †
2030 targets only
Based on 2030 NDC targets* †
Pledges & targets
Based on 2030 NDC targets* and submitted and binding long-term targets
Optimistic scenario
Best case scenario and assumes full implementation of all announced targets including net zero targets, LTSs and NDCs*
† Temperatures continue to rise after 2100
* If 2030 NDC targets are weaker than projected emissions levels under policies & action, we use levels from policy & action
+4°C
+3°C
+2°C
+1.5°C
+0°C
Policies & action
+3.4°C
+2.7°C
+2.2°C
2030 targets only
+3.0°C
+2.5°C
+2.0°C
Pledges & targets
+2.6°C
+2.1°C
+1.7°C
Optimistic scenario
+2.3°C
+1.8°C
+1.5°C
1.5°C PARIS AGREEMENT GOAL
WE ARE HERE
1.3°C Warming in 2023
PRE-INDUSTRIAL AVERAGE
Global mean temperature increase by 2100
Climate Action Tracker
CAT warming projections
Global temperature increase by 2100
December 2023 Update


2100 WARMING PROJECTIONS
Emissions and expected warming based on pledges and current policies
Climate Action Tracker
Dec 2023 update
Global GHG emissions GtCO2e / year
70
60
50
40
30
20
10
0
-10
-20
1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Historical
2030 target gap
19–22 GtCO2e
Warming projected by 2100
Policies & action
+2.5 – 2.9°C
2030 targets only
+2.5°C
Pledges & targets
+2.1°C
Optimistic scenario
+1.8°C
1.5°C consistent

Hard-to-Decarbonize Industries

For many industrial sectors an all-electric future powered by solar and wind is simply not feasible. Unfortunately, some of the most polluting industries are also the most difficult to decarbonize. These include steel production, cement, or the chemicals industry, as well as shipping and aviation. For most industrial processes, the problem is heat, with very high requirements that cannot be met through electrification. Or the very process itself is carbon intensive due to its basic chemistry.

Another factor is the very narrow profit margins these sectors have been built upon for decades, with an exceedingly small variance being the difference between profit or loss, and large economies of scale are already baked-in. There are also national security concerns, both in terms of energy security, or domestic production capacity for critical goods and industries. Finally, there is the high capital cost of assets, with long lifespans that make strategic pivots difficult to do in a globally competitive marketplace. This has caused firms to delay investments until they have more certainty of the best direction for them.

Greening these industries requires a distinct set of approaches to those in the consumer realm, and this must be clearly recognized by climate advocates as well. Battery Electric Vehicles (BEVs) are well suited for most commuters and consumers to decarbonize their daily transport habits, but the size, scale, and runtime requirements for large machines runs aground of the basic realities between weight, capacity, and runtime. While some sectors require renewables, electrification, and greater energy efficiency, others will require this *plus* alternative fuels like ***Green Hydrogen*** or its green derivatives Methanol and Ammonia, along with integrated CCS or novel CDR to reach Net Zero.

Governments must take the lead to establish clear pathways for industries to decarbonize that does not leave them with too much uncertainty in their financial planning, or at a comparative disadvantage that undermines adoption. Greater regional coordination can help bridge gaps to global policy planning.

Reducing emissions still remains the best way to 'decarbonize'—simply don't pollute. Yet once all options have been used, residual emissions remain, which may be impossible or uneconomical to remove. CDR must fill this gap, and serve as the bridge to transition to new means of powering these sectors.

Net-Zero Pathways

Even in the most optimistic of scenarios, with rapid and deep emission cuts, which no climate agreement has shown the appetite for thus far, the chance of limiting warming to the +1.5°C threshold by 2100 stands at just 14%. Just this year 2023 has set numerous new warming records, including crossing the +1.5°C threshold during the year for 1/3 of days. It is thus likely that the threshold will be fully crossed within this decade at the current pace. There are currently no credible pathways of staying below the 1.5°C Paris temperature target, and 2.0°C is becoming more and more unlikely as well.

In spite of this current reality, the need to explore all measures is only increasing. CDR alone cannot undo the emissions of today or the past, even with massive scale up from current volumes. Instead, it can be the backstop that certain sectors rely on during transition, and later the key negative emissions tool. Until then however, it is one part of the everything at once approach. These are;

Renewable Energy – Wind, Solar, Hydro, Nuclear – The most obvious of any Net Zero pathway, the massive scaling out of primarily wind and solar energy resources to not only satisfy future demand levels, but to fully replace the legacy fossil fuel-based system. The mix of this system will depend on the assets developed, as well as the state of the grid they are connected to. Without the ability to connect and switch between renewable sources to use power on-demand without ramp-up issues, fossil systems like LNG will remain a necessary part of the energy mix, ideally with integrated CCS.

Electrification – As we build out renewable energy at sufficient scales, ever increasing demand for electricity will ramp up with economic growth and the energy transition. This is most visible in areas like Battery Electric Vehicles (BEVs) in the transport sector to replace gasoline engines. An EV that charges on a grid powered by fossil fuels will still be more efficient than a gasoline car, but not nearly as renewable as it could be if the grid itself was renewable. Another sector, which became a focal point in Europe's increased use of coal in the past year, is building heating that relies on oil and gas burners. A shift to heating pumps will be another challenge to remove emissions from everyday life. Electrification powered by renewables goes hand-in-hand to decarbonize economic activity.

'Green' Hydrogen

It is unclear if Carbon Dioxide Removal (CDR) and the Green Hydrogen (H2) sector will be complementary partners working in tandem towards Net Zero, or will end up in competition for the same limited financial resources in climate finance or project finance. For the hard-to-decarbonize industries both CDR and Green H2 offer pathways to Net Zero and cleaning up 'residual' emissions. Ideally, they will be closely linked and complementary to build both sectors together.

CDR technologies will play a role in the transition from 'Grey' to 'Blue' H2, whereby fossil fuels are used to create H2 gas via Steam Methane Reforming (SMR), as typically done now, but the CO2 produced in the *Grey* process is captured and stored durably, making it *Blue*. This will be key to first building out the H2 economy and its necessary support infrastructure. While then going *Green* will require a new production process, typically linked to giant electrolysers run on renewable energy splitting water into H2 and O2 gas.

From *Grey* to *Green,* emissions are reduced and then removed while providing a highly useful fuel for many sectors like cement, fertilizer, steel, mining, shipping and aviation fuels, which account for nearly 25% of annual emissions and cannot be currently electrified. H2 or NH4 can also be a key tool for energy storage, and back-up systems paired to renewable assets.

CDR technology paired with H2 gas production can go even further, producing carbon-*negative* hydrogen. Whereby the H2 production process removes carbon from the atmosphere, and the fuel is used without producing GHGs. Such a transition would help bend the emissions curve for the toughest industries and make them net negative, undoing their large legacy emissions over time.

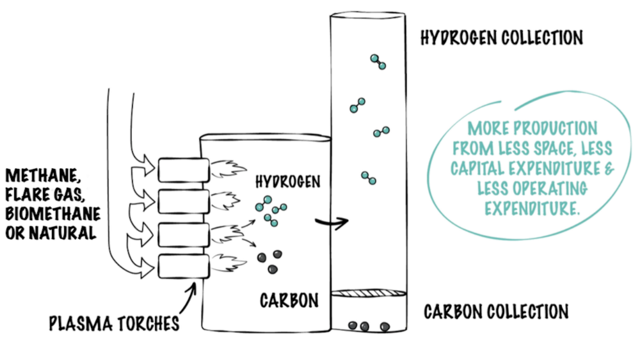
Companies like Planetary Hydrogen and Equatic are using the scale and natural processes of the ocean to enhance it's natural carbon sink processes while producing H2 with green energy. 'Emerald' Hydrogen is another color of the H2 rainbow shown below, which uses a plasma arc to split methane (CH4) molecules into H2 gas and solid carbon (e.g. HiiROC). 'Turquoise' H2 uses a similar pyrolysis process to Biochar, turning methane into H2 and solid carbon, potentially sourced from waste materials as well.

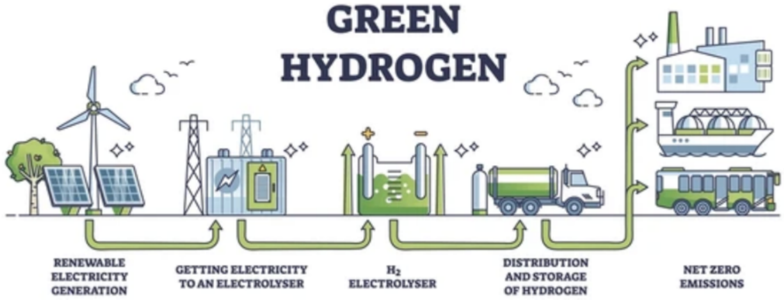
Today, H2 gas made via SMR produces 9 kg of CO2 per 1 kg of H2. Electrolysis requires roughly 50 kWh to produce 1 kg of H2, which holds an energy content of 33 kWh—a 34% loss. A Green H2 future will require massive increases in available renewable energy, with increased efficiencies, and should work in tandem with CDR to transition and scale the sector.

The Hydrogen Rainbow

Black / **Brown** H2 – Coal-fired SMR
Grey H2 – LNG-fired SMR
Blue H2 – SMR with CCS
Green H2 – Renewable-powered Electrolysis

Pink H2 – Nuclear-powered Electrolysis
Yellow H2 – Solar-powered Electrolysis
Emerald H2 – Methane Thermal Plasma
Turquoise H2 – Methane Pyrolysis





Efficiency – The low-hanging fruit for the Net Zero transition pathways is the energy efficiency of networks, systems, batteries, etc. Reaching all climate targets, from CO2e emission levels to global temperature goals, becomes easier with every percent gain in energy efficiency across the economy. Less energy demand for BEVs, desalination plants, green hydrogen electrolyzers, or home heating and cooling systems, leads to more energy available that makes the grid more flexible and able to focus on renewables throughout. The scale of the problems with energy transition reduces with increased efficiency and must be a core focus with corresponding investment.

Storage – Energy storage is another key aspect to unlocking the first two points above—renewables and electrification. Power demands are often inverted from the production cycle, with the highest solar generating capacity at a time of relatively lower consumption, while nightfall sees a spike in demand as resources wane or do not exist. Storage seeks to plug these gaps by allowing for on demand power from stored renewable energy production. This is often thought of related to large scale battery storage, whether at the home or utility level scale. Another option for some regions or geographies is a pumped storage system—utilizing excess daytime energy to pump water into reservoirs at elevation, and then draw this down as hydropower during the evening to meet energy demand. Other solar projects seek to use stored heat that can be converted to energy. Storage will be the key to truly phasing out fossil fuel-based energy systems to make renewables more robust and durable through adverse conditions.

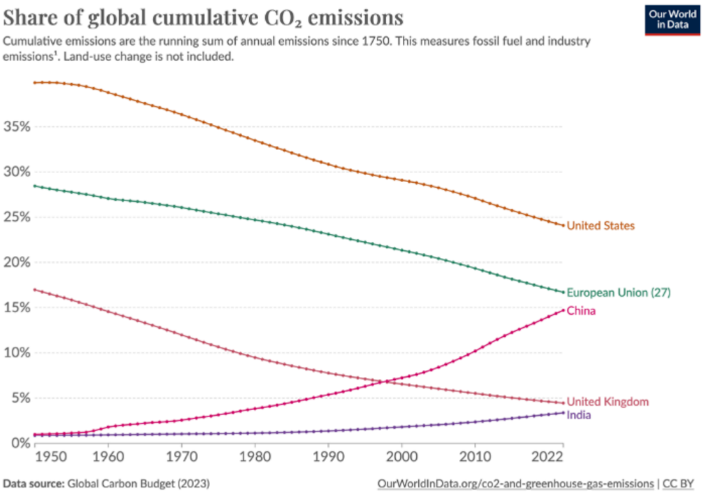
Hydrogen – For the hard-to-decarbonize heavy industries like steel, cement, or agriculture, or even the mining vehicles needed to build BEVs and battery storage, the mix of solutions above will not be sufficient or economical. Green Hydrogen may fill this gap to provide the power, heat, and energy that is efficient and economical for key sectors, particularly heavy industry. Today, grey and black / brown hydrogen production are the norm, while blue hydrogen with CCS can serve to transition, to a green hydrogen future that generates an emissions free fuel source that can be used in the production of steel, cement, aviation fuels, shipping transport, and fertilizers. In areas like the trucking industry, Fuel-cell EVs (FCEVs) powered by hydrogen can achieve the power, range, and refueling requirements for that sector better than current BEVs. A two-tiered system of H2 FCEVs and BEVs could be cheaper than one. For the consumer, this means a battery charging infrastructure for BEVs, and a hydrogen refill station system for most commercial vehicles, a-la gasoline and diesel pumps at our fueling stations today.

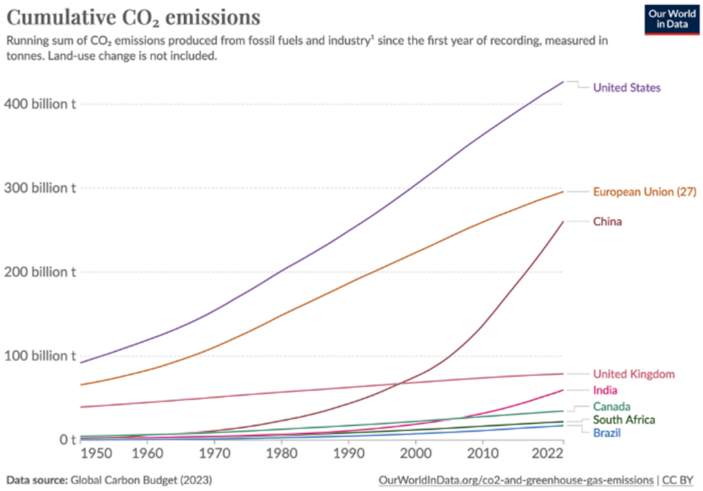
CDR – The last but certainly not least component to a true Net Zero emissions pathway, is Carbon Dioxide Removal. Done at scale, with novel methods that help to augment earth's natural processes to achieve at first Net Zero, and then negative emissions. CDR can be a key partner to an emerging hydrogen industry as well, as it seeks to transition from Blue to Green processes and bring down its costs. The key for both H2 and CDR will be the cost per kg/ton of their product or service, as it relates to the permitted carbon price.

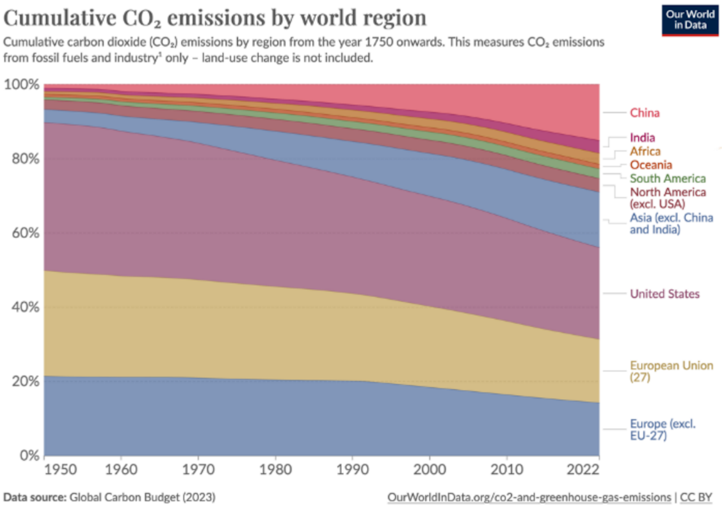
As we explored in the previous issue looking at the history of global climate cooperation, coordinating the actions of countries is difficult when they compete in a global marketplace shaped by geopolitical realities. In the time that climate has truly been studied, and carbon emissions have been considered as a GHG pollutant, the trend of global emissions have shifted from the US, UK & EU towards Asia and its emerging economies. While the percentage shares of total emissions are changing, peak emissions have still not yet been met by any major emitting country.

While the major legacy emission producers are leveling off and trying to bend their curve, China and India are still accelerating, and negotiations that center around a 'just' transition seek to carve out exceptions that allow emissions growth for longer. Leaving questions of national equity aside for now, the global carbon system simply does not have the capacity to continue on this path. We need to reach Net Zero as soon as possible, and then into negative emissions to reduce the total CO2 concentration in the atmosphere. This makes CDR technology, and investment in it from the richest countries and those with the most legacy emissions, ever more necessary. To its credit, with the Inflation Reduction Act the US has set the groundwork to be a leader in CDR technology and take the lead on scaling up carbon removal, which is only fair with the largest share of past emissions.

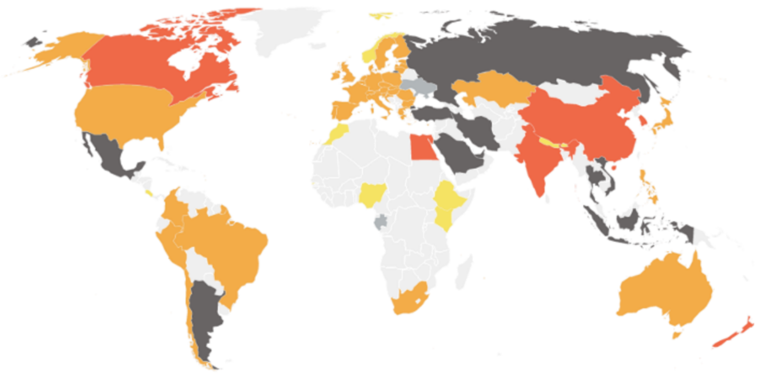
From heavy industries to later developing countries, a large role for CDR will be required alongside simultaneous efforts to de-carbonize, electrify, and shift to renewables at large scale.

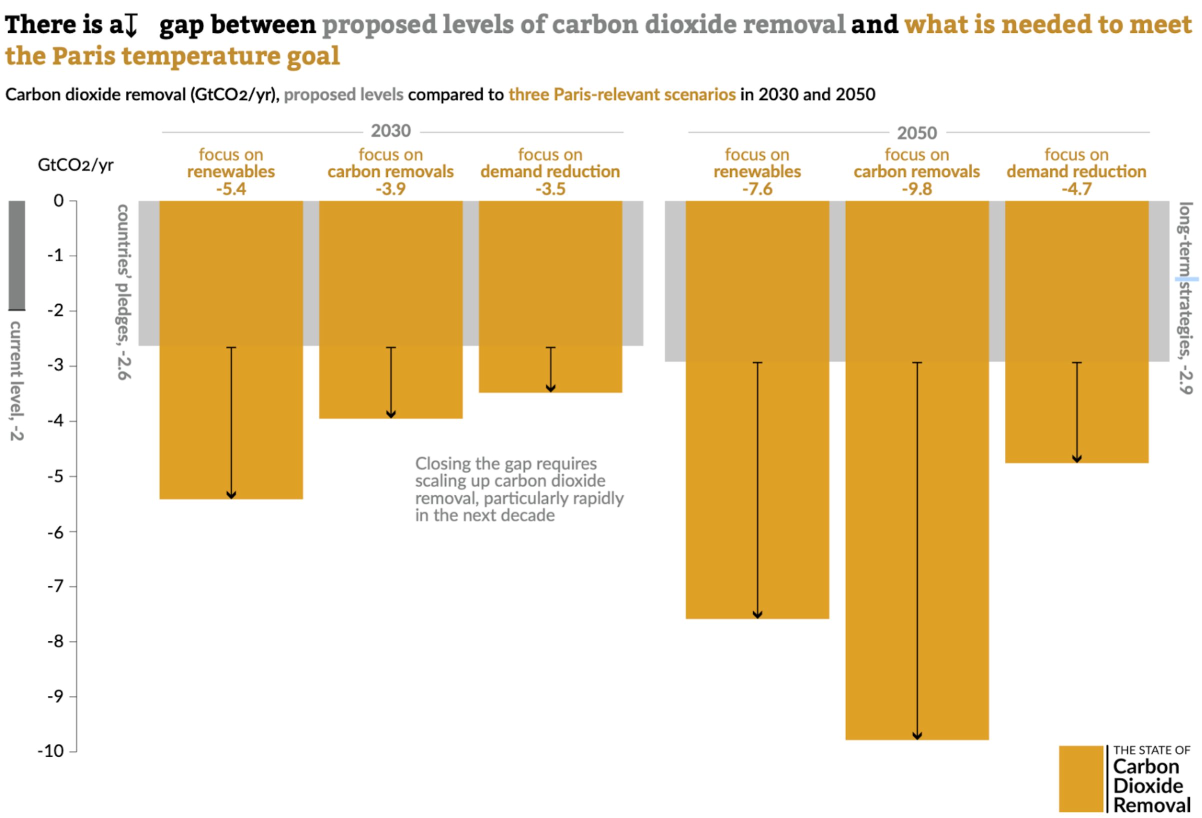


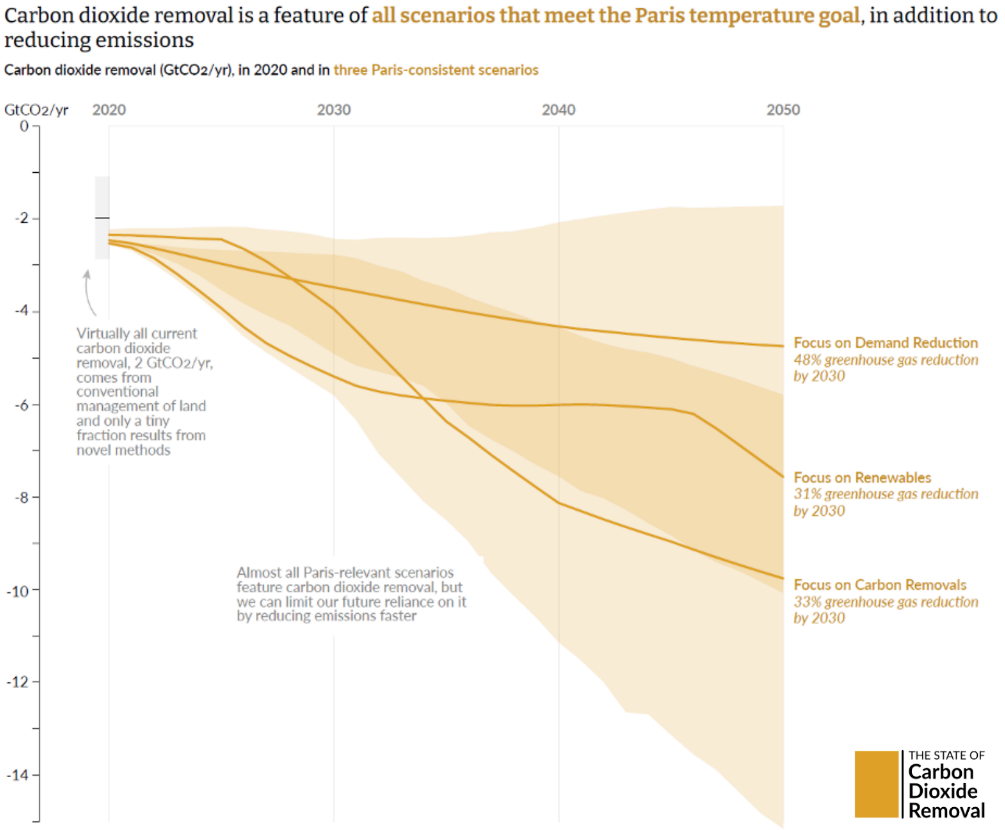




[From Almost Sufficient to Critically Insufficient - Climate Action Tracker, Dec. 2023]







The above chart conveys the various scenarios of getting to Net Zero emissions by 2050 to meet the 1.5°C and 2.0°C temperature targets in the Paris Agreement, and the amount of CDR required. Effectively, even with a 50% reduction in CO_2 emission levels by 2030, between 4-5 $GtCO_2e$/yr of CDR would be necessary. Further, such a scenario is becoming increasingly unlikely to be a viable consideration.

With a focus on increasing renewable energy—such as COP28's promises to triple renewable energy production by 2030—and a corresponding 31% reduction in CO_2 levels, still ~8 $GtCO_2e$/yr of CDR would be required as a midpoint estimate. A similar reduction in GHGs that achieves this through a focus on CDR methods requires ~10 $GtCO_2e$/yr, with up to 15 $GtCO_2e$/yr potentially—15 billion tons, annually.

The tremendous spread of probabilities, and the track record thus far of being slow and behind targets for several decades, makes it likely we will drastically overshoot both the 1.5°C and 2°C targets, requiring more carbon removal efforts in the future to restore the climate to around 300ppm CO_2 concentration. The need for equitable economic development and with ever more people on the planet makes this higher estimate outcome almost inevitable.

As such, the precise need for CDR is a direct function of our other policy choices, and how quickly they are enacted. With each year of delay the need for CDR increases, and delays to removing fossil fuels from the energy mix will require more negative emissions technology to bring down atmospheric CO_2 levels. The 'CDR-rush' needs to begin now in earnest, with its role shifting to meet the emission demands over the next 20 years, as both a climate restoration tool and as a means to Net Zero for residual emissions.

However, CDR cannot be viewed as a silver bullet or be allowed to generate 'moral hazard', allowing for more polluting as usual while hoping to clean up emissions on the back end. The 3 guiding principles of CDR must be followed, with emphasis on its additionality and durability. CDR is required *alongside* deep emission cuts, just to right the ship or correct its course. To meet the Paris temperature targets without the use of CDR would require even deeper emission cuts than the global community have shown they are willingly to make, particularly at the pace required.

All tools and approaches are needed in an everything-everywhere-all-at-once response to the world's greatest transboundary environmental issue and collective action problem.

Global Carbon Cycle

The global carbon cycle is a natural process that involves the exchange of carbon between the Earth's atmosphere, oceans, land, and living organisms. It plays a crucial role in regulating the planet's climate. The cycle can be broadly divided into two main components: the short-term carbon cycle and the long-term carbon cycle.

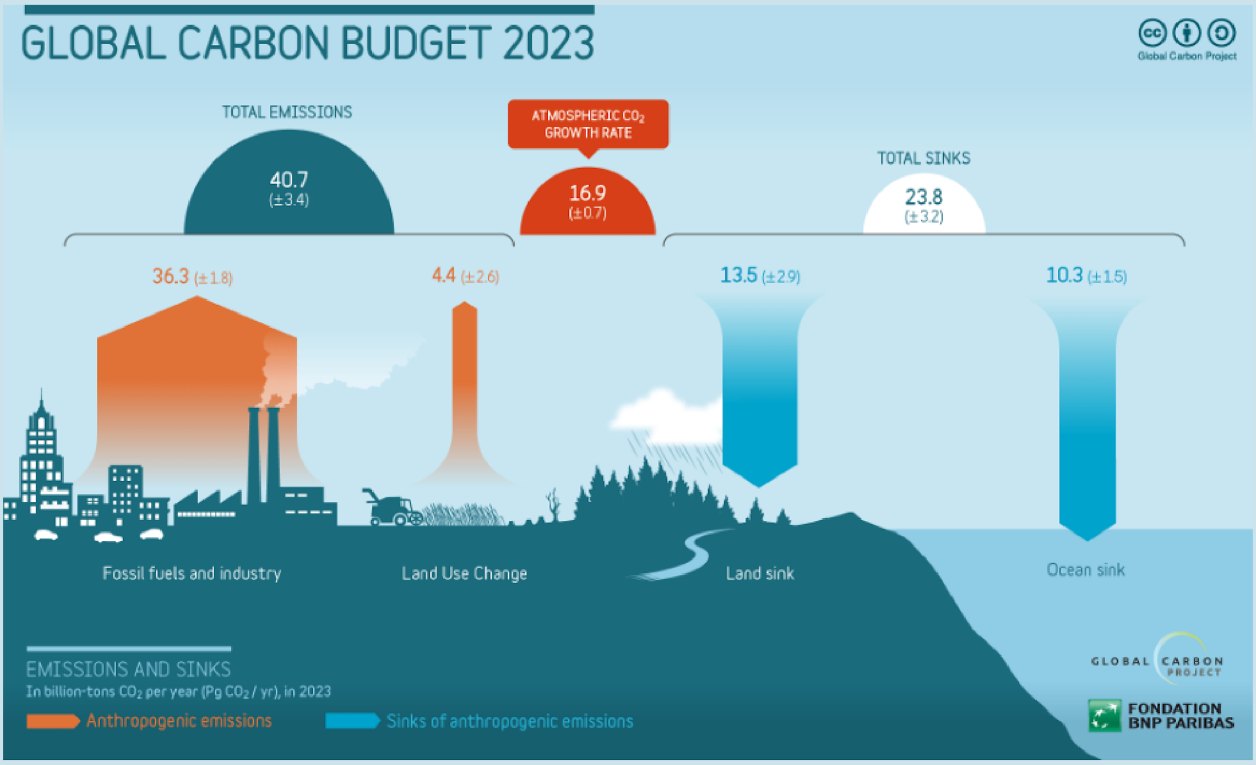
1. Short-Term Carbon Cycle:

- Photosynthesis: Plants, algae, and some bacteria take in carbon dioxide (CO2) from the atmosphere during photosynthesis, converting it into organic compounds such as sugars used for growth.
- Respiration: Living organisms, including plants, animals, and microorganisms, release CO2 back into the atmosphere through respiration as they metabolize organic compounds for energy.

2. Long-Term Carbon Cycle:

- Decay and Decomposition: When living organisms die, their remains undergo decomposition. Decomposers like bacteria break down organic matter, releasing CO2 back into the atmosphere during this process.
- Fossilization: Over long periods, some organic matter is buried and may eventually become fossil fuels (coal, oil, and natural gas), storing carbon underground.
- Volcanic Activity: Volcanic eruptions release CO2 and other gases into the atmosphere, also contributing to the carbon cycle.

Human activities, particularly the burning of fossil fuels and deforestation, have disrupted the natural balance of this global carbon cycle, leading to excess CO2 being released into the atmosphere, contributing to the greenhouse effect and causing climate change. Efforts to mitigate climate change often focus on restoring and enhancing natural processes within the carbon cycle, such as afforestation, reforestation, and sustainable land management.



Scaling Solutions —
The State of CDR

Having established the need for CDR as an integral part of reaching Net Zero and then negative emissions, how far away are we from where we need to be? Simply stated we need to move from megatons (Mts) to gigatons (Gts), or from millions to billions of tons of CO_2 per year.

First there is a distinction that must be drawn between Carbon Capture & Storage (CCS), Carbon Capture Utilization & Storage (CCUS), and Carbon Dioxide Removal (CDR). Each of these sectors relate to the capture of carbon emissions by any number of methods or technologies, but really come from different philosophies that make for key distinctions. CCS has often been seen in a negative light, as primarily an oil and gas industry concept pushed to help prolong the use of its legacy assets, to revitalize depleted oil wells, or as a means of 'greenwashing' the sector. This can also be seen with blue hydrogen, being a bridge fuel between grey to green hydrogen, which would also make significant use of existing oil & gas industry infrastructure in the process.

Let's first go over each of these acronyms and what they mean in practice, and why the focus of this briefing is on CDR. In brief, CCS is about reducing carbon emissions while they are being created, while CDR is about removal and durable storage to create negative emissions. CCUS is the further use or recycling of its captured CO_2, to help make the economic case for CCS technology and its extra costs.

CCS — Carbon Capture & Storage

Carbon Capture & Storage (CCS) is a technology designed to mitigate climate change by capturing CO_2 emissions at their source, typically from industrial sources like power plants or gas production, and preventing their release into the atmosphere. The process involves capturing the CO_2, transporting it, and securely storing it underground in geological formations, including in depleted oil and gas reservoirs. CCS aims to reduce the overall carbon footprint of fossil fuel-based energy systems, offering a transitional solution while transitioning to cleaner energy sources. Despite its potential, its deployment in practice has faced several challenges such as cost, infrastructure, and public acceptance, posing hurdles to its widespread adoption and necessitates ongoing research and development to be more effective.

CCS is effectively a bolt-on emissions reduction solution that seeks to limit the carbon impact of a plant or process that generates CO_2 emissions by capturing it at its source before it reaches the atmosphere. Once captured, it then must be stored, which could be done in a short-term way, or durably for long-term storage. Utilizing this captured CO_2 for another process, or to sell as its own by-product, is the related process of ***CCUS – Carbon Capture Utilization & Storage.***

CCS for the use of CO_2 gas for enhanced oil recovery ('EOR') from otherwise depleted wells has the longest history of experience but is not in fact a carbon negative process. It amounts to increasing carbon emissions at a decreasing rate, as opposed to simply unabated emissions.

CCUS is the more economics-focused cousin of CCS, whereby an additional business case is made for the usage of the captured CO_2 for other industries, processes, or products, including EOR. CCUS improves the value-add case for reduced emissions, but does not aim to reduce the current CO_2 concentrations in the atmosphere, or to prevent their increasing.

CDR — Carbon Dioxide Removal

CDR comprises various technologies or approaches to actively extract carbon dioxide from the atmosphere, aiming to combat climate change by reducing CO_2 concentrations. Techniques include Direct Air Capture (DAC), afforestation / reforestation, or enhanced weathering, and ocean-based methods like blue carbon. Each of these methods seek to either store captured CO_2 underground, in biomass, or via enhanced natural processes that absorb and store carbon—mimicking and speeding up the earth's natural carbon cycle.

CDR is a critical component of climate change mitigation, providing a means to achieve negative emissions and balance out residual CO_2 emissions for the hard-to-decarbonize sectors. However, challenges like scalability, environmental impacts, and ethical considerations underscore the need for comprehensive assessments and the sustainable implementation of CDR strategies. There will not be one method, standard, or form of CDR, but a wide variety of approaches of varying sizes across a wide range of geographies. That said, there will likely be winners and losers as the best and more economically viable approaches win out over time.

The processes of CCS / CCUS are related to CDR in that they share the concept of capturing CO2 from the atmosphere, whether directly or indirectly. But a second principle defines the distinction, which is the durable storage of the captured CO2.

CCS methods that are attached to an industrial or chemical process is a derivative of the CO2 emitting process and amounts to an emission *reduction* practice as opposed to a *removal* practice. At even 100% efficiency, which is highly unlikely to be reached, emissions will likely still increase across the value chain. The ethos of CDR is to be carbon negative from the outset, and to remain so for centuries to millennia. This is referred to as durable carbon storage.

Guiding Principles—

The landmark State of CDR report from January 2023 provides some useful principles to define CDR, with the first two illustrated herein.

Principle 1: The CO2 captured must come from the atmosphere, not from fossil sources. The removal activity may capture atmospheric CO2 directly or indirectly, for instance via biomass or seawater.

Principle 2: The subsequent storage must be durable, such that CO2 is not soon reintroduced to the atmosphere (decades to centuries).

Principle 3: The removal must be a result of human intervention, additional to Earth's natural processes.

To truly be CDR, a project or technology must be carbon negative, combining robust durability in its storage, and be truly additional to natural processes. Like the carbon emissions they seek to remove, they must be anthropogenic (human-caused).

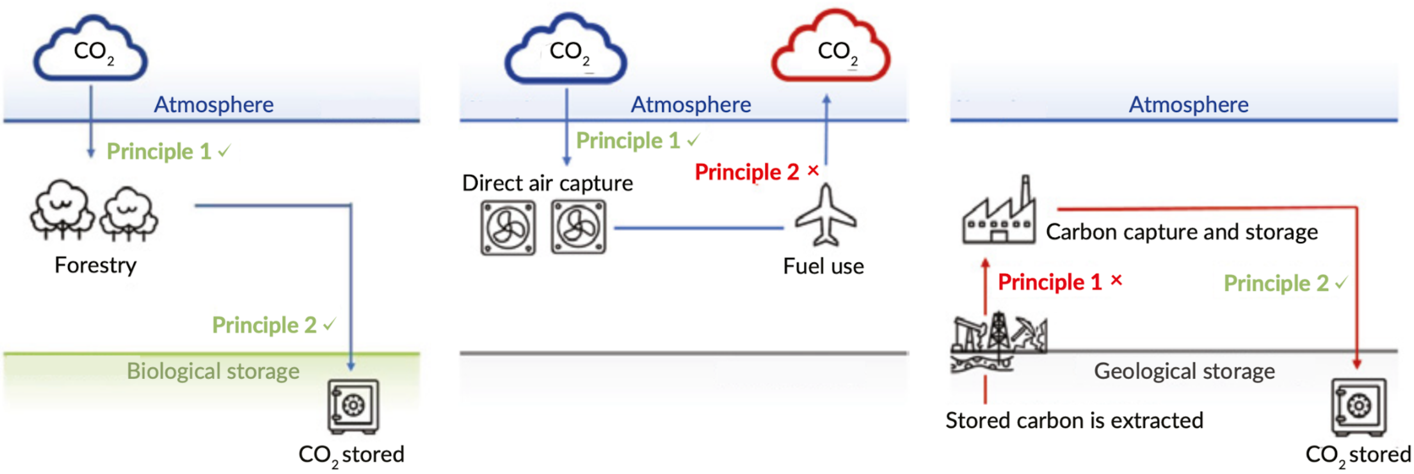
These distinctions and their importance have been ever more apparent with recent issues in the measuring and accounting practices employed by some in the voluntary carbon credit markets, which will be explored deeper in a future issue.

Such issues include selling the right to further pollute against current natural carbon sinks, dubiously counting or double-counting the actual emissions reductions being made, or having forestry-based projects literally go up in smoke. Yet the emissions they were meant to offset have already gone out the pipe. Such offsets can actually be worse than nothing.

For this reason, the type of CDR and its inherent limits should also be guiding principles for which sectors may buy off their emissions. The cheapest forms should be reserved for climate restoration efforts, while the most technical and durable solutions (which inherently cost more) are available to companies looking to buy-off their emissions from somewhere else.

The State of CDR Report also points out that today nearly all carbon removal comes only from Land Management practices, such as Afforestation and Reforestation, with only a tiny percentage coming from the 'novel' or technical processes; the areas which need to drastically scale-up to meet climate targets. Of this small sliver, just two types have formed the vast majority of 'technical' CDR—BECCS and Biochar, followed far behind by DAC.

We will explore each of these, and how they compare to potential other approaches being pursued.



State of CDR Report, 2023 – https://www.stateofcdr.org/

BECCS — BioEnergy Carbon Capture & Storage

Bioenergy Carbon Capture & Storage (BECCS) is a strategy that combines bioenergy production with a carbon capture & storage (CCS) process. Biomass, such as crops or forestry residues, is burned as a fuel source to generate energy, and the resulting carbon dioxide emissions are captured before release. The captured CO2 is then stored underground to prevent its contribution to atmospheric GHG levels. This is not quite the same as CCS based on fossil fuels, however.

BECCS not only produces energy but also results in negative carbon emissions by removing CO2 from the atmosphere when the biomass is first created, and the CCS process prevents it loss while producing energy. In practice, the CCS doesn't need to be 100% efficient to be net-negative, unlike when combined with a fossil fuel source. While seen as a potential tool for achieving net-negative emissions, BECCS also faces challenges related to land use, the sustainability of the fuel feed source, and technological feasibility.

It meets the principles set forth above for both carbon removal from the atmosphere, and its storage, provided that the biomass is indeed carbon negative, and that the storage used is sufficiently durable.

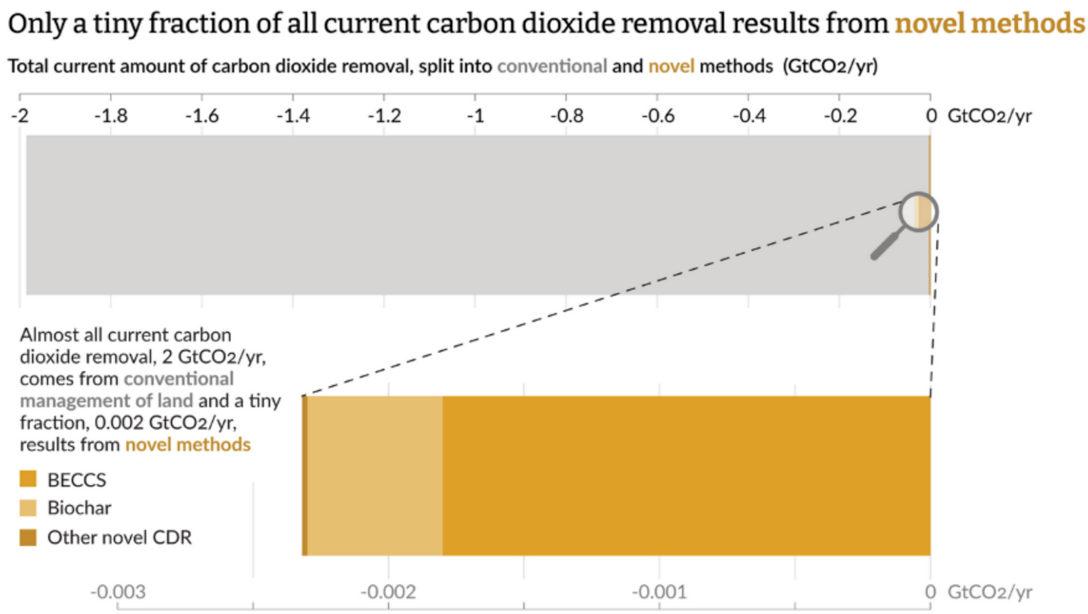
The goal of BECCS is to achieve negative carbon emissions, meaning that more CO2 is removed from the atmosphere during the production of the biomass than is released when converting it to bioenergy. This negative carbon balance is important in the context of mitigating climate change, as it helps to reduce the overall concentration of CO2 in the atmosphere.

Like other natural CDR solutions however, there are issues with scalability and land use changes compared to the overall CO2 reduction achieved. Similar to forestry-based carbon projects, there are limits to land availability to utilize this approach, particularly at scale.

Like CCS vs CDR, biomass has both a CCS component and a CDR component. Other biomass focused companies like Charm Industrial or Graphyte, seek to take waste biomass from the growing of crops, concentrate this into Bio-oil or blocks, and then store it in the ground. The purpose of this is CDR, taking natural carbon removal from vegetation growth, and storing it without decomposition or re-releasing the carbon pulled from the air. Here the focus is on being as carbon negative as possible, without the need to choose between food or energy production as only the unused waste products are used.

The energy producing aspect of BECCS makes it an attractive option to at least replace fossil fuel based systems and contribute to the energy grid mix in a sustainable way. How carbon negative it performs in practice will be determined by many factors.

As with all these technologies, the key is the execution to achieve its specified aims. BECCS is clearly a far better alternative to coal-fired power plants, and some former coal plants like Drax in the UK serve as an example of how converting these carbon emitting plants can be made into carbon neutral at least, and carbon negative at best. Provided the land and fuel feed source conditions permit, BECCS can form a key part of the energy transition.



Biochar — Pyrolysis for Soil Carbon Sequestration

Another rapidly emerging CDR method, with additional synergistic benefits for agriculture, is Biochar. Biochar is a form of biomass recycling, where biomass waste or purpose grown plant material is converted into charcoal through a process called pyrolysis that burns the biomass in a low-oxygen environment, which converts the biomass carbon content into a decay resistant form. Once the biochar is buried and added to soil the carbon stays locked in this form for up to centuries, making it highly durable, though not fully permanent. Certainly, long enough for Net Zero and the Paris temperature target timelines.

Furthermore, by adding biochar to soils there are numerous crop benefits as well, from greater water retention to resist drought, better nutrient storage, and more beneficial microbials that leads to better crop yields with less fertilizer requirements and less water demand. Making biochar usage the norm in farms and gardens would have great benefits across the water-food nexus while also removing carbon. The key, as with other biomass solutions, is scaling up and having enough biomass available to use it at scale.

The use of biochar in heavily depleted land areas has also been shown to be effective. As a concept, currently barren and damaged land at former mining sites could be infused with Biochar to then grow plant material biomass, which could be harvested and converted into bio-oil and stored underground as well. Rehabilitating otherwise contaminated land areas into small scale CDR projects.

Biochar is considered among the most ready technological CDR solutions today, and by 2030 could account for up to 1 - 3 $GtCO_2e$ of CDR annually.

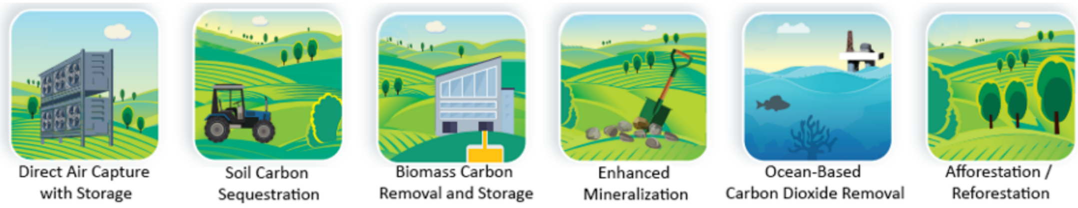
DACCS (DAC) — Direct Air Carbon Capture & Storage

Direct Air Carbon Capture & Storage (DACCS) is a technology designed to reduce atmospheric carbon dioxide levels by pulling it directly from the air. It involves using specialized chemical processes or materials to capture the CO_2 as it passes, and once captured to typically store it underground in geological formations to prevent re-release into the atmosphere.

DACCS aims to address emissions from various sources, including those that are challenging to decarbonize. While considered a promising tool for achieving negative emissions, challenges such as its own energy input requirements (and the source of this energy), the overall cost per ton (among the highest of CDR methods today), and thus its scalability still need further refinement for widespread implementation, making ongoing research and development crucial for its success.

In places like Iceland with a natural abundance of geothermal energy this can be more easily deployed, as being done by Climeworks and Carbfix. In places like Oman, the current lack of green energy sources can mean that the DAC process is simply chasing its tail, as the carbon emissions from its power input reduces the efficiency of its removal, even before storage has taken place. While DAC that runs on green energy and is tied to a concentrated CO_2 source, paired with a durable CDR technique like enhanced weathering, can make this play much more feasible.

The exact process of DAC is still being refined as well, with different solvents and chemical processes being tested to find more efficient ways of extracting CO_2 from the air and lowering its energy needs. The average cost today is about $1,000 per ton, down from over $2,000 per ton, but still far from the industry goal of $100 per ton in the next decade. Paired with the rollout of other technologies in the Net Zero pathways, DAC can be a critical support to durable CDR that is not limited by land use constraints.



Enhanced Rock Weathering (EW)

Enhanced Weathering or Rock Weathering is a geo-engineering approach to CDR, pulling CO2 from the atmosphere by accelerating earth's natural processes. It involves the controlled application of minerals such as olivine to surfaces where they react with CO2, converting it into stable carbonates. Other types use basalt spread over crops like biochar, and the CO2 in rain becomes locked into the basalt as carbon.

EW processes mimic and amplify the Earth's natural weathering mechanisms, which sequester carbon on geological timescales. Proponents argue that enhanced weathering has the potential to offset anthropogenic CO2 emissions, mitigating climate change in the most durable ways. However, its feasibility, environmental impacts, and scalability are subject of ongoing research and debate, necessitating careful consideration of ethical, social, and ecological implications.

Trees—A brief note on the original CO2 Direct Air Capture technology; trees and plants. Already we have seen how most of the 'technological' approaches to dealing with carbon removal are in fact mostly enhanced natural processes, with nature remaining among the best direct means of removing carbon from the atmosphere.

They cannot be the only solution however, as the time and space required to handle global carbon emissions do not match up. The natural carbon cycle has been made imbalanced on two fronts; one from the excess carbon emitted by humans taken from underground, and second by reducing the carbon sinks available for natural removal processes.

Thanks to remote sensing and modern technology, along with on-the-ground efforts to support such estimates, it is now possible to make some calculations about the actual number of trees existing on Earth today, as well as related metrics such as total biomass. There are an estimated ***3 trillion*** trees on Earth today. A vast number, and also 8x larger than what was thought to exist only decades prior. The pace of deforestation has in fact slowed in many places, but we are still losing 15 billion trees annually.

What is more remarkable, 3 trillion trees most likely represents a 50% loss during the period of human history. Restoring these numbers, and not just limiting or slowing their loss, is another critical tool to correcting the global carbon cycle.

In the United States, massive deforestation arriving with colonization drastically reduced the number of forests that covered the continent. While great progress has been made to recover these losses, according to the North American Forest Commission, there are still just 66% of the trees that there were in only 1600 CE. Much of the pace of this loss was stemmed in the 1920s, and by 1997, tree growth exceeded tree harvest by 42%, leading to a recovery where at least the east coast now has double the number of trees it did 70 years ago.

We have seen how human activity and development has reduced tree stocks and then brought them back again. This needs to be employed at scale globally, wherever possible. Urban greening is another effort that can help us to better adapt to the effects of climate change like the heat island effect, while increasing the carbon sinks available.

As known from carbon offset schemes, there is not enough room on Earth to plant trees that will offset all the carbon humans plan to emit. Preservation is good, but restoration is better. Ireland has pledged to plant 440 million trees to help combat climate change, by planting 22 million a year over 20 years, but every year the planet loses a net -10 billion trees, by cutting down 15 billion and re-planting 5 billion.

Truly reversing this trend requires planting more than we lose, trending back towards the 6 trillion trees estimated to exist prior to human activity. This should be the aspirational target for restoring nature's own DAC carbon system. This can be accomplished through replanting efforts, *Natural* CDR, and efforts like Urban Greening, that increase trees and plant cover wherever possible, to absorb carbon, clean air, and cool urban heat centers.

Afforestation & Reforestation—Natural CDR

Natural CDR methods such as afforestation or reforestation, which still requires humans to influence and cultivate its path, are currently doing all the heavy lifting in CDR today. There are some key distinctions between these terms and what they mean in practice.

Afforestation is the intentional process of planting trees and vegetation in areas that were previously devoid of forest cover. It aims to create new forests, enhancing ecological balance, conserving biodiversity, and mitigating climate change by absorbing carbon dioxide as they grow.

Afforestation can also help to combat soil erosion, promote water conservation, and provide a habitat for various species. This practice contributes to sustainable environmental management and the overall well-being of ecosystems, while capturing carbon as it grows.

Reforestation involves replanting trees in areas that have experienced deforestation or forest degradation, to restore and replenish existing forests, promoting biodiversity while mitigating climate change through carbon sequestration and preventing soil erosion. Reforestation also supports ecosystem resilience, provides habitat for wildlife, and contributes to sustainable resource management.

Both afforestation and reforestation seek to plant more trees and contribute indirectly to CDR using nature's original DAC process. However, when the planting is dominated by a single species of tree for example, this can create greater risks of reversal whereby a blight or pest can take out more of the planted trees than in a diverse forest. There is still no substitution for natural biodiversity, with a variety of trees and plants in balance that thrive off each other.

A related concept is that of ***Agroforestry***, which is the cultivation of field crops and livestock using natural forestry, mixing crops between and under trees, or with cattle grazing under them. Examples of the types of agroforestry include wood pasture, intercropping, alley cropping, or grazed orchards.

The Forests of the Sea—Kelp

Forestation is not only limited to land management practices. Kelp beds in the sea can store 20x the amount of carbon per acre as do land-based forest equivalents, and kelp will also grow up to 30x faster. This has led to their rapid recovery in places like San Francisco, after a 90% collapse just a few years prior.

The ocean is one of the largest natural carbon sinks on the planet, but a warming ocean that traps more carbon increases acidification and damages ocean life. One of the best places to help balance the carbon cycle are in the oceans, to reverse these affects and allow the oceans to restore atmospheric balance. As we have seen in the global carbon budget overview, the ocean has absorbed an increasing amount of carbon over the decades, more than anticipated, which has helped to mitigate the rising concentration of carbon emissions in the atmosphere.

Kelp beds are kept in balance between grazers like urchins and fish, and predators which prevent the grazers from destroying a kelp forest. Removing the balance of predators by over fishing or pollution leads to increasing grazer populations, which can then wipe out entire kelp forests. Warming waters also limit their growth and will be an ongoing concern with increasing ocean temperatures caused by climate change.

Carbon Kapture is a CDR project that seeks to pull carbon from the oceans as kelp, store it locked in useful products, and sink the remainder onto the seabed, where it will store the carbon for centuries.

Blue Carbon—

The majority of the Earth's terrestrial carbon reserves are located in peat-lands and coastal wetlands, encompassing mangroves, tidal marshes, and sea-grasses. Referred to as "blue carbon," these wetlands store carbon in their sediments and plants.

Unfortunately, a significant portion of the world's mangrove, sea-grass, and salt marsh areas have been lost in recent decades, degrading at alarming rates—sometimes up to 4x faster than rain forests.

Annually, 2–7% of blue carbon sinks are disappearing. The restoration and expansion of these wetlands and peat-lands present an opportunity to extract CO_2 from the atmosphere and sequester it in sediments and biomass.

Mangroves have been looked at as a powerful adaptation and mitigation tool, as they can store carbon, and protect coastlines simultaneously. Wetlands, especially peatlands or bogs, can instead emit a great deal of CH_4, methane, a far more powerful though shorter lived GHG. Still, it is an attractive low coast CDR method that can take advantage of resources that may otherwise be ignored.

Ocean Alkalinity Enhancement (OAE)—

Similar to making forests in the sea with kelp beds, the same enhanced weathering processes on land that use rock to interact with CO_2, some of the same alkaline substances such as basalt and olivine can be finely ground and mixed with seawater to combine with CO_2, reducing carbon levels while also reducing ocean acidification.

Ocean Alkalinity Enhancement or OAE, is a form of ocean-based EW, or mCDR (marine CDR). The cost of this process has the potential to be highly competitive, and similarly does not compete for land resources. However, to be used at scale the simple math may hinder its effectiveness, as 2-3 tons of rock is needed to interact with 1 ton of CO_2. Using only this method would require more rock than is mined globally today, just to grind it up and add it to the oceans. However, it is another arrow in the quiver to fight against CO_2 in the atmosphere and oceans.

Ocean Iron Fertilization (OIF)—

Potentially the cheapest form of CDR available, Ocean Iron Fertilization or OIF looks to stimulate the production of phytoplankton in the ocean in iron-deficient areas. By adding iron where it is currently deficient, the limiting factor on phytoplankton growth is removed allowing it to rapidly grow and capture carbon from the atmosphere in the process.

Once the phytoplankton dies, it sinks to the ocean floor and sequesters it for centuries. At least in theory, as this has not yet been done at scale, and a 2009 experiment found that most of the phytoplankton boom it caused, were eaten by zooplankton, rather than sinking to the deep sea. It could also help create ocean dead zones by depleting dissolved oxygen levels. However, at a potential cost of just a few cents per ton, with no limits on land usage, and the potential to remove gigatons of carbon, it remains a point of interest for ongoing research.

Nature vs Nurture — Carbon-tech Landscape

The scaling up of CDR requires turning operations that deal with just thousands of tons, into those that deal with billions of tons—turning lemonade stands into Amazons. As we have reviewed the technological landscape of CDR today a few key themes emerge:

- A nature versus technology dichotomy is deceiving, as the real comparison is between nature vs. 'nurture'—or enhancing and speeding up the earth's natural carbon cycle processes.
- The final cost per ton of CO2 removed is a direct factor in its scalability, and if it can be viable for climate restoration purposes.
- Natural and technical CDR have nature-based limits due to available land, fuel feed sources, etc.
- The variety of potential CDR approaches available are why a wide variety should be pursued at once, to do everything possible now and discover new breakthroughs along the way.
- Inherently this means some projects will fail to secure sufficient funding, or to scale over time and continue on. However, if they indeed capture the carbon they set out to, it will still not be a waste.

For a transitional period, BECCS is *far* better than burning coal, and DAC for enhanced weathering or blue hydrogen production is useful, and not a impediment to protecting forests or farming kelp bed forests in the oceans. Just as no one renewable energy technology should be solely counted on for Net Zero future, no single CDR technique can be singled out to reach either Net Zero or the negative emissions to restore the climate.

Cost per Ton CO2e Removed

As a new and emerging market with stiff competition, it can be difficult to obtain precise estimates on the full operation costs, capital costs, and thus the final cost per ton of CO2 removed, which would be charged to customers such as governments or carbon credit buyers. Like many start-ups, novel CDR firms are not profitable or sustainable today in terms of their business model, but with scale, support, and patience, could become majors success bets. As such, some of the most expensive forms of CDR being pursued like DAC, have and continue to receive the most funding.

Estimates per ton vary by method and by company, but the range of costs per ton CO2 removed can vary from a few cents, to several thousand dollars, with widely varying input requirements in energy or land.

Drax, which converted plants from coal to BECCS has agreed deals with carbon brokers at $300 per ton, and a goal of 12 million tons by 2030, for a facility in the United States. DAC has been quoted to cost between $300-$600 per ton, and upwards of $2,000 per ton. Climeworks currently quotes at $1,400 per ton, with a goal of $100 per ton in the future. Biochar methods range from <$1-$200 per ton, while Charm's bio-oil solution agreed to $600 per ton with Frontier, aiming to lower by 37% by 2030 with its scale-up. Carbfix in Iceland uses abundant geothermal energy, stating it's EW method costs $25 per ton, and Graphyte's Carbon Casting is stated to already be below $100 per ton.

Afforestation
$3-30/tCO$_2$

Habitat restoration
$10-100/tCO$_2$

Building with biomass
$0/tCO$_2$

Soil carbon sequestration
$-10-+3/tCO$_2$

Biochar
$0-200/tCO$_2$

Enhanced weathering
$50-500/tCO$_2$

Direct air carbon capture and storage (DACCS)
$200-600/tCO$_2$

Bioenergy with carbon capture and storage (BECCS)
$100-300/tCO$_2$

The wide range of costs for CDR must be kept in context with its additionality, durability, and current scale. Some expensive solutions today could drastically reduce in cost, and will not be constrained by natural limits. Other solutions can be done cheaply and at even scale, but will be more limited over time.

The right blend of approaches, and pairing CDR credit needs to methods/costs is key. Emission reductions must come first. A company that could reduce its emissions but instead buys CDR credits as being more efficient economically is a sub-optimal outcome for the climate. A hard-to-decarbonize company may rely on CDR credits, but only if truly additional, durable, and accountable against their emissions.

Bio-oil – Charm Industrial
Charm Industrial seeks to run the oil extraction process in reverse, taking biomass and converting it to bio-oil, then injecting it back into the ground. Hence their slogan, 'Put Oil Back in the Ground'. Focusing on agricultural residues, they take biomass that has pulled carbon from the atmosphere and now has no usage, pyrolyzes it to convert the biomass into bio-oil, which is then injected through wells that return the carbon to where it came from.

Acting as a form of carbon recycling, Charm looks to keep its costs and energy inputs low, while not competing for land resources, by instead working with agriculture as its feed source. While biochar uses pyrolysis to make a soil additive that then works with the soil, Charm seeks to directly sink it back into the ground. By using this process, the durability of the storage is far greater than that of biochar.

Carbon Casting – Graphyte
Graphyte is a simple but elegant solution to CDR that leverages biomass production with the least amount of energy required—carbon casting. Biomass, particularly in the form of crop waste or residuals, or timber by-products and waste, is dried, then pressed and compacted into blocks. However, rather than try to transform it, it is simply wrapped in an impermeable barrier to lock in the material and prevent its decomposition, and then stored.

Enhanced Weathering – UN-DO
UN-DO is an enhanced rock weathering pathway that uses crushed basalt rocks spread over farmland, allowing a natural process to take dissolved CO2 in rain and turn it into solid carbon as it interacts with the basalt in the soil. The process is passive as it relies on rainwater to bring the CO2 / carbonic acid from the atmosphere and interact with the rock. It's fine ground processing speeds up the natural process that would otherwise occur, increasing the surface area for the chemical reaction. This takes a timescale of millennia and reduces it to decades. The other benefit however is similar to that of biochar, in that the ground basalt benefits the agricultural production.

In practice, a basalt process like UN-DO's can work in tandem with a bio-oil or biomass process like Charm or Graphyte, to better grow crops, sequester carbon in their soils, and then also take their waste products and store them as sealed biomass or injected bio-oil. Thereby better using our lands for food production and to sequester carbon at the same time.

DAC & Enhanced Weathering – 44.01
For 44.01 in Oman, their process seeks to use CO2 and water (carbonated water), which is injected into peridotite geological formations that are readily accessible in the landscape of Oman. This process takes a very slow million-year natural process and reduces it down to just 1 year, allowing for truly robust and permanent carbon storage. The source for their carbon, comes from partners like Climeworks using DAC methods to pull CO2 from the atmosphere and combine it with water before injection. A pilot project in neighboring UAE is seeking to use DAC with seawater for peridotite mineralization as a first of its kind project. Relying on solar power agreements and hard-to-decarbonize industries for its carbon source, 44.01 seeks to be a regional player in the CDR market surrounded by oil and gas, and pivoting towards hydrogen.

As explained by 44.01's Founder and CEO Talal Hasan, in the simplest terms, their process injects highly concentrated Soda water (CO2 dissolved in water) deep into natural rock formations to mineralize CO2 into rock for permanent storage. Their process recovers and recycles the water used through the process, accelerating a natural mineralization process by more than 100,000 times. It is technical augmentation of a natural carbon sink process, shortening decades to be less than 12 months.

The key reactive mineral in this process is olivine. Olivine is present in peridotite in higher concentration than any other rock, which means it can mineralize more CO2, faster, than comparable rocks. The higher density of the injection fluid ensures it cannot move upwards to shallow groundwater or affect the local environment due to solubility trapping. Heat in the process also pushes the water back to the surface, for further CO2 injection and reuse.

While there are many places with peridotite and many forms of enhanced weathering techniques, Oman is one of a handful of places in the world with readily accessible peridotite exposed on the surface, which is typically under the earth's crust 40 kilometers below the land surface. This provides Oman with some comparative advantages to build out its CDR infrastructure related to Enhanced Rock Weathering, and sell carbon credits that are both additional and durable.

In-situ carbonation of peridotite could consume ~1 billion tons of CO2 per year in Oman alone, affording a low-cost, safe, and permanent method to capture and store atmospheric CO2.

The studies of Peter Kelemen and Jurg Matter over the past two decades have investigated and proven the concept that 44.01 seeks to achieve and scale up—locking atmospheric CO2 back into the Earth using the exposed mantle peridotite of Oman, which is typically found beneath the earth's crust.

In a 2008 paper, when atmospheric CO2 levels were 385 ppm, they calculated that Oman's exposed mantle peridotite had the potential to store all CO2 emissions since the Industrial Revolution. In the 15 years since, CO2 concentration are now over 420 ppm, and the need the high quality CDR is only increasing.

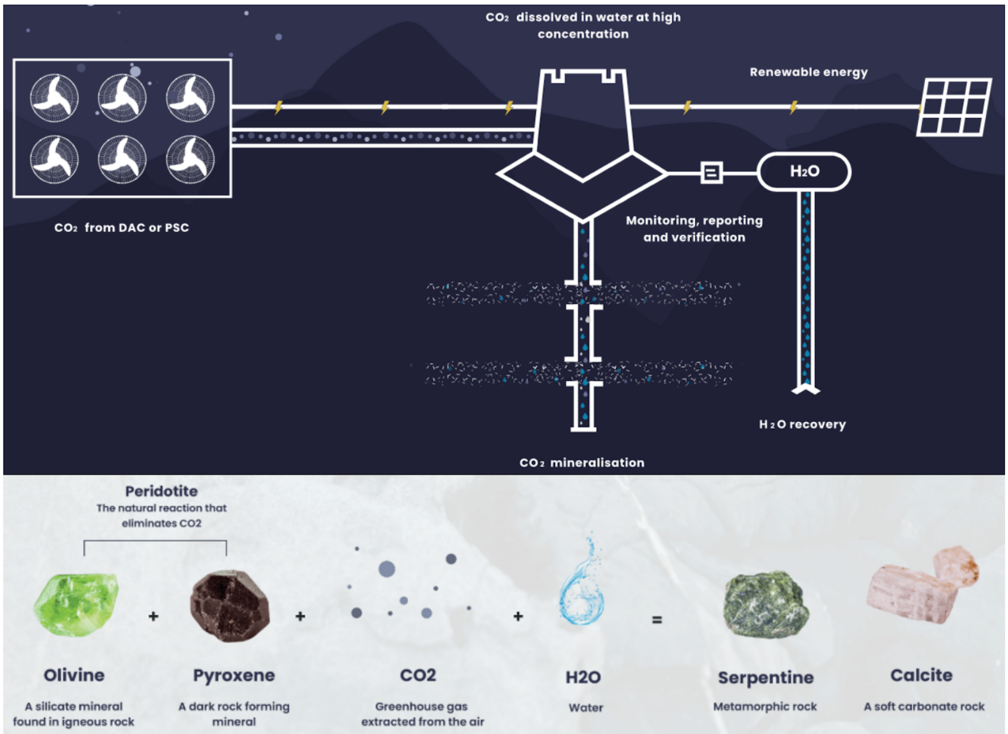
In Oman, the Samail "ophiolite"—a thrust-bounded slice of oceanic crust and upper mantle—is >350 km long and ≈40 km wide, and it has an average thickness of ≈5 km (7). Of this volume ≈30% is mantle peridotite. Adding 1 wt% CO2 to the peridotite would consume ¼ of all atmospheric CO2, an amount approximately equivalent to the increase since the industrial revolution. Converting all Mg cations in the peridotite to carbonate would consume ≈7·1016 kg (77 trillion tons) of CO2.

Similarly large ophiolites are in Papua New Guinea (≈200 × 50 km in area), New Caledonia (≈150 × 40 km), and along the east coast of the Adriatic Sea (several ≈100 × 40 km massifs).

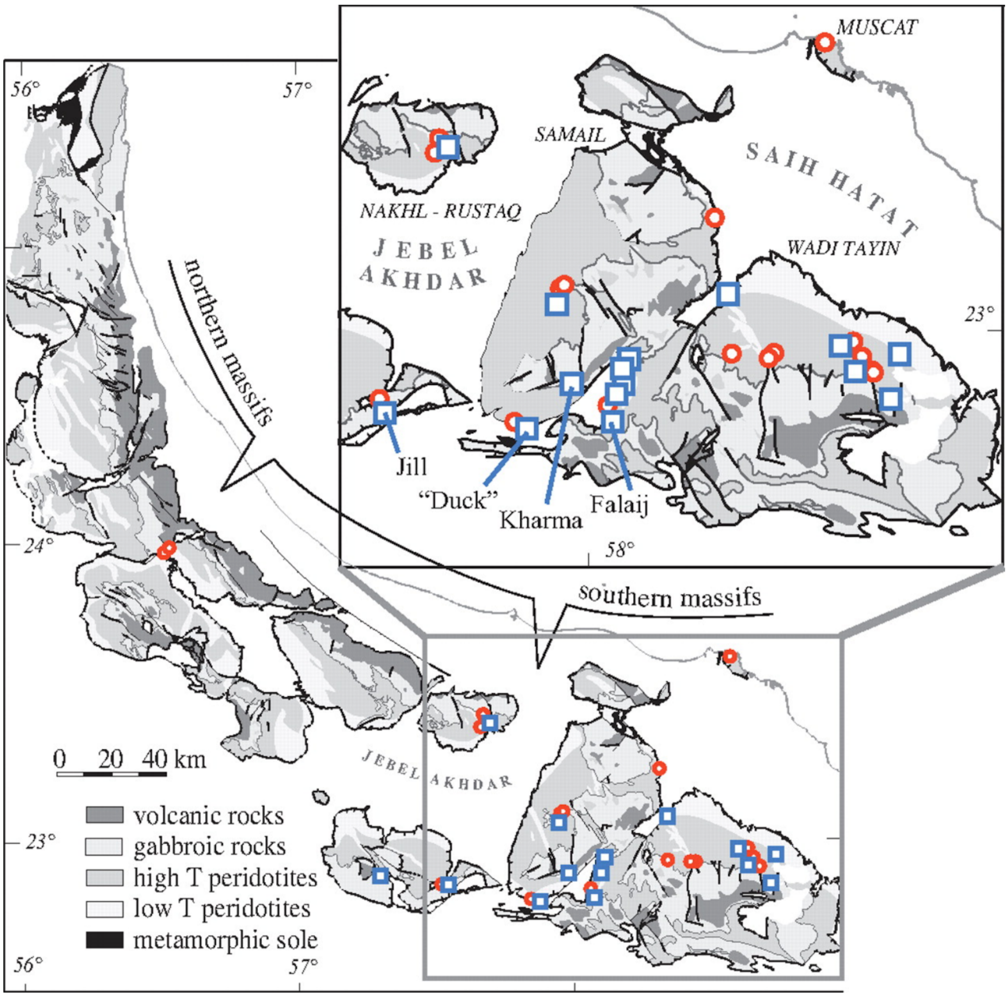
A stated aim of 44.01 is to slash the cost of its CDR to less than $100/ton CO2 removed with permanent storage. While there are many CCS methods that currently fall under <$100/ton or even $10/ton, the key difference is their permanence, the risk of reversal, and the need for costly monitoring over time.

As discussed, there is a spectrum of CDR with important differences in their processes and attributes that are also reflected in their costs. 44.01 will rely on Direct Air Capture to source its CO2, which is currently the most expensive source of atmospheric CO2 removal, to then mineralize it in their process. This is the current choke point in scaling up to reduce cost.

Oman is only just beginning to build out its renewable energy sector, with the Ibri-2 solar field online since 2022 with 500 MW potential, paired with a 1,500 MW natural gas plant. This should increase rapidly alongside Oman's drive for a Green Hydrogen economy in the coming decade, but a clean power source and low carbon processes are also key to reaching its CDR goals.



Source: *44.01*



Source: In situ carbonation of peridotite for CO2 storage - Peter B. Kelemen, Jurg Matter

CDR Market Making – 'Vaccine Model'
Frontier's Advanced Market Commitment

With the increasing need for novel CDR methods and innovations today being so important for realizing Net Zero by 2050 (and increasingly important with the delay of phasing out fossil fuels) a page has been taken from the vaccine production playbook to help make this carbon removal market a reality.

Frontier is a climate partnership created by the payments company Stripe and its partners to pool together the resources of major companies that are looking for high quality durable carbon credits. Partners like Alphabet (Google), Meta (Facebook, Instagram), Shopify, Workday, H&M Group, Autodesk, JP Morgan Chase & Co., and McKinsey Sustainability, pre-purchase durable carbon credits created by novel methods across a variety of CDR pathways. The idea is fairly simple, to guarantee an off-taker for their projects so they can scale their concepts and put new solutions on the market. To date, Frontier have contracted $170 million USD and over 357,000 tons of CDR across 32 different projects. This method helps to solve one of the largest financing challenges for new infrastructure projects, the off-taker risk, and allowing for that transitionary phase between idea, proof of concept, and operating.

By guaranteeing purchases of tons of CDR, companies are able to prove their concept to other investors and work towards scaling up production operations. This is the same Advanced Market Commitment used by governments in the pre-purchase of vaccines, to help mitigate the high up-front investment costs by guaranteeing a market or customer will exist, if developed. The risk for Frontier is that the project does not deliver, or delivers outside of the metrics needed to continue scaling and operating.

Across Frontier's 32 project portfolio a few common themes emerge, with DAC and Enhanced Weathering accounting for more than half (18), with 10 and 8 projects each. Further, many of the DAC methods are ultimately paired to EW methods that lock the carbon away as rock, or for use in cement. Of the nearly 160,000 tons of contracted CDR in the Enhanced Weathering pathway, 155,000 of it comes just from Lithos, using superfine crushed basalt on farmlands. For Lithos, the carbon removal process is passive, with 3 tons of fine basalt rock spread over farms pulling in 1 ton of CO_2 from the soil, while the farmer receives better soil and increased crop yields.

Other EW approaches have been mentioned, including the use of basalt on farm crops, but a key focus of Lithos is leveraging software and science for a cradle-to-grave approach to measuring, recording, and verifying (MRV) its carbon removal process. At a cost per ton of ~$370, this is higher than other similar approaches of $250-$300/ton.

The metric that is often referenced with CDR is $100/ton in the next 10 years, with 10 billion tons annually by 2050. With 10 $GtCO_2e$/yr at $100/ton, it would mean a $1 trillion USD annual market. With a $300 or $600/ton rate, the costs increase accordingly. With too high of a cost per ton, climate restoration of atmospheric CO_2 levels will not be done. We need new methods that can be done cheaply and at scale, for industry to get to zero, and then move into negative emissions territory.

The increasing need for highly durable and additional CDR and the size of the sector today shows there is a long way to go in the coming decades. Frontier's Advanced Market Commitment is one such effort to rapidly scale up the CDR market.

Once criticism is that CDR is ultimately taking funds from other renewable or decarbonizing projects, and allowing for more pollution for longer. In addition, once these other mitigation areas do succeed, CDR firms will lose their customers as there will be no emissions to remove. In reality, we are still a very long way from reaching Net Zero across the entire economy, and from the scale today to what is needed, alongside economic growth, a lack of customers for CDR may never materialize, but price will be a determining factor for the sector.

Valuing Carbon

Whether $1, $100 or $500, the value and viability of CDR technologies is tied to the cost of carbon, and how we value or undervalue it. In environmental economics the cost of pollution is undervalued due to its *externalities*, an impact or outcome that occurs external to the transaction or use of the product, like the burning fossil based fuels.

These can be either positive or negative externalities, where a product is undervalued considering the other benefits it gives indirectly, or it is overvalued (under costed), when considering its indirect damages. Carbon emissions are a perfect example of this in terms of size, scale, and timing from use to impact.

Accurately valuing carbon and its environmental impact as a GHG entails elevating the cost associated with the use of carbon-intensive fuels and activities to accurately reflect their impacts. This can be achieved through various means, ranging from direct or indirect taxation to market-based mechanisms, resulting in increased costs and the intended shift in economic behavior. In some scenarios, employing command-and-control strategies may involve the outright prohibition or stringent regulation of any sufficiently harmful product or practice. Currently, this approach is not feasible for carbon due to a scarcity of viable alternatives, but the landscape is expected to evolve rapidly in the coming decades.

In this way, we need an appropriate carbon price, higher than what it is today, which accounts for—or *internalizes*—the external damage it does by being released and accumulating in the atmosphere. There are several different methods for valuing carbon, including the Social Cost of Carbon (SCC), the Marginal Abatement Cost (MAC), as well as market-based carbon pricing schemes that range from a carbon tax to trading schemes.

The SCC estimates the value economic damage caused by emitting 1 additional ton of carbon dioxide. It provides a benchmark for policymakers when evaluating the cost-effectiveness of different emission reduction strategies. The MAC is a calculation of the costs for reducing 1 ton of CO2 emissions, to better compare the costs per ton of a chosen intervention.

Market-Based Carbon Pricing includes carbon taxes and cap-and-trade systems. Carbon taxes set a price on each ton of emitted carbon, incentivizing businesses to reduce their emissions to minimize the financial impact on them. Cap-and-trade systems establish a carbon emissions cap, allowing companies to trade their carbon allowances, promoting emissions reductions where they are most cost-effective.

Additionally, the Shadow Price of Carbon (SPC) is an internal carbon pricing tool used by businesses to assess the financial impact of potential future carbon pricing regulations, such as a future high fine per ton of CO2 emitted. This aids companies in making informed investment decisions that consider carbon-related risks.

For many of these tools, the purpose is comparison, and they are not meant to model the damage of climate impacts on a business, person, or economy.

The cost of carbon is an extremely important question, which will be explored deeper in the final Transboundary Carbon briefing issue. It is deeply linked to both the CDR technology market, and the continually expanding carbon credit markets—a new and relatively undeveloped and unregulated market. The success or failure of CDR technology, and reaching Net Zero in time for the Paris temperature targets, will likely depend on the carbon credits market and the carbon valuations underpinning them.

For a CDR technology company, a higher carbon price means their technology is automatically more competitive at its current credit selling price point, which is determined by their own process, operating, and capital costs. A low carbon price makes them too expensive to be utilized. For most firms, the path of lowest cost will generally win.

However, a catch-22 for the CDR sector is that they want the price of carbon credits to be low enough to encourage purchasing and growth, and directly seek to lower their costs to better compete. A higher cost of carbon and a lower cost of carbon credits provides the correct incentives. Yet if credits are too cheap and easy to obtain, firms could put off decarbonizing or that energy efficiency investment (which may cost more now) to instead purchase cheaper credits. This further delays completing the Net Zero transition.

The price of carbon is also a key component for Green Hydrogen, with current fossil methods averaging $2/kg, and green methods average $15/kg. Green methods need to come down in cost to be viable, and the legacy grey or black methods need to be properly accounted for to encourage this transition. For hydrogen, the value offer is simpler as a drop-in fuel to replace current fossil-based systems. For CDR, the value offer is less direct and tied to selling carbon credits. Both markets will be worth over a trillion USD per year in the coming decades.

CDR is both a process and philosophy, towards the removal of carbon from the atmosphere or oceans, to restore balance to the global carbon budget. Natural CDR or Nurtured CDR makes little difference to the carbon budget, but there are profound differences in terms of cost and scale, and thus how quickly we will implement it to reach Net Zero in time. 'Carbon-tech' will be necessary to overcome the limits of natural processes and must be invested in ***now*** in order to be ready for the future, particularly as we continue to fall behind the Paris temperature targets.

Sources for Further Learning

44.01 –
https://4401.earth

Climate Action Tracker –
https://climateactiontracker.org/

Carbon Credits –
https://carboncredits.com

Carbon Disclosure Project –
https://www.cdp.net/en

Carbfix –
https://www.carbfix.com/

Charm Industrial –
https://charmindustrial.com/

Climeworks –
https://climeworks.com/

CO2RE –
https://co2re.org/

Frontier Climate –
https://frontierclimate.com/

Global Carbon Project –
https://www.globalcarbonproject.org/

Graphyte –
https://www.graphyte.com/

International Energy Agency (IEA) –
https://www.iea.org/

IPCC Sixth Assessment Synthesis Report (AR6) –
https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Lithos Carbon –
https://www.lithoscarbon.com/

NASA Earth Observatory –
https://earthobservatory.nasa.gov/

The State of Carbon Dioxide Removal –
https://www.stateofcdr.org/

UN-DO –
https://un-do.com/

Woods Hole Oceanographic Institution –
https://www.whoi.edu/know-your-ocean/ocean-topics
/climate-weather/ocean-based-climate-solutions/

Key Reports

[1] The State of Carbon Dioxide Removal – 1st Edition (2023) doi:10.17605/OSF.IO/W3B4Z

[2] Carbon Removal: How to scale a new gigaton industry – McKinsey Sustainability (December 2023)

[3] Net Zero Roadmap: A Global Pathway to Keep the 1.5C Goal in Reach – International Energy Agency (2023)

[4] The Time for Carbon Removal Has Come – BCG (September 2023)

Acknowledgements

MEDRC's Transboundary Waters Practitioner Briefing series has been developed for industry practitioners and government officials at the request of MEDRC's member countries, with sponsorship provided by the Netherlands. The briefings are meant to be informative and practical, providing an overview of the subject matter material, while remaining accessible to various backgrounds and disciplines. The briefings serve to develop shared knowledge and serve as a basis for further discussions between partners. If you would like to learn more about these subjects, please see the section 'Sources for Further Learning'.

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Developed for water industry practitioners and government officials at the request of MEDRC's member countries, MEDRC's Practitioner Briefing series serve as a guide to trends in transboundary environmental cooperation. The initiative is intended to bridge the academic-practitioner gap in the sector by providing short, accessible and practical overviews, focusing on a different theme.

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