Inside this report

State of Technical CDRs

While the market for Technical CDRs is nascent, it is growing at a rapid pace.

Estimated Supply & Demand

Demand for high-quality technical CDRs and carbon storage is expected to outstrip supply in 2030.

Estimated Transactions Volume

Volume of technical CDR transactions are projected to be in the range of 50 $MtCO_2$ - 180 $MtCO_2$, per year in 2030, with an average price of $180 - $220 per tonne CO_2.

Technical CO_2 Removals Market: Present and Future

GEET KALRA, JAHNAVI MUPPANENI, MARGARET BERTASI, MICHAEL PROUDFOOT & NAVENDU SHARMA

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EXECUTIVE SUMMARY

Carbon removals ("removals") will play a pivotal role in the global commitment to emission reduction and climate change mitigation. There is a pressing need for decisive and impactful growth in the removals industry to meet the aggressive goals being established by both the private and public sectors. Technical carbon removals are a promising solution, though they are still relatively young and under-adopted compared to their natural counterparts. However, technical removals have seen massive adoption lately after the latest IPCC report of 2022. In the first four months of 2022, 0.43 $MtCO_2$ of technical removals have been purchased (including a single deal for 0.4 $MtCO_2$), which is already a far greater number compared to the negligible amount purchased just two years ago. The current supply remains limited, but the total available capacity of technical removal projects across the globe stands at roughly 3 $MtCO_2$.

We examined the current state of five different technical removal approaches to project the supply and demand for certified technical carbon dioxide removals (CDRs) in 2030. To start, we looked at the current and historical purchases of removals in the voluntary carbon market. We expect that the demand in 2030 may come from both voluntary and compliance carbon markets. On the supply side, we conducted an in-depth literature review for each technology and projected future capacity and price points. We used this research to arrive at our findings pertaining to the removals market in 2030.

The main findings were that the demand for certified technical removals in 2030 could range between 30.7 $MtCO_2$ to 623 $MtCO_2$ per year, depending on the adoption by various compliance markets. Looking at the pace of investment in the sector and projections made by various suppliers, we estimated that the CO_2 removals market will have enough supply to meet up to 210 $MtCO_2$/yr of demand in our base case scenario. This supply, given the current projections, could rise as high as 450 $MtCO_2$/yr in an optimal case scenario. Based on the trends we have observed, we predict that the technical CDR market will most probably lie between 50 $MtCO_2$ to 180 $MtCO_2$ per year with an average price across technologies ranging from $180 to $220 per ton of CO_2. Biochar, BiCRS, and DACCS are expected to lead demand preferences, with DACCS garnering the most interest among the three. We also performed empirical analysis on existing CDR projects and found that the price of those CDRs depended significantly more on factors such as *permanence (durability)* and *additionality*, as opposed to factors such as *negative effects on the environment*. We believe such a trend will continue through to 2030 in the removals market.

To meet the global net-zero target by 2050, it is important that technical CDRs become cost-competitive with nature-based removal solutions. After accounting for the additional benefits that technical CDRs offer such as permanence and additionality, we believe that an average price of $90-100 per tonne for highly additional and permanent CDRs would result in corporations considering the purchase of technical CDRs in lieu of nature-based removals. Adoption of CDRs by compliance markets will accelerate the innovation and development in the technical removals market and would be a significant catalyst in achieving this price drop.

This research was conducted by Geet Kalra, Jahnavi Muppaneni, Margaret Bertasi, Michael Proudfoot, and Navendu Sharma at Tuck School of Business at Dartmouth College as part of the First-Year Project course with input from South Pole.

INTRODUCTION

Certified tonnes of Carbon Dioxide Removals (CDRs) will be an essential part of the Intergovernmental Panel on Climate Change's (IPCC) recommended goal of limiting global, post-industrial temperature rise to 1.5ºC. Currently, there are 950 Gt of anthropogenic CO_2 in the atmosphere, concentrated at 415 ppm. To meet the goal laid out by the IPCC, and later adopted at the Paris Climate Accord, at the minimum, 5-7 $GtCO_2$ will need to be removed from the atmosphere per annum by 2050. Beyond 2050, annual atmospheric CO_2 will need to be removed at a rate of 20 $GtCO_2$ per annum to keep the aggregate atmospheric temperature rise below 1.5ºC. Industries are steadily shifting their stance on carbon emissions as they move toward net zero goals and implement mitigation methods to capture carbon at the source of emission. However, further efforts must be taken to address the high levels of atmospheric carbon.[iii]

The use of removals today will directly offset hard-to-abate residual emissions and reductions in atmospheric carbon in the near term. While still relatively modest today, supply is anticipated to increase as demand rises for CDRs. Removals are sourced according to two distinct classifications: nature-based and technical. Nature-based removals methods are an important component to the reduction of atmospheric CO_2, but given the challenges, we believe that the total amount that needs to be removed cannot be done by nature-based solutions alone.[1] This study will therefore focus on technical removal processes which capture carbon dioxide from the atmosphere in a mechanical fashion. In particular, the study will explore four discrete technologies: Biomass Carbon Removal and Storage (BiCRS), Direct Air Capture and Carbon Sequestration (DACCS), Biochar, and Enhanced Weathering. Mineralization applications were considered for inclusion, but the current state of technology is too underdeveloped for any carbon capture to be considered additional. At present, mineralization serves as a viable storage technology which is still developing atmospheric CO_2 removal capacity.

Carbon capture and sequestration from negative emission technologies (NETs) are currently traded in voluntary markets. Prices vary significantly in these markets, with prices for removals typically reflecting the quality of the corresponding CDR. This report will use the following nine considerations in determining CDR quality.[iii]

1. ***Durability*** – Average duration of carbon stably sequestered
2. ***Additionality*** – Measures if the VCM investment really enables additional carbon removals
3. ***Innovation*** – Novelty and efficiency of the technology used in capturing and sequestering carbon
4. ***Risk*** – Drawbacks associated with capture and sequestration methodology
5. ***Social Co-benefits*** – Consequential benefits to employment, education, and social welfare
6. ***Environmental Co-benefits*** – Consequential benefits to surrounding environment such as improved soil or water quality
7. ***Connection to Business*** – Consequential co-benefits in business
8. ***Location*** – Mobility and ability to affect climate in local communities
9. ***Price*** – Price of a CDR

Long-term demand for technical removal facilities will depend on the progression of policy and industrial adoption of abatement technologies. The scientific justification for promoting removal technologies, while apparent, is not enough for swift adoption alone. There are feasibility and capacity constraints strongly related to the price of the captured carbon and the development of demand in the market. Additionally, political pressure stemming from the Paris Climate Accord is driving countries to establish regulations around emissions abatement and net negative technologies. As these policies become more prevalent, the value of carbon may exceed the energy value of the inputs used in capture.[iv]

While the policy is a significant driver of demand in the carbon market, there is also significant voluntary market appetite. Thus, the global carbon market is bifurcated and will be treated as such throughout the course of this report. While actors within the compliance market will purchase carbon credits to offset their unavoidable production of greenhouse gas emissions (GHG) to avoid regulatory penalties, the voluntary carbon market consists of consumers that wish to hedge compliance, drive further development in NETs, build conscientious environmental policies, and of course, improve the environment.[v] However, we anticipate that it will be policy that significantly drives demand moving forward, and that supply of technical CDRs will scale quickly once these demand signals become more apparent.

[1] Nature-based removals are achieved through utilizing natural processes and include afforestation, soil sequestration, and mineralization. These methods are higher risk and provide lower durability because of their vulnerability to natural phenomena. For example, the trees planted and credited for afforestation carbon removals are susceptible to forest fires, which would release the captured CO_2 back into the atmosphere prematurely.

TECHNICAL CDR OVERVIEW

BIOMASS CARBON REMOVAL AND STORAGE (BiCRS)

BiCRS is a relatively new term introduced by the ICEF in 2020 and refers to all technologies that use biomass to remove CO_2 from the atmosphere and sequester it for long periods of time. BECCS (bioenergy carbon capture and storage) is included under the umbrella of BiCRS and is a more specific categorization of removal in which biomass is burned to generate energy and the CO_2 is captured. BiCRS technology has been around for 20 years and there are several operational facilities today. BiCRS has enormous potential in removal efforts and can command high prices because of its durability.

BIOCHAR

Biochar is a form of charcoal created through pyrolysis using elevated temperatures (300-600ºC) and biomass inputs such as wood, sawdust, crop residues, or manure – without the presence of oxygen. The biomass used in the production of biochar naturally captures CO_2 throughout its lifetime. When biomass is normally discarded and left to decay, it releases the carbon it captured over its lifetime back into the atmosphere. By collecting this biomass instead and placing it into a kiln to go through pyrolysis, the carbon is concentrated and secured within the charcoal-like compound where it will remain stable and can be sequestered in soil. There are many biochar facilities operating, but most are still small-scale. Biochar is an attractive technology when looking toward the future since it offers 1,000-year durability when generated at high temperatures, but there are still questions around the feasibility of such large-scale production.

DIRECT AIR CARBON CAPTURE AND SEQUESTRATION (DACCS)

DACCS is a process that utilizes technology to remove carbon dioxide directly from the atmosphere. DACCS' technological readiness, high additionality, the durability of 1,000 years, fast scalability, and low social and environmental risks make it an attractive investment opportunity. However, its vast energy requirements, infrastructure needs, small co-benefits, and low maturity raise concerns for the future. [vi] There are currently two DACCS facilities in operation and more in the planning phases.

ENHANCED WEATHERING

Enhanced weathering is a theoretical proposal to remove CO_2 by spreading large quantities of finely ground rock material onto extensive land or water areas to accelerate the natural weathering process. On land, enhanced weathering is usually proposed for agricultural fields as it has the ability to increase soil fertility. In marine environments, it's known as ocean alkalinity. Adding ground minerals directly to the ocean or dumping them in beaches increases CO_2 uptake. While no projects exist yet at scale, research and trials are being conducted through several projects.[vii]

MINERALIZATION APPROACHES

Different approaches at mineralization were considered for inclusion in the study scope, but the current state of technology appears too underdeveloped for any carbon capture to be considered additional. At present, mineralization approaches are viable storage technologies. Technologies that capture atmospheric CO_2 would become more prevalent in the future.

DEMAND

OVERVIEW OF COMPLIANCE MARKETS

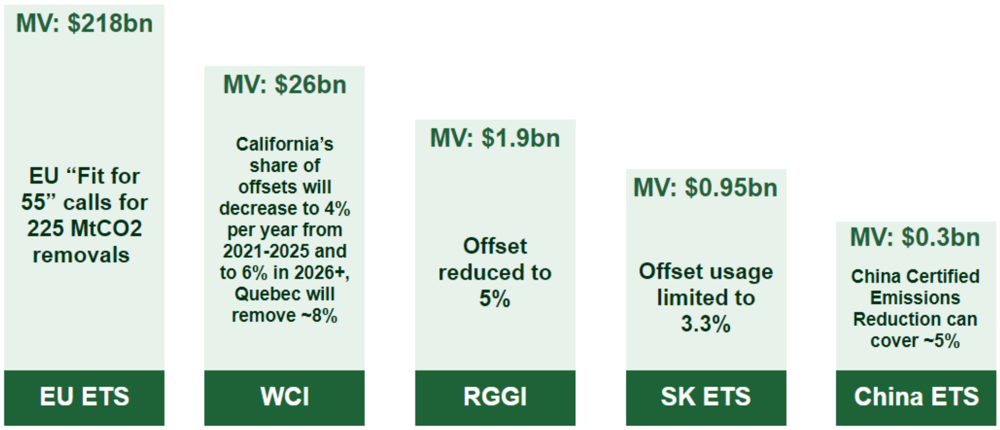

Figure 1: The top five compliance markets and the allowance of removals.

Compliance Carbon Markets (CCMs) operate either as cap-and-trade programs with requirements established by Emissions Trading System (ETS) that are in turn regulated by government entities and laws or as baseline and credit programs. Governments usually impose a regulatory cap on emissions by granting a limited allowance of emissions per sector or company. Allowances for excess emissions need to be purchased on the market and unused allowances can be sold. The motivation for CCMs comes from regulation; prices have historically been driven by government intervention and response to economic crises. According to Refinitiv, the total market size in 2020 for CCMs was $261bn with 10.3 $GtCO_2$ being traded.[viii] Global emissions covered by an ETS in force nearly doubled in 2021, rising from 9% to 16%, as the number of systems grew from 21 to 24.[ix] There are currently 24 ETSs globally, with eight more scheduled to begin operations and another 14 under consideration. Notably, China launched its first ETS in 2021, and now one-third of the global population lives under an ETS jurisdiction.[x] China has the largest ETS with a market volume of ~7800Mt of CO_2, followed by the EU ETS which has a market volume of ~1500Mt of CO_2.

We conclude that CDRs could capture up to up to 600 $MtCO_2$ per year of demand by 2030 based on the following assumptions:

- The U.S. commits to 300-500 $MtCO_2$ removals per year by 2050 using technical CDRs assuming only 10% of total removals will be achieved by 2030.
- The EU 'Fit for 55' generates 225 Mt CO_2 in removal demand by 2030.

Regions	Carbon Removals Allowance	Technical CDR Potential (Mt) by 2030
EU ETS	225 Mt	225
U.S.	30-50 Mt	30-50
SK	3.30%	19.14
China	4.0%	312
Total		**606.14**

N.B. Technical CDR demand assumes the upper bound of allowance in each ETS

The number of jurisdictions enforcing carbon pricing, and subsequently, the volume of emissions covered continues to increase year over year. Though carbon pricing is becoming widespread, various studies have shown that carbon prices will need to rise to $50-$100/tCO_2 over the next decade to stimulate the emissions reductions from mitigation required to meet the Paris Agreement's goal of limiting global warming to well below 2°C. At present, only 3.76% of global emissions are subject to a carbon price above $40/$tCO_2$, which is still below the recommended price levels.[xi] A significant rise in carbon prices will be required over the next decade to ensure governments reach their commitments to achieve net-zero emissions and limit global warming in accordance with the Paris Agreement.

OVERVIEW OF VOLUNTARY MARKETS

Voluntary carbon markets (VCMs) allow carbon emitters to offset their unavoidable emissions by purchasing carbon credits produced by projects targeted at removing or reducing CO_2 from the atmosphere. Carbon trading in the VCM began in 1989 through deforestation avoidance. While VCMs have had a bumpy ride in the past 33 years, the carbon market has grown to a little under $1bn today. The future looks even brighter with 1,535 companies across the globe committing to Net Zero targets.[xii]

There are several motivating factors for consumers to purchase removals. When buying removals, consumers are likely to consider the multitude of effects of their purchase. Each of the technologies mentioned in this report is removing carbon from the atmosphere, but through different methods and with varying results. Consumers are aware of this differentiation and are often discerning when choosing between different technologies.

Corporations voluntarily purchase removals primarily out of a sense of responsibility or interest in bolstering their reputation. Removals consumers are considerate of the duration of the storage corresponding to their purchase and the risks involved with that removal process. These two traits are the most influential in the effects of purchasing removals on a company's reputation. The company is most likely concerned with having to face the recourse for using a flawed technology. Durability is also influential to the consumer because it ensures that the carbon is legitimately sequestered and there is no greenwashing. Finally, the environment co-benefits and connection to business allow the consumer to craft a compelling narrative for investing in projects generating removals.

Each of the technological approaches mentioned in this report has a different macro demand-pull towards public acceptance. This macro demand pull is caused by varying adoption and investment to support these technologies.

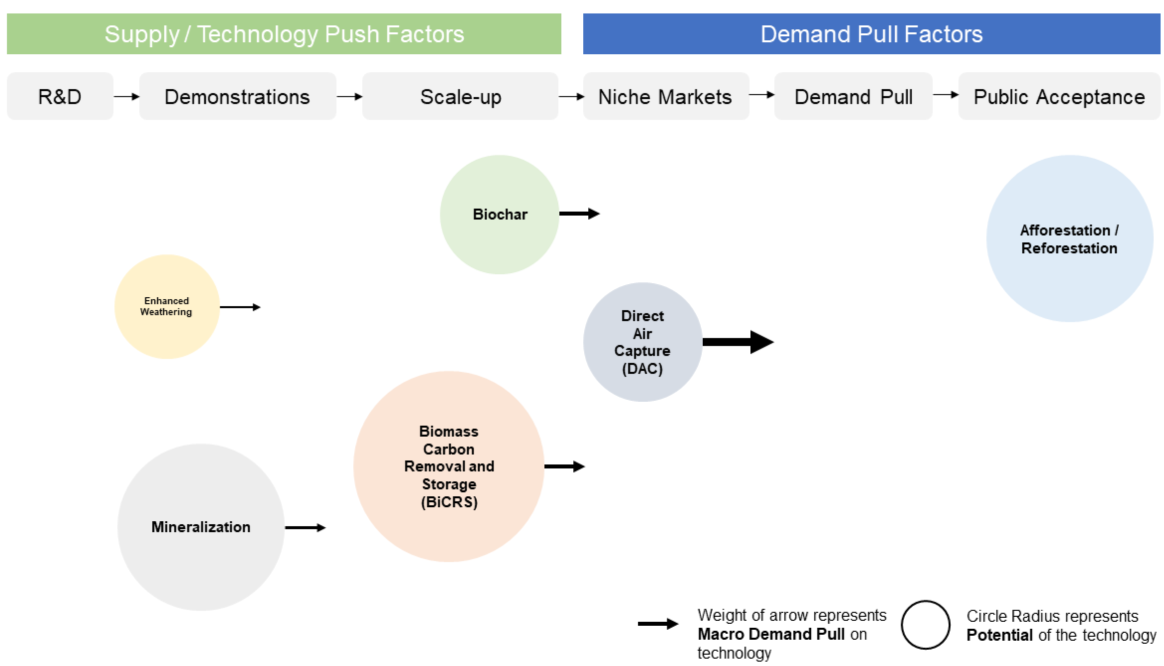

Figure 2: Current demand and potential for technical CDRs

PROJECTIONS FOR DEMAND IN 2030

While there is no comprehensive research that estimates the demand for technical CDRs at any future time, there are estimates of the size of the voluntary carbon market in 2030, 2050 and beyond. Demand for technical CDRs will depend on the 'project-related' factors mentioned in the 'Introduction' above – nine considerations in determining CDR quality.

UPPER BOUND OF VOLUME

To predict market demand for technical CDRs, we estimated both the lower and upper bounds of technical removal quantities. The upper bound was calculated based on the global residual emissions removal needed to achieve the 1.5°C reduction. A commonly referenced estimate is a global reduction of 5-7 $GtCO_2$ by 2050 and 1-2 $GtCO_2$ by 2030.[2] [xiii] This 1-2 $GtCO_2$ includes non-technical removals, such as Nature-Based Sequestration (NBS), afforestation, and CCS. In our model, we assume that the quantity of removals will reach 1 $GtCO_2$ by 2030.

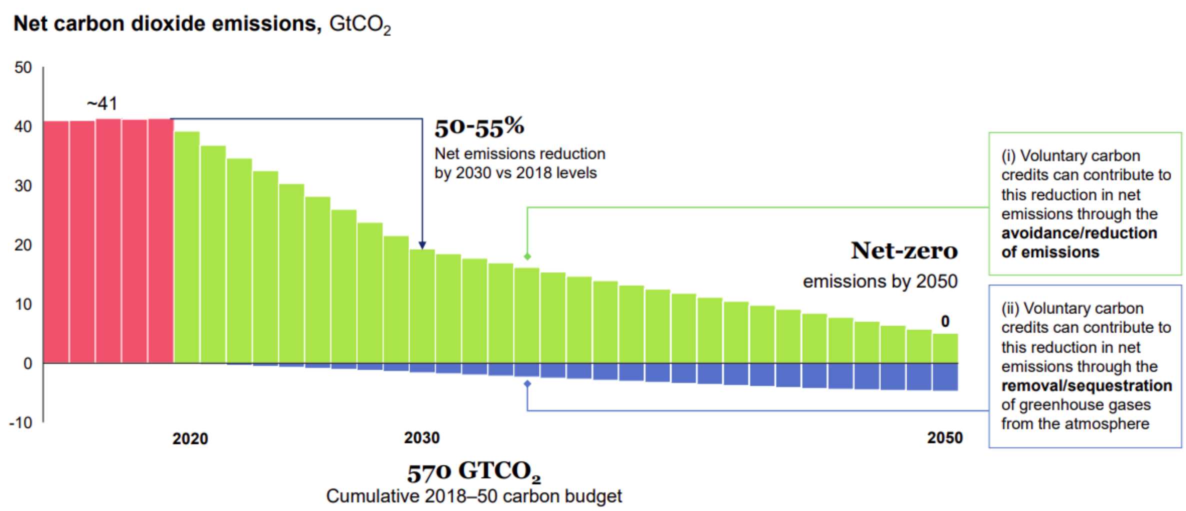

Figure 3 : McKinsey 1.5ºC Scenario Analysis; IPCC; Le Quéré et al. 2018

As we are only interested technical CDRs, we relied on the following assumptions for nature-based removals. REDD+ and NBS, had capacity of ~35 $MtCO_2$ in 2020, and are expected to grow at 20% per annum in order to remove 216 $MtCO_2$ by 2030. CCS had a removal capacity of 40 $MtCO_2$ in 2020 and is expected to grow at 15% per annum to 161 $MtCO_2$ in 2030. These are justified assumptions because technical CDRs cannot replace CCS, especially in oil and cement industries. We estimated the upper bound of technical CDRs to be 623 $MtCO_2$.

We acknowledge that this bound can only be realized if the price and desirability of technical CDRs can be developed to the point that makes them attractive than other removal options. However, we believe this can be made possible through large-scale integration of technical CDRs into compliance markets. With this demand signal, government budgets and philanthropic capital would be required to subsidize such technological approaches until they can be proven at scale.

[2] Trove Research contested this assumption for voluntary markets with a range between 0.5-1.5 $GtCO_2$.

LOWER BOUND OF VOLUME

The lower bound was calculated from net-zero targets of countries across the globe, known as the Nationally Determined Contributions.[xiv]

We filtered countries based on their pursuit of the following end targets: 1.5°C targets, carbon negative, carbon neutral(ity), climate neutral, climate positive, net-zero and zero-carbon.[3] This resulted in a sample set of 120 countries. The current total net CO_2 emissions from the sample set is 37.6 $GtCO_2$ per annum. On average, countries have an interim target of abating[4] 38.8% of these emissions by 2030, which translates to 14.6 $GtCO_2$ per annum. Based on the 1.5°C pathway data, approximately 5-10% of the total abatement should come from negative carbon emissions (NET) in 2030. Therefore, 0.73-1.46 $GtCO_2$ is a reasonable estimate for the total volume of NETs by 2030, given technical removals constitute 0.05% of the total NETs.

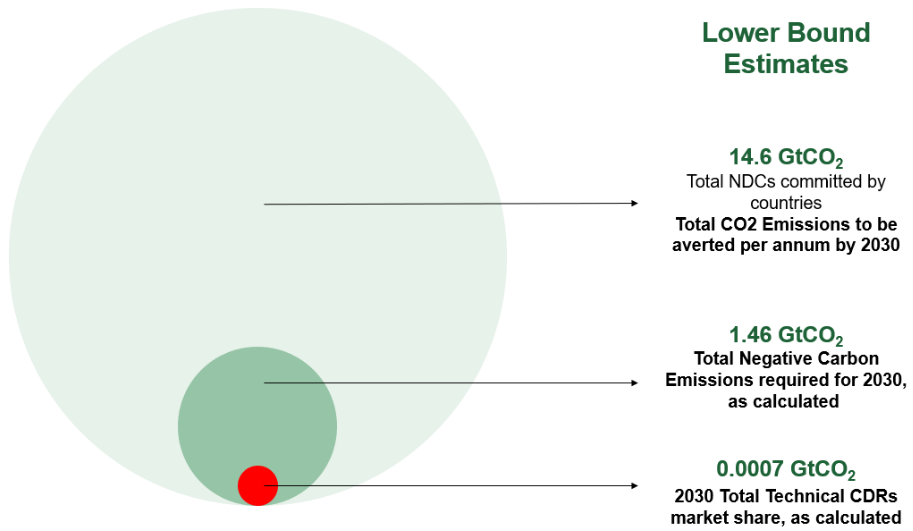

Figure 4: Lower bound estimation

We found the initial lower bound to be 730 $ktCO_2$ per annum (in the range of 0.05-1% of total CCS). An additional 30 $MtCO_2$ was then added to that figure based on US' commitment to removals (mentioned in CCM Overview above). Thus, our final lower bound prediction is 30.7 $MtCO_2$.[5] Assuming an average price of \$300/t[6], the voluntary market demand will be ~342 $ktCO_2$ per annum by 2030.

As shown in Figure 5, the demand for technical CDRs will fall between the predicted upper and lower bounds. It will vary by price, supplier, and other project-related factors as mentioned earlier in this report.

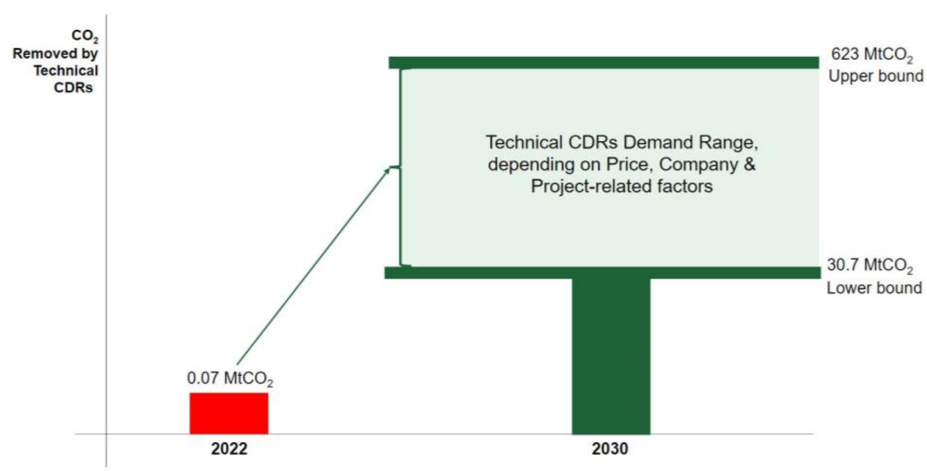

Figure 5: Upper and lower bound estimates for the technical CDR demand in 2030

[3] The following end targets were specified:1.5C target, absolute emissions target, carbon negative, carbon neutral, climate neutral, climate positive, emissions intensity target, emissions reduction target, GHG Neutrality, net zero, science -based target, zero carbon, zero emissions.
[4] Here, 'abating' refers to both emission reduction and negative emissions (including removals).
[5] This number is validated by the predictions in Frontier's latest announcement of an advanced market commitment of \$925mm from 2022 to 2030.
[6] Stripe hasn't publicly promised the average price of CO_2 or the number of tonnes. \$300/t is an aggressive assumption based on internal analysis

DEMAND CURVE PREDICTION

Having estimated the upper and lower bound volumes in the demand curve, we next predicted the prices at each of the two bounds. To estimate the lower bound price, we assumed that there will be no new technological investments that would meaningfully depress price. However, we also assumed that pre-existing commitments in both the compliance and voluntary markets will be fulfilled. In such a scenario, we predicted minimal or no change from today's technical CDR prices. Another major assumption was that the compliance market will make up the bulk of technical CDR purchases and influence the upper bound prediction. Demand will be driven primarily by price in both the voluntary and compliance carbon markets.

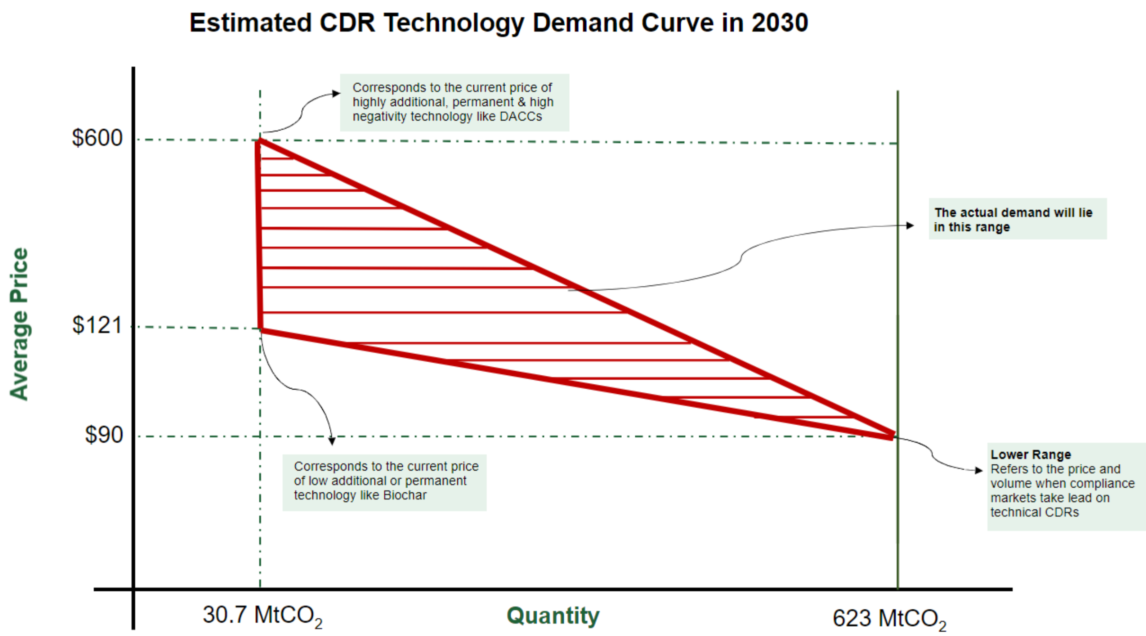

Figure 6: Estimated demand curve for technical CDRs in 2030[7]

SUPPLY

The current technical removals industry is still young and there are many uncertainties around the direction of its growth. Our first step in predicting the 2030 supply curve was understanding the state of the industry at present. We evaluated the current capacity and pricing of each of the five technologies through an in-depth literature review and developed our modeling methodology based on our findings. While the numbers we found in our literature reviews were impressive and exciting, technical CDR commitments have historically been optimistic. With that in mind, we chose a more conservative approach to better reflect the limitations on commercial viability and widespread adoption of these technologies over the coming years.

To predict the supply curve, we built two scenarios for estimating marginal abatement cost (MAC) curves for 2030. Below are the assumptions that we made in our estimate:

> **General Assumption** - Supply capacities and corresponding prices as stated and projected by companies and other institutions are likely to be optimistic. To date, the realization of removal facilities has fallen short of initial commitments and projections. This trend of over-committing is likely to carry through into 2030. The precedent for this assumption can be seen in the continual struggles that companies face in overcoming the significant hurdles that accompany the implementation of such novel technologies at scale.[xv]

[7] EU-ETS estimates a price of ~$90 by 2030.

Mineralization	
Details	Mineralization projects primarily provide a means of utilization and storage. They do not function as a distinct removal technology in any significant capacity. Enhanced Weathering projects, while sometimes cited as mineralization technology, are instead categorized here under Enhanced Weatherization. Additionally, there are mineralization projects that focus on carbon utilization, and these projects must be discounted as a carbon removal additive. Operational mineralization projects that function as carbon removal technology will likely advent post-2030.
Biochar	
Capacity	There is currently 0.3198 $MtCO_2$/yr captured through certifiable biochar.[xvi] This is based on the current European estimates of 0.135 $MtCO_2$/year[xvii] and North American estimates of 0.1848 $MtCO_2$/year.[xviii, xix, xx] Biochar supply figures assume a 1:3 biochar to carbon ratio and 4 cubic yards of biochar as equivalent to 1 tCO_2.[xxi] Biochar production capacity is assumed to grow at a 75% CAGR as the market for high-quality, certified biochar grows.
Price	The ranges in empirical literature likely contain lower quality, uncertified biochar that skews the price. Therefore, we assume that the prices of high-quality certifiable biochar today are the upper bound of most empirical literature at ~$120/$tCO_2$.[xxii] Due to advances in kiln technology and increased biomass feedstock availability, we expect these prices in 2030 to decrease to ~$85t/$CO_2$, the approximate mean of the empirical price range. In the optimistic case, we assume that advances in technology have reduced the cost to produce to $65t/$CO_2$.
Enhanced Weathering	
Capacity	Research has projected 150 $MtCO_2$ capacity for Enhanced Weathering. Based on the low number and small scale of current Enhanced Weathering projects, we assume that only 1/5 of that projection will be available by 2030 in the base case and 1/3 of the projected capacity will be available in the optimal case.[xxiii]
Price	We assume that today's prices for enhanced weathering are at the upper bound of empirical estimates, ($50-$200). We assume that advances in technology allow the price to be reduced to ~$150 by 2030. In the optimistic case, the technology advances faster than anticipated and prices drop to the lower middle quartile of the empirical range.
BiCRS	
Capacity	Today BiCRS production facilities remove 2.5 MtCO2/year.[xxiv] Planned facilities will provide an additional 25 MtCO2/year of capacity by 2025, bringing the global total to 27 MtCO2/year.[xxv] BiCRS may attract significant investment throughout this decade as it offers a ready method of deep carbon sequestration which may support a significant CAGR. We can use the current and 2025 estimates to assume a ~58% CAGR from 2025 to 2030 and suggest that BiCRS could be capable of producing 250 MtCO2/yr. by 2030. This is an optimistic assumption, however, and it is likely BiCRS technology will either lack the available biomass or appropriate funding to grow at such a rate. So, in the base case, we will instead use a slower rate of ~35% post-2025, which results in 100 MtCO2/year.
Price	We assume a rough median value of ~$175 from an empirical price range based on the model given on Page 13 of ($88 - $288).[xxvi] The optimistic case assumes that increased availability of biomass would drive prices down slightly to ~$150.
DACCS	
Capacity	Currently DACCS facilities capture 0.117 $MtCO_2e$/yr. We know that additional capacity of 1 $MtCO_2e$/yr., 0.0075 $MtCO_2e$/yr., and 1 $MtCO_2e$/yr., will become operational in 2024, 2025, and 2026 respectively. This established a global DACCS capacity of 2.12450 $MtCO_2$/yr. in 2026.[xxvii, xxviii] DACCS is likely to be the focal point of major carbon removals investing throughout this decade and into 2030. Upcoming designs have been proposed by DACCS industry leaders alongside commitments to 500 $MtCO_2$/yr. by 2040. This gave us some trends for future industry growth. Looking back to our general assumption about supply it is reasonable to assume that a proposal of this sort may encounter significant hurdles in meeting this commitment, and resultantly produce on a more limited scale of 250 $MtCO_2$/yr.by 2040. We used this industry data to estimate an industry CAGR of 120% through 2030, slowing to a 60% CAGR from 2030 to 2040 when it reached 250 $MtCO_2$/yr. Using industry leaders for a benchmark, we can apply this 120% CAGR to the projected 2026 supply of 2.12450 $MtCO_2$/yr. and reasonably assume that there will be 50 $MtCO_2e$/yr. available in 2030. The optimistic assumption for DACCS capacity assumes that the industry grows 20-30% faster than our industry benchmark and results in a global capacity of 100 $MtCO_2$/yr.
Price	The 2030 DACCS price of $250 is another interpolation of a published range ($100-$300).[xxix, xxx] We assume that today's price is the upper bound and that increases in technology and availability drive from the peak into the upper quartile. The optimistic case assumes that the technology advances at an increased rate to a price of $175.

MARGINAL ABATEMENT COST CURVES

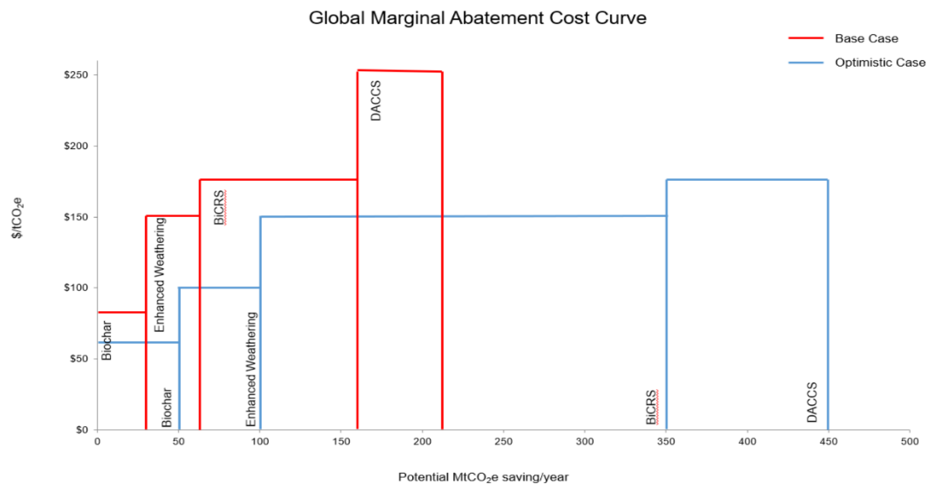

Figure 7: Projected base case and optimistic case MAC curves for 2030

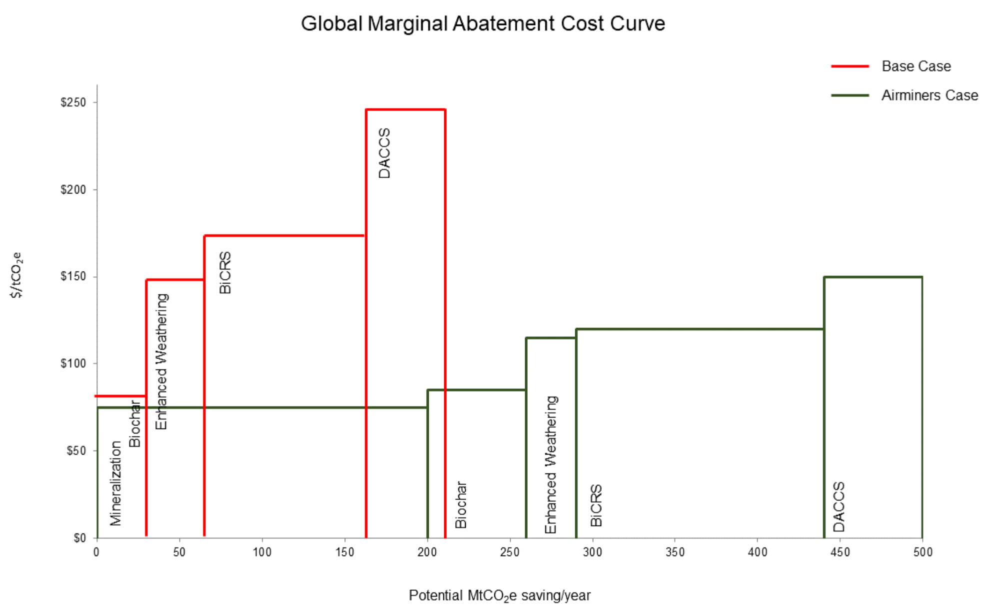

Figure 8: Our base case MAC curve compared to AirMiners' MAC curve constructed from Stripe's proposal data[8]

In our base case, the total supply of technical CDRs is predicted to be ~210 $MtCO_2$/yr by 2030 (58% less than projected in a comparable analysis by AirMiners),[9] while in our optimistic case, we would expect a capacity of ~450 $MtCO_2$/yr would be achieved (10% less than projected in a comparable analysis by AirMiners). At base case capacity, the average price for technical CDRs should be ~$165/tonne to meet demand, - about 50% higher than the ~$110/tonne predicted in both the optimistic case and AirMiners' model.[xxxi] It is important to note that the numbers above do not account for buyer preferences around technical CDRs.

[8] Note: Mineralization projects do not yet function as a distinct removal technology in any significant capacity. There are operational mineralization projects, but they focus on carbon utilization, and these projects must be discounted as a removal additive. Operational mineralization projects that function as removals will likely advent post-2030.

[9] 500$MtCO_2$ is the capacity from AirMiners' prediction adjusted for omission of mineralization.

Factors that drive the purchase of technical CDRs in the VCM include price, additionality, permanence, social and environmental benefits, and risk, amongst others.[xxxii] To account for these preferences, we rated each of these factors on a 1-5 scale across the four technologies. Then, we multiplied the scores with a weighted significance corresponding to each factor.[xxxiii] The 'Total' row below is the resulting estimate of the preference for the technology by buyers in the voluntary carbon markets. Based on our analysis, DACCS, BiCRS, and Biochar will drive demand in the technical CDR market moving forward. BiCRS and Biochar are dependent on the availability of high-quality biomass, therefore out of these three technologies, DACCS has the highest potential for widespread adoption.

	DACCS	BiCRS	Biochar	E. Weathering	Weight
Durability	5.00	5.00	4.00	4.00	16%
Additionality	5.00	4.00	4.00	5.00	11%
Innovation	5.00	3.00	2.00	4.00	7%
Risk	4.00	4.00	4.00	2.00	14%
Social	3.00	3.00	5.00	3.00	9%
Environmental	3.00	4.00	5.00	3.00	11%
Location	2.00	3.00	5.00	4.00	11%
Connection	4.00	3.00	4.00	3.00	9%
Price	2.00	4.00	3.00	2.00	11%
Total	3.68	3.80	4.05	3.30	100%

Table 1: Estimating technology prioritization for buys in voluntary carbon markets[10]

[10] These are performance metrics where a score of 5 is preferred i.e., low price, high additionality, and high durability.

EMPIRICAL MODELING OF PROJECT-RELATED FACTORS

To determine the relationship amongst a few of these factors that drive purchases, we performed empirical analysis on the 219 projects split across those purchased by Stripe and proposals received by Microsoft RFP.[xxxiv]

We performed linear regression on 55 projects that had data across parameters of negativity, price, additionality, and permanence. The description and estimation of each of these parameters are as below:[xxxv]

1. **Negativity**: Negativity reflects the emissions intensity of different carbon removal solutions, and we define it as 1 minus the ratio of gross project emissions to gross climate benefits, including carbon removal and storage. Calculating negativity depends on a life cycle assessment that quantifies project emissions and climate benefits. If emissions are low relative to the climate benefits, this metric will approach 1.

2. **Price**: These are per tonne CO_2 prices are taken directly from public project offerings.

3. **Additionality**: Additionality refers to the causal relationship between the funds a climate project seeks, and the climate benefits it claims. The categorical variable of additionality is valued using the metric given in Appendix.

4. **Permanence**: Permanence of the project is the duration over which carbon storage can be reasonably assured, in years.

Regression results:

$$\log(price)=0.46144+0.02515\times negativity+0.44737\times \log(permanence)+0.31766\times add\_mild+0.83457\times add\_high+\epsilon$$

Variable	Estimate	Pr(>|t|)
Intercept	0.46144	0.35806
Negativity	0.02515	0.95311
Log (permanence)	0.44737	0.00514**
Add_mild	0.31766	0.32007
Add_high	0.83457	0.02066*
R^2	0.4824	
p-value	$9.22e^{-07}$	
Residual std error	0.5755	

ϵ represents all other factors such as (i) technology's connection to the business, (ii) technology's innovativeness, (iii) location, (iv) social co-benefits, (v) risks associated with technology, (vi) reputation/publicity, and (vii) company factors

CONCLUSIONS

1. The demand for technical CDRs is projected to lie between 30.7 $MtCO_2$ to 623 $MtCO_2$ per year, resulting in total market size of \$3.6 billion - \$56 billion by 2030.
2. Compliance carbon markets may contribute ~600 $MtCO_2$ to technical CDR demand. The extent of demand depends on the acceptance of technical CDRs by compliance markets across the globe, and the fulfillment of net-zero targets by countries.
3. Given the purchases this year, we estimate that the total transaction volume needs to increase by ~200% YoY to reach the upper limit of 623 $MtCO_2$ by 2030
4. The supply of technical CDRs is projected to lie between 210 $MtCO_2$ to 450 $MtCO_2$ per year by 2030, resulting in a shortfall of supply in an upper bound demand scenario of 623 $MtCO_2$.
5. Other research studies may have overestimated supply, resulting in projected prices for CDRs being underestimated.
6. Demand and supply in 2030 would clear at 50 $MtCO_2$ to 180 $MtCO_2$ with an average price ranging between \$180-\$220 per tonne of CO_2.
7. DACCS, BiCRS, and Biochar should drive the demand in the technical CDR market until 2030, with DACCS CDRs having the highest potential for generating demand.
8. The current price in the technical CDR market depends significantly more on factors such as *permanence (durability)* and *additionality* than traditional VCM factors such as *negative effects on the environment*. We believe such a trend will continue for the next decade in the CDR market.
9. At an average price of \$90-\$100 per tonne for highly additional and permanent technology, corporations would be indifferent between nature-based or technical CDRs. The adoption of CDRs by compliance markets will accelerate the innovation and development in the technical CDR market and would be a significant catalyst in achieving this price drop.

MONITORING, REPORTING, AND VERIFICATION

The future market for removals will need to define by two primary drivers: production capacity and certification. Production capacity will need to expand on an exponential scale to meet the growing demand, and the capacity satisfying demand will need to be certifiable through consolidated regulating bodies. Certification will be key in supporting the growth of the market for two reasons. First, MRV ensures that the quantity and quality of the carbon being removed are accurate and can be measured against standardized benchmarks, which must be a requirement for regulated schemes. Second, it ensures that the additionality of a removal justifies the payment for that activity, providing the market signal and incentive to generate negative emissions.

Currently, there are no globally recognized regulatory bodies that monitor the removals market. For any efforts in the removals space to grow and corporations to feel more comfortable making greater purchases of carbon removals, there needs to be stronger monitoring, reporting, and verification (MRV).[xxxvi] In recent reporting, a survey across all stakeholders in the carbon removals market found that 76% of respondents, buyers, and suppliers desired more guidance and increased protocols surrounding technical removals. The same survey also shows that out of the respondents with technical removal inventories, only 3% accounted for the GHG removed through the technologies mentioned in this report – due to a lack of guidance and data, not a lack of demand.[xxxvii]

Based on our analysis, most of the technical removal credits are sold through private players including Puro, Patch, Climacrux, and Carbonfuture. The major challenge with the carbon credits industry – which seems to persist in the case of removals too – is that there is double claiming of the same mitigation outcome towards both the private sector's carbon neutrality outcome and the host country's NDC. This illustrates the need to have a standardized framework, supported by a regulatory agency for removals, to scale in voluntary markets as they ensure that the carbon removed remains additional.

Independent certifying institutions are currently making standardization attempts. Organizations such as Verra, the Gold Standard Foundation, and Plan Vivo all issue carbon credits based on removal approaches supported by their proprietary verification systems. The issued credits, while certified, offer the purchaser varying degrees of certainty across different measured attributes. These institutions offer certified credits, but the attributes of the actual credits may vary significantly without any unified regulatory oversight.[xxxviii]

In addition to independent standard-setting organizations, voluntary market platforms such as Puro.earth, Nori, and MoorFutures offer carbon credits with varying approaches to categorizing their product offerings. Puro.earth offers credits primarily generated by biochar and carbonated building materials, Nori offers credits from agricultural sources, and MoorFutures focuses on nature-based solutions. These voluntary marketplaces offer a variety of products with assorted certification claims.

This patchwork approach to certification may result in a lack of confidence and uncertainty that could stifle investment to support technical removals. Guidance from institutions that are critical to the net-zero agenda such as the Science Based Targets initiative (SBTi) should help the market by providing greater direction on certification needs and requirements that can assist companies looking to invest in the short term to secure the eligible removals they need to meet future obligations.

APPENDIX

1. <u>Metric for Additionality in empirical modeling</u>
   In the empirical modelling of project-related factors, additionality is calculated using the metric below, followed by actual categorical values assumed

Low Additionality	Climate benefits claimed by the project are unlikely to be additional because they are likely to occur independently from the proposed investment. This could be because the proposed activity is already commonplace or required by law. In other words, climate benefits that project claims are logically implied by pre-existing commitments.
Medium Additionality	Climate benefits claimed by the project might be additional, but we cannot validate them with confidence. This is used when the evidence of additionality is mixed, without a clear balance establishing the finding of additionality or non-additionality.
High Additionality	Climate benefits claimed by the project are likely to be additional. This could be because the project proposes an unconventional action, has relatively high costs or has no inherent commercial value outside of its climate benefits.

	Low Additional	Medium Additional	High Additional
Add_mild	0	1	0
Add_high	0	0	1

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