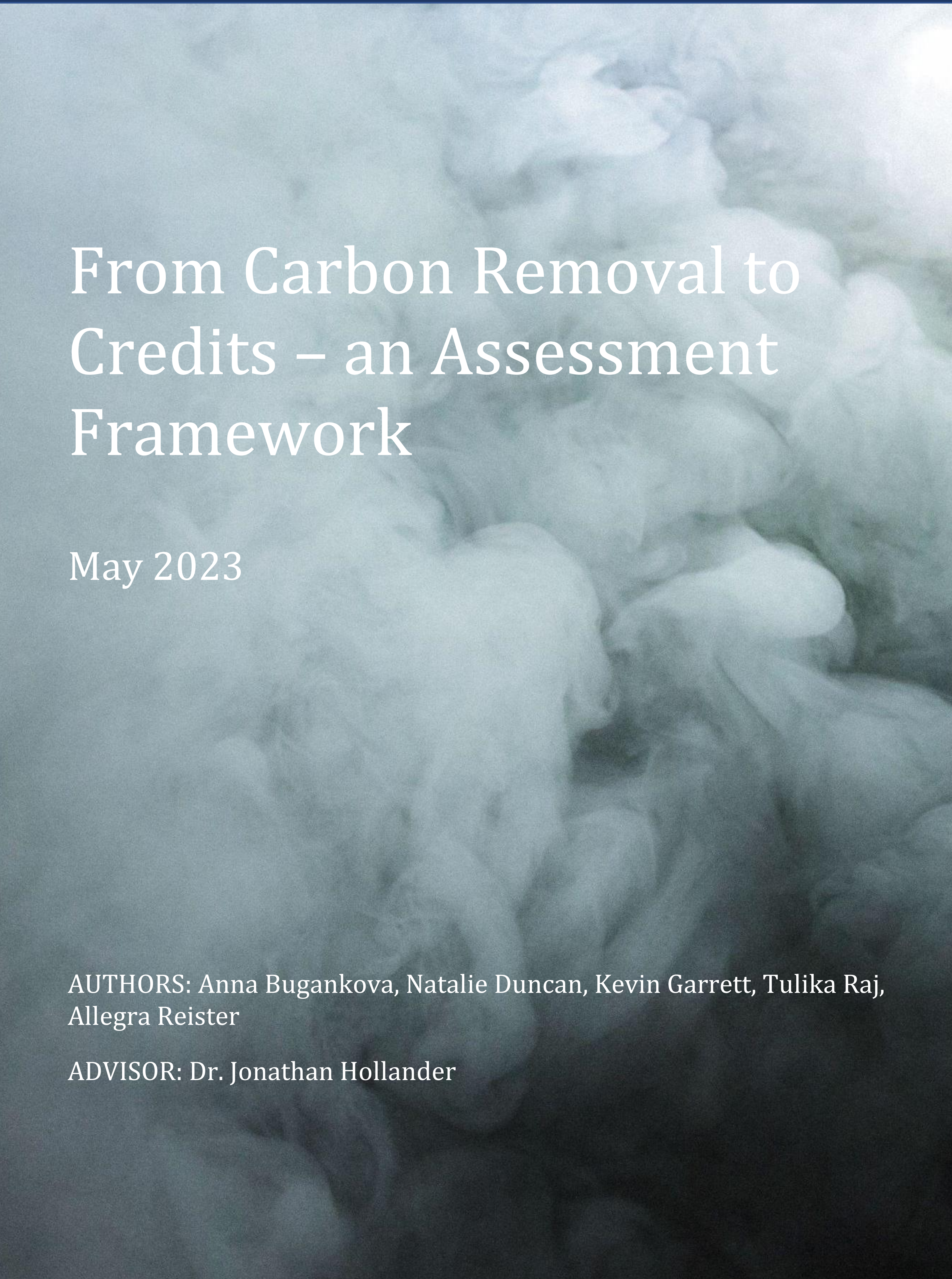

From Carbon Removal to Credits – an Assessment Framework

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EXECUTIVE SUMMARY

To limit global warming and mitigate its effects, it is necessary to enact emissions reduction initiatives and deploy CDR technologies. Currently, the CDR space is nascent but fast growing. There is an information gap related to CDR technology readiness, particularly as it relates to the generation of carbon credits for the voluntary carbon market (VCM), which is a key mechanism for financing. To address this gap, this report proposes a taxonomy of CDR technological pathways and a framework to evaluate different CDR technologies' readiness to generate carbon credits.

The hypothesis is that creating a naming taxonomy that stakeholders agree upon will set the foundation for a common baseline to perform technology evaluation. The assessment framework will use these named CDR technologies as an input and through the evaluation of a set of criteria, users will be able to assess readiness to generate carbon credits and identify barriers to scaling.

In this report, CDR technologies are grouped by how each technology captures and stores carbon dioxide (CO_2). Subsequently, the assessment framework identified 10 different criteria against which each technology should be scored under two buckets of technology risk and credit issuance risk. A case study evaluation of the taxonomical naming structure and the assessment framework reveal minimal friction in the use of the taxonomy and the assessment framework. Limitations to the use of the latter are primarily due to issues with data availability. Future work should focus on further case study evaluations and field testing with CDR project developers.

ACRONYMS & ABBREVIATIONS

AAU - Assigned Amount Unit

ACR - American Carbon Registry

BECC - Bioenergy with Carbon Capture

CCS - Carbon Capture and Storage

CDM - Clean Development Mechanism

CDR - Carbon Dioxide Removal

CER - Certified Emission Reduction

CO2 - Carbon Dioxide

CO2e - Carbon Dioxide Equivalent

DAC - Direct Air Capture

DACS - Direct Air Capture and Storage

ETS - Emission Trading System

ERU - Emissions Reduction Unit

ESG - Environmental, Social, and Governance

EU ETS - European Emission Trading System

GHG(s) - Greenhouse Gas(es)

GS - Gold Standard

IPCC - Intergovernmental Panel on Climate Change

IRA - Inflation Reduction Act

I-REC Standard - International Renewable Energy Credit Standard Foundation

JI - Joint Implementation

LCA - Life Cycle Assessment

MRV - Measuring, Reporting, Verification

TRL - Technology Readiness Level

VCM - Voluntary Carbon Market

VCS - Verified Carbon Standard

DEFINITIONS

Additionality - Emission removal or reduction is considered additional only if it would have not occurred in the absence of a project/activity.

Carbon Credit - A certificate of purchase representing the removal of one ton of carbon dioxide. Credits are bought by purchasers or emitters.

Carbon Market - A space where carbon credits are sold. Brokers can act as go-betweens between buyers and sellers.

Carbon Registry - An organization that issues, tracks, transfers, and retires carbon credits. Registries have a set of approved methodologies that allow project developers to generate carbon credits.

Double Counting - Occurs when the same carbon offset is sold simultaneously on more than one exchange, or when the project is counted in multiple carbon budgets, for example, when both the financier and recipient of a carbon project claim credit for a single project.

Leakage - Net change of emissions outside of the project boundary caused by the implementation of that project that leads to increased emissions in another area.

Methodology - A set of criteria established by carbon registries to quantify a project's emission reductions or removals and issue carbon credits.

Project - A carbon mitigation or removal activity implemented to generate carbon credits through certification with an approved carbon credit methodology.

Project Developer - An organization or individual that develops a carbon mitigation or removal project.

Technology - A technology for CO_2 removal is a specific method that can be reproduced. A project is an application of a technology.

INTRODUCTION

In its Sixth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) states that to keep global warming limited to 1.5°C by the end of the century global greenhouse gas (GHG) emissions must peak between 2020 and 2025, followed by rapid emissions reductions from 2030 to 2050 to reach net zero in 2050. The report also notes that "deploying [carbon dioxide removal] CDR methods to counterbalance residual GHG emissions," especially from the energy and industrial sectors, will be an essential part of the transition (IPCC, 2022).

While CDR technology has an important role to play in decarbonizing our socioeconomic systems, it is relatively nascent. There are several open questions about how this technology can be commercialized and scaled to reach carbon reduction goals established by the IPCC. This project aims to address some informational gaps that can help answer this question and ultimately, help this technology scale.

Client Overview

The I-REC Standard is a not-for-profit, which serves as an accreditation body facilitating standardized renewable energy credit schemes across the world. The I-REC Standard primarily operates in the renewable energy sector and is expanding to hydrogen and CDR (I-REC Standard, n.d.). The client is interested in reducing uncertainty for the CDR ecosystem – from technology inventors and project developers to carbon credit buyers.

Problem Statement & Scope

Carbon markets are trading systems where carbon credits are purchased and sold. These markets are infamously opaque. Both the demand and supply sides of the market struggle to discern credit quality and appropriate pricing. This challenge is exacerbated by the number of differing CDR pathways available and the rapid innovation in this sector. Finally, there is significant and rising demand for carbon credits, especially high-quality credits with long-term carbon sequestration.

The client has requested the capstone team to develop a clear framework that can be used to assess emerging CDR technologies' readiness to generate carbon credits, especially in the near future. The client expects this framework to be a useful tool to navigate the complexity of the CDR landscape and help prioritize methodologies development for the most promising technologies. This tool is intended to be open-source and used freely by market participants and the academic community.

While the intention for the scope of the project was to develop a tool that can be used across all CDR technology types, given timing restrictions and capacity limitations, the capstone team has narrowed the scope to terrestrial CDR (i.e., not ocean-based) using technology solutions (i.e., not nature-based solutions).

The key deliverables from the capstone project will be:

- A brief taxonomy of CDR technological pathways; and
- A framework to evaluate different CDR pathways, specifically across their ability to generate carbon credits, including a case study demonstrating how this framework can be used.

Research Methods

The capstone team identified three work streams for the project: 1) Carbon Markets Overview, 2) Taxonomy of Removal Types, and 3) The Assessment Framework.

The initial desk research drew on the extensive literature review from academic institutions, regulatory bodies like the European Commission, industry organizations similar to our clients, and subject-matter experts (e.g., Carbon Direct, BCG). This information was augmented via targeted interviews with personnel from carbon registries, CDR project developers, MRV (measurement, reporting, and verification) specialists, consultancy firms, and academic circles. The team also sought regular feedback from the clients to ensure that our findings aligned with the scope.

First, the team conducted research on carbon credits and offsets, removal vs. reduction credits, voluntary vs. compliance carbon markets, and how a carbon credit is issued as well as developed an understanding of the methodologies used by some of the most popular carbon registries. The primary aim of this workstream was to learn how carbon markets function today and some of the challenges these markets face.

Concurrently, the team started developing a taxonomy of different terrestrial CDR technology pathways. This was perhaps the most complex workstream that involved developing a comprehensive map of the different families of CDR technologies, using the International Energy Agency (IEA, 2022) and registries as the basis for the grouping approach. Each technology was evaluated according to the following steps: 1) how it works, 2) its key differentiators, and 3) its strengths and weaknesses. The main goal for this workstream was to understand both the differences and similarities between CDR technologies and their ability to generate carbon credits, which then informed the development of the assessment framework.

After the first two workstreams were in place, the team started working on the assessment framework. After identifying several criteria that impact the risk associated with CDR technologies, the team established two assessment categories – technology risk and credit-issuance risk. Combined, these categories devised a qualitative scoring system to assess the performance of a given CDR technology against each criterion. These were then tested with expert interviewees and further honed based on guidance from the client. Once the criteria and scoring system were in place, the team developed a case study of a single CDR technology to demonstrate how to use the framework.

The results have been summarized in this paper and in an Excel-based tool, which the client can use for assessment.

PART 1. CARBON MARKETS OVERVIEW

What is a Carbon Credit?

Carbon credits, also referred to as carbon allowances, act as a permit or certificate to emit a certain amount of CO_2 or carbon dioxide equivalent (CO_2e). Activities that emit CO_2e *use* carbon credits and those that remove or prevent it from being emitted *produce* carbon credits. Most importantly, this permit is *tradeable* and standardized (in terms of volume): one carbon credit is equivalent to one tonne of CO_2e.

The History of Carbon Markets

The history of carbon credits can be traced back to the Kyoto Protocol. In 1997, national scale measures to limit and reduce GHG emissions were proposed under the Kyoto Protocol for the first time. Three market-based mechanisms were established to meet these commitments — 1) the Clean Development Mechanism (CDM), 2) Joint Implementation (JI), and 3) International Emissions Trading (IET). These three mechanisms work together to create carbon credits and international carbon markets or compliance markets (NEFCO, 2019).

The CDM allows countries with emissions reduction or limitation commitments to implement emission-reduction projects in developing countries as defined in Article 12 of the Kyoto Protocol (UNFCCC. n.d.). These projects can earn Certified Emission Reductions (CERs), which are tradable credits that can be used towards achieving Kyoto targets. An example of a CDM project is rural electrification using renewable sources of energy.

Similarly, JI is a mechanism that allows countries to achieve emissions-reduction targets flexibly by investing in such projects in other countries as well. By doing this, the investor countries can count the emissions reductions achieved by their international projects as progress towards their own domestic emissions-reduction goals. These investments generate Emissions Reduction Units (ERUs). Moreover, the JI mechanism created two classes of countries — those whose emissions dropped ahead of the agreed-upon pace set by their targets, i.e., those with a surplus of Assigned Amount Units (AAUs) of CO_2e, and those whose emissions reductions lagged the target pace, i.e., those requiring opportunities to invest in JI initiatives (NEFCO, 2019).

Finally, the IET created a formal market mechanism, which allowed for the trading of different types of carbon instruments, notably CERs, ERUs, and AAUs, for countries to meet their emissions reduction targets. This was the beginning of a formal carbon market.

How is a Carbon Credit Created?

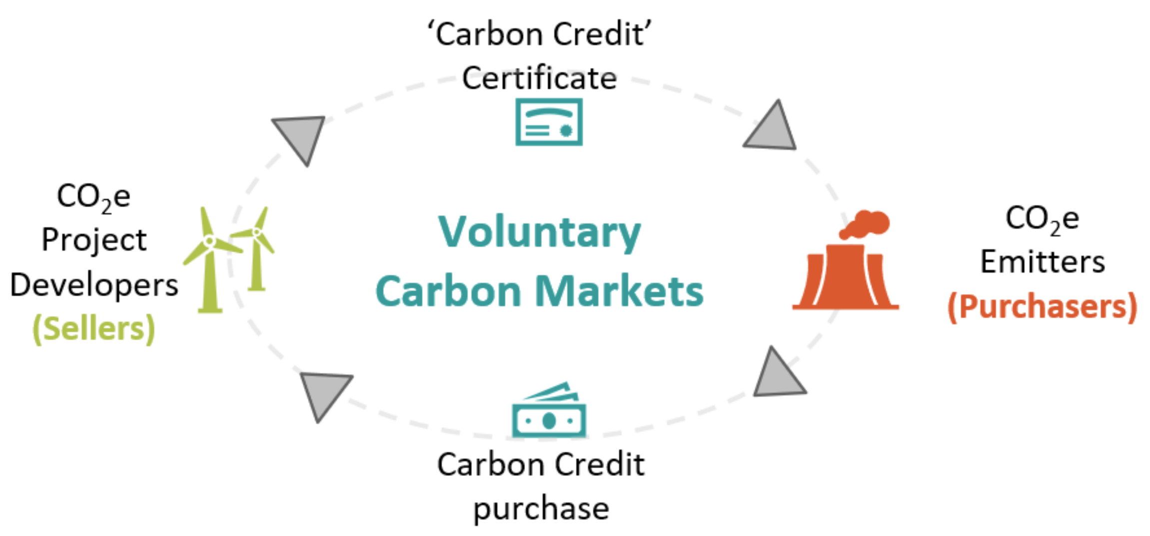
There are two different approaches to creating carbon credits. The first builds on the approach proposed by the Kyoto Protocol, where carbon credits are created by government or regulatory bodies (e.g., the European Commission). A given annual allowance of CO_2e (and thus, carbon credits) is allocated to regulated emitters participating in the compliance carbon markets free of charge each year. Similar to the JI mechanism, some emitters have an excess supply of credits each year (since their CO_2e emissions are lower than the regulator-allocated maximum, i.e., their "cap"), and others that have an excess demand for credits (since their CO_2e emissions are higher than their cap).

Because the underlying credit is a tradable instrument, emitters can buy and sell these to satisfy their annual requirements. This is the logic behind the "cap and trade" approach of the compliance markets, where carbon credits are the traded instrument.

The second approach varies significantly. Before discussing this, it is worth clarifying that the terms 'carbon credits' and 'carbon offsets ' are often used interchangeably. There are two definitions for carbon offsets in the industry literature – one school of thought considers an 'offset' to be the practical process or specific activity that removes or reduces CO_2e from the atmosphere, such that carbon offsetting generates a carbon credit (Courtnell, 2023; EPA, 2018). The other suggests a carbon offset is similar to a credit, i.e., it is also an accounting instrument that represents one tonne of CO_2e. The difference, however, stems from the source of the instrument: an offset is generated by a *voluntary* project, rather than earned by a regulated entity that emits below the annual emissions cap (Rivera & Sebring, 2022).

For this paper, a carbon offset will be defined as a process or activity that removes or reduces CO_2e emissions. Once a carbon project is developed and the results of an offsetting project/activity are *measured, reported, and verified*, typically by a third-party, carbon registries issue an associated number of carbon credit certificates. These certificates can then be purchased by emitters; thus, supporting the offsetting project/activity. This process is outlined in Figure 1.

Figure 1: Carbon Credit Issuing Process in Carbon Markets



Source: Graphic adapted from Streck, Dyck, and Trouwloon, 2021.

Finally, it is worth noting that in the same way that carbon credits can be created, these can also be retired. Once a carbon credit buyer claims emission reductions from a credit, the credit is transferred to a retirement account and can no longer be sold or traded.

Carbon Markets

Carbon markets are a trading mechanism that allows carbon credits to be bought and sold (UNDP Climate Promise, 2022). Well-functioning carbon markets are an important tool in mitigating climate change, as these create an efficient means of disincentivizing carbon emissions throughout the economy while concurrently incentivizing switching towards non-carbon means of production (IPCC, 2022).

As noted earlier, there are two types of carbon markets: compliance and voluntary, each with different regulatory guidelines. The global compliance carbon market grew ~164% in 2021 to €762 billion in value ($850 billion USD) and 16 Gt of CO_2 in volume (Refinitiv, 2023). The European Emission Trading System (EU ETS) was the largest compliance market in the world in 2022, representing almost 90% of the value and 77% of the volume of the global market. The VCM, in contrast, is much smaller but growing much faster: the global market was $2 billion USD in value and quadrupled vs. 2020 (Shell & BCG, 2023). Further, future growth in the VCM is expected to be much higher as well, with the market forecast to grow to $10-40 billion in value by 2030 (Shell & BCG, 2023).

While both markets share some similarities on the supply side, the demand side of each market is very different.

Compliance carbon markets are mandatory systems regulated by national, regional, and/or international policy or regulatory guidelines. The demand side of this market is a mix of regulated entities, typically companies and governments. Compliance markets are often set by Emissions Trading Systems (ETS), operating on the principle of 'cap-and-trade'. Regulated entities ('participants') are issued a fixed annual quota of emission credits (i.e., the 'cap'), and over time, regulators decrease the 'cap' on carbon emissions, incentivizing companies to reduce their operational emissions. Participants can 'trade' unused carbon credits or purchase additional credits on an open market to satisfy the requirements and participate in the market because they are compelled to by regulation. The CDM and the EU ETS are the best-known compliance trading programs globally.

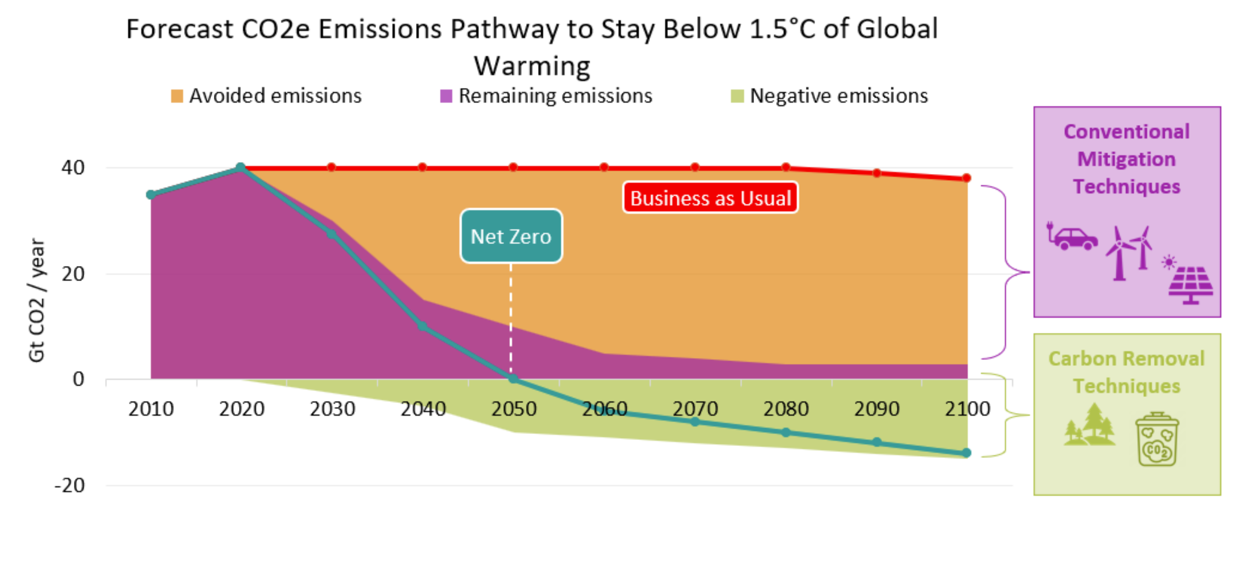
On the other hand, VCMs are not mandated by a governing body and thus are less tightly regulated. As a result, the demand side of these markets is more varied and can include private individuals and corporations with sustainability targets that are not legally binding. Any entity can purchase carbon credits and participate in the market voluntarily. Since participants and exchanges in VCMs do not have to adhere to strict regulatory scrutiny, the quality and accuracy of offsets can vary widely.

PART 2. TAXONOMY OF REMOVAL TYPES

What is CDR?

CDR refers to the process of removing CO_2 from the atmosphere to reduce the atmospheric concentration of CO_2 (IPCC, 2022). Although referred to as CO_2 'removal', CDR techniques typically span both the removal and durable storage of atmospheric CO_2. The IPCC includes CDR as part of a roster of critical tools that, if deployed promptly and at scale, could limit global warming to 1.5°C above pre-industrial levels (IPCC, 2022).

Figure [2]: Forecast CO_2e Emissions Reduction Required to Stay Below 1.5°C of Global Warming



Source: Graphic adapted from World Resources Institute, n.d.

Honegger, et al. (2021) note four principles that differentiate CDR from other mitigation activities: "(1) atmospheric CO_2 is physically removed, (2) then permanently stored out of the atmosphere, (3) all up- and downstream GHG flows are considered in the calculations, and (4) the atmospheric net-CO_2 flow balance is negative". Based on this framework, CDR does not include point-source capture of CO_2 emissions (e.g., CO_2 emitted by a coal-fired power plant or industrial process) and instead focuses exclusively on *atmospheric* emissions. By doing so, it offers the potential to address 'legacy emissions' of CO_2 i.e., CO_2 that has previously been released into the atmosphere, largely due to human activities since the start of the industrial age (DOE, n.d.). CDR is in effect the opposite of producing CO_2 emissions which is why it is often referred to as a 'negative emissions' technology (IPCC, 2022). It is often viewed as a tool for decarbonizing sectors of our economy that are the hardest to decarbonize, such as the energy and industrial sectors (e.g., steel, chemicals, and cement manufacturing).

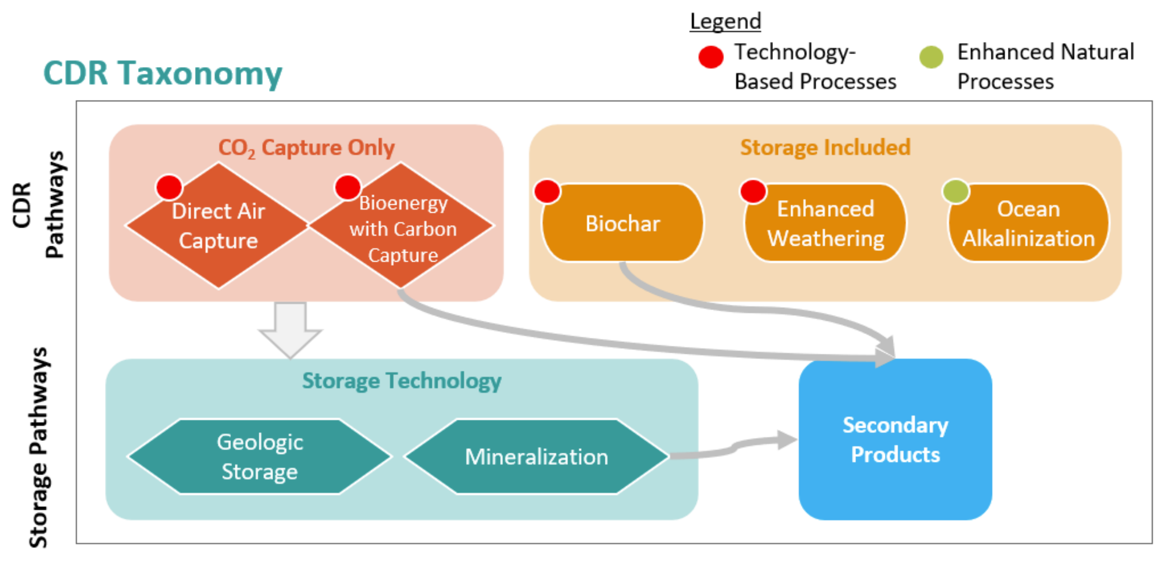
There is a vast array of approaches for CDR, each with varying removal and storage efficacy, scalability potentials, development costs, and second- and third-order consequences. While there are several CDR methodologies, these can be grouped into two main archetypes:

1. **Engineered/technology solutions:** These solutions seek to harness chemistry or physics to capture and store CO_2 from ambient air (e.g., direct air capture (DAC) using a chemical sorbent); and
2. **Nature-based solutions:** These solutions enhance existing natural processes (e.g., increasing photosynthesis rates or CO_2 uptake in soil). Nature-based solutions are further divided into land-based solutions and ocean-based ("blue carbon").

Recently, CDR has attracted a significant amount of capital flows: $7 billion of institutional capital has been invested globally in companies developing carbon capture technology since 2013 (Pitchbook, 2023). Further, policy incentives globally have also been expanding, including grant funding, tax rebates, government procurement, etc., based on the '*IEA Policies Database for Carbon Capture, Utilization and Storage*'. CDR technologies are at varying stages of development and maturing, making it important to understand the actual potential of each method in safely capturing and storing CO_2 at scale.

Technologies Overview

Figure [3]: CDR Taxonomy



Source: Capstone team's internal schematic

CDR technologies can be looked at from a variety of perspectives. Technologies can be nature-based or technological, can be either a point-source capture or distributed, or can either create secondary products or not. As CDR and storage are inextricably linked, these technologies must be thought of as whether or not they include storage as well. Some technologies merely capture CO_2, which can then be stored in any manner. Some technologies store CO_2 as they capture it, such as biochar or enhanced weathering. No subsequent storage method needs to be found. Finally, some technologies are purely storage, but because of their durability and scalability must be considered for this paper, as they are an important piece of the puzzle.

CDR Technologies and Storage Types Summary

CDR	CDR Type	Capture Type	Storage Type	Secondary Products
DAC	Technology-based	Atmospheric	Not inherent	Yes, if stored through mineralization
BECC	Technology-based	Point source	Not inherent	Yes
Enhanced Weathering	Enhanced natural processes	Atmospheric	Biosphere	No
Ocean Alkalinization	Enhanced natural processes	Atmospheric	Ocean	No
Biochar	Enhanced natural processes	Point source	Biosphere	Yes

- CDR Type: This attribute defines the basis of the technology.
  - Technology-based: Involves the use of engineered systems or technologies to capture CO_2 from the atmosphere.
  - Enhanced natural processes: Involves increasing the natural ability of the Earth's systems to remove CO_2 from the atmosphere.
- Capture Type: The attribute defines how CO_2 is captured.
  - Atmospheric: Uses specialized equipment that captures CO_2 from the air and does not require a concentrated source of emissions.
  - Point source: Uses technology to capture CO_2 at the point of release with high concentrations of CO_2.
- Storage Type: This attribute defines how each CDR technology is related to the storage of CO_2.
  - Not inherent: CDR technologies that do not have inherent CO_2 storage require the use of storage technology, such as mineralization or geologic storage to sequester the CO_2 that has been captured.
  - Biosphere: CO_2 stored in terrestrial organic matter, such as in soil, biochar, and minerals.

- Ocean: CO_2 dissolved in water forms carbonic acid, which reacts with dissolved minerals in the water to form bicarbonate and carbonate ions.

- Secondary Products: Some forms of CDR create by-products that have market value. When secondary products have possible revenue-generating uses, additionality can be more difficult to determine.

CDR Technologies Without Inherent Storage

Direct Air Capture

DAC is the method of removing CO_2 from the atmosphere and then storing CO_2, typically in geological formations, deep underground, or utilizing it in industrial processes. DAC works by using specialized equipment to intake air from the atmosphere and then capture and extract the CO_2 that is present in the air. DAC is the process of capturing CO_2 and must be paired with a storage pathway. There are two primary methods for capturing CO_2:

Liquid DAC

Liquid DAC involves using a liquid sorbent, typically an aqueous solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH), to capture CO_2 from the air. The air is passed through the liquid sorbent, which reacts with the CO_2 to form a bicarbonate solution. The CO_2 can then be separated from the bicarbonate solution and stored or used for other purposes. A common method of storage is to compress the CO_2 gas into a liquid state, which allows for easier transportation and storage. The liquid CO_2 is typically stored in high-pressure tanks or underground in geological formations, such as depleted oil and gas reservoirs or deep saline aquifers.

Another option for storing liquid DAC CO_2 is to utilize it in industrial processes, such as for the production of fuels or chemicals. In these cases, the liquid CO_2 can be used as a feedstock for chemical reactions, where it is transformed into other products, such as methanol or urea. Liquid DAC is typically more energy-efficient than solid DAC, but it requires a constant source of water and produces a liquid waste stream.

Solid DAC

Solid DAC, on the other hand, uses a solid sorbent material, such as metal-organic frameworks or amine-functionalized silica, to capture CO_2 from the air. The air is passed through the solid sorbent, which adsorbs the CO_2 onto its surface. The CO_2 can then be released from the sorbent by heating it or reducing the pressure and stored or used for other purposes. The advantage of solid DAC CO_2 storage is that the carbonates formed are stable and do not pose a risk of release into the atmosphere or the environment. Furthermore, the mineralization process can have a positive environmental impact by producing materials that can be used in construction, agriculture, or other industries. Solid DAC requires more energy to regenerate the sorbent and can be more expensive than liquid DAC.

Both liquid DAC and solid DAC have their advantages and disadvantages, and the choice between the two depends on various factors, such as the specific application, the availability of water, the cost of the sorbent material, and the energy requirements for capturing and releasing CO_2. Both technologies are still in the early stages of development and are not yet widely deployed at scale, but they hold promise as a way to mitigate climate change by removing CO_2 directly from the air.

BECC

Bioenergy with carbon capture (BECC) is a technology that combines the use of biomass energy with carbon capture to achieve negative emissions.

In BECC, biomass such as wood chips or agricultural waste is burned to generate energy, which can be used to produce electricity or heat. The CO_2 that is emitted from biomass combustion is then captured and can be stored underground or in other long-term storage solutions, such as mineralization or utilization. As biomass was grown through photosynthesis, which is a natural process that captures CO_2 from the atmosphere, the carbon emissions from burning biomass can be offset by the CO_2 that is captured and stored through carbon capture and storage (CCS). Therefore, the process of producing energy from biomass and capturing the CO_2 from it can result in a net reduction of CO_2 in the atmosphere.

CDR Technologies That Include Storage

Enhanced Weathering

The concept of weathering of silicate rocks drawing down CO_2 and altering climate on a global scale is one with precedent in the geologic record. It has been argued that the weathering of the Deccan Traps, large deposits of basalt that were deposited throughout the Indian subcontinent around 65 million years ago, contributed to changing the Earth from a hot-house to a cold-house state, eventually leading to glaciations and permanent presence of ice sheets at the poles (Kent and Muttoni, 2008).

The principles for enhanced mineralization are largely the same. A silicate mineral combines with CO_2 to form a carbonate mineral and a simplified silicate mineral – a generalized reaction is displayed below (Hills et al., 2020).

$$(Ca,Mg)SiO_3(s) + CO_2(g) \rightarrow (Ca,Mg)CO_3(s) + SiO_2(s)$$

The resultant silicate mineral will be stable for thousands of years - when carbonate minerals weather, they do not release CO_2. To date, the only active enhanced weathering methodology is one created by Puro.Earth. Verra formed an enhanced weathering methodology working group in November 2022.

In practice, enhanced weathering is the reaction of ground silicate-rich rock with a fluid containing CO_2. This fluid can be surface water, ocean water, or simply the atmosphere. Mine tailings are a popular choice for spreading - the rock has already been ground for another purpose and mining operations frequently mine through host rocks rich with mafic minerals. Puro.Earth has developed a methodology for enhanced weathering in which ground rock is distributed among soils. There are also interesting applications of enhanced weathering to remediate brownfield sites contaminated with Ca-rich sediment (Board, 2019).

Ocean Alkalinization

Ocean alkalinization, also called artificial ocean alkalinization, refers to a suite of methods that aim to increase the pH of the ocean to alter its ability to store CO_2. It can be separated into three techniques - direct ocean alkalinization, indirect ocean alkalinization, and iron fertilization.

The major advantage to ocean alkalinization is that oceans are a massive available sink of carbon. The oceans currently store about 38,000 Gt of carbon, more than twenty times the value of all the carbon that has been anthropogenically released since the industrial revolution (Renforth and Henderson, 2017; Friedlingstein et al., 2022).

Direct Ocean Alkalinization

The principle behind direct ocean alkalinization is the fact that CO_2 is absorbed in water as carbonic acid (H_2O+CO_2 -> H_2CO_3). Because the Earth's oceans equilibrate with the atmosphere, anthropogenic releases of CO_2 have led to increased oceanic carbonic acid and thus ocean acidification. However, in alkaline water, carbonic acid will dissociate to form bicarbonate and carbonate ions (HCO_3- and H_2CO_3-, respectively). Direct ocean alkalinization is the use of materials into the ocean, typically lime or weathered limestone, to increase alkalinity and change carbonic acid into bicarbonate and carbonate. Because lime is among the more commonly suggested materials to use for alkalinization, the process is also referred to as ocean liming.

The newly formed carbonate and bicarbonate ions in the ocean will react with naturally supersaturated ions such as magnesium and calcium to form carbonate minerals. This reduction in carbonic acid in our oceans will put our ocean's level of CO_2 in disequilibrium from our atmosphere, causing the oceans to draw down CO_2 from the atmosphere to re-equilibrate (Renforth and Henderson, 2017).

Indirect Ocean Alkalinization

Indirect ocean alkalinization uses the electrodialysis of ocean water as a means of carbon removal. In this process, bipolar membrane electrodialysis can be used to either increase or decrease the pH of water. Either process can be used to remove CO_2. The first process termed the base process acts on the same principles as direct ocean alkalinization. After creating more alkaline water using electrodialysis, the process plays out the same as if lime or weathered rock were used (de Lannoy et al., 2018). The other configuration, termed the acid process, uses electrodialysis to increase the acidity of water in the system. This acidification will cause the spontaneous formation of CO_2 gas bubbles in the water as the water seeks to balance its relative levels of carbonic acid, carbonate, and bicarbonate. This degassed CO_2 is collected for future storage (de Lannoy et al., 2018).

Ocean alkalinization is an attractive suite of techniques. The potential for storage is enormous, the raw materials (such as lime) are readily available and abundant, and there would be the massive secondary benefit of fighting ocean acidification, which could help preserve coral reefs and other sensitive ocean ecosystems that are important for biodiversity.

Ocean alkalinization is far from a zero-risk method. There could be significant local swings in pH at the sites where alkaline substances are applied, with not much known about the potential impacts on local life, including primary producers (Burns and Corbett, 2020). The bottom line on ocean alkalinization is that while it has great potential, the biogeochemical feedbacks are simply not well enough understood, and this set of methods should not be deployed until there is a stronger understanding of its implications.

Biochar

Biochar refers to the black, carbon-rich material left behind when burning organic material in a low-oxygen environment at a variety of temperatures. Biochar, like many sustainable practices, is a technique with a long history that is now being revisited as a means for storing carbon. The most successful ancient practitioners of biochar were residents of the prehistoric Amazon rainforest. These Amazonians used biochar as a means of enhancing the fertility of soils. These enhanced soils, known by the Portuguese name terra preta (black earth) are in many cases still intact from over 500 years ago. This shows the stability of biochar as a material, its ability to enhance soils, and its potential use as a means of storing carbon (Tenenbaum, 2009).

The three major techniques used to create biochar are pyrolysis, torrefaction, and hydrothermal carbonization. Each of these methods involves placing the feedstock into reaction chambers that operate at specific temperatures and pressures. One of the strengths of biochar is the variety of source materials that can be used ranging from compostable products to crop and forest residues to animal carcasses and municipal biowaste (Wang et al., 2021). The abundance of organic waste that is generated makes biochar an exciting avenue for carbon storage. It is also highly regarded as a means of creating renewable solid fuels.

Pyrolysis

Pyrolysis is the most commonly used method of creating biochar (Wang et al., 2021). Pyrolysis takes place at a wide range of temperatures, from 300-800°C, but 500-800°C is a more efficient temperature range (Chatterjee et al., 2020).

Torrefaction

Torrefaction is classified as a type of mild pyrolysis, in which the feedstock is thermochemically made more hydrophobic. Torrefaction is done at lower temperatures than pyrolysis, from ~200-300°C. Torrefaction is a well-regarded method to create biochar that will be used as a fuel (Chen et al., 2015).

Hydrothermal Carbonization

Hydrothermal carbonization is a method that works best with wet biomass, thus avoiding a pre-drying step that must take place for pyrolysis and torrefaction. It takes place at low temperatures and pressure - from 180-250°C and at surface pressure (Sivaprasad and Manandhar, 2021).

Biochar has promising applications after its creation with uses in environmental remediation, construction materials, or, as native South Americans did centuries ago, to enhance agricultural soils. Because of its wide range of secondary uses, varieties of possible inputs, and ease of creation, biochar is seen as one of the most well-established forms of CO_2 removal.

Storage Technologies

Mineralization

In Situ Mineralization

In situ mineralization is the injection of CO_2 as a supercritical fluid into geological strata. Not only will the strata store the CO_2, but the intention is that the CO_2 will react with the host rock (typically a mafic or ultramafic rock such as basalt, gabbro, or peridotite) to form stable silicates. Tests have demonstrated that CO_2 does not leak out of in situ systems, but more research needs to be done on what sort of carbonate minerals are forming and their permanence (Board, 2019).

Ex Situ Mineralization

Ex situ mineralization includes the introduction of rocks, minerals, or industrial waste into reactors, where they are combined with CO_2 fluid at high temperatures and pressures. The specialized equipment and transport costs associated with ex situ mineralization raise the costs of these methods. However, there is potential for secondary products to be created from the carbonates, the selling of which would buffer the cost of mineralization.

Combined, in situ and ex situ carbon mineralization have enormous potential to store carbon worldwide. Because of its storage in geological deposits, in situ methods have the largest potential. Together, there is a total global storage capacity between 10,000 and 100,000 Gt of carbon (Gadikota, 2021).

Surficial

Surficial carbon mineralization is the reaction of ground rock, typically mine tailings, with fluids with enhanced levels of CO_2.

A limiting factor for certain applications of enhanced mineralization is the availability of material. Wollastonite has been shown in tests to be among the most reactive minerals for enhanced weathering, but it is usually found in nature in limited seams as a contact metamorphic mineral at the boundary between an intruding magma body and a carbonate host rock. Thus, it is estimated that the global stock of wollastonite is on the order of 100 million tons (U.S. Geological Survey, 2023). As about 0.33 tons of CO_2 are removed per ton of weathered wollastonite, this represents a removal of ~33 Mt of CO_2 (Board, 2019).

Geologic Storage

Geologic Storage operates similarly to mineralization in that CO_2 is injected into the subsurface, but with this type of storage, no mineralization reactions will take place. Instead, the CO_2 is stored as a gas, where it is covered by an impermeable layer and unlikely to escape. One such option is known as sedimentary basins, referring to the depleted oil and gas reservoirs (they are also referred to by this name) that are now candidates for the input of a resource instead of its extrusion. Once, these sedimentary basins stored carbon in the form of hydrocarbons such as oil and methane. Now, the carbon is being returned to these basins as CO_2. Another is saline aquifers, which have more storage capacity than depleted oil fields (Luo et al, 2022).

Scope of Analysis

As defined by the client, the scope of this analysis is limited to technology-based carbon sequestration solutions, most notably excluding nature-based solutions. Within the technology-based solutions space, capture of point-source emissions and carbon capture utilization is also excluded. Only technologies that had permanence of over 100 years were evaluated, which is the minimum that many established registries, such as C-Capsule (C-Capsule, 2023) and Puro.Earth (Puro.Earth, N.D.) will accept.

PART 3. CDR AND THE CARBON MARKET

CDR in the Carbon Markets Today

Avoidance vs. Removal Credits

Before discussing the state of the VCM today, it is worth noting that there are two broad archetypes of credits within this market: 1) avoidance and reduction credits, which their names suggest, are created by activities or projects that either avoid or reduce the production of CO_2e; and 2) removal credits, which are created via activities or projects that remove CO_2e from the atmosphere (Shell & BCG, 2023). 80% of the carbon credits issued in the VCM between 2015-21 were avoidance credits (Shell & BCG, 2023).

Avoidance credits are generated by a range of projects including renewable energy generation and nature-based solutions like land use change and deforestation avoidance. If all the CO_2 in the atmosphere and ecosystem were contained in a bathtub, these projects are equivalent to reducing the influx of CO_2 into the tub by turning the tap down. In contrast, removal credits are equivalent to unplugging the bathtub to remove the CO_2 already in the tub. Typically, CDR projects as defined in this report would generate removal credits.

The State of the Voluntary Carbon Market

As noted earlier, VCM is experiencing rapid growth. In a recent global survey of 200 participants (Shell & BCG, 2023), buyers of carbon credits reported the following insights: 55% of respondents reported their carbon credit purchases as non-discretionary, despite increased economic challenges; 83% reported that their emissions cover targets will continue to grow, as company net-zero commitments evolve, and 13% believe these will span 100% of their company's emissions by 2030; further, 92% of buyers expect their average portfolio price to increase ~60% from the current average of \$15-20/tCO_2 to \$25-30/tCO_2. Taken together, these data point to strong latent demand for carbon credits in the VCM.

Figure [4]: Summary of the Key Sources of Market Dissatisfaction in the VCM

Source: Shell & BCG, 2023

While the latent demand is strong, the market is not perfect. The figure above summarizes some of the key sources of dissatisfaction among credit buyers, which are likely to influence the way both demand and supply evolve in the future.

The top five challenges reported can be summarized into two main problems:

- **Lack of Transparency:** Voluntary markets are entirely dependent on transparency. The system only works if the carbon credits are accurately accounted for, priced, and represent real carbon reductions. The reported challenges with price, quality assurance, and data availability all indicate a broader challenge with transparency, which will need to be addressed as the market grows. This is particularly important in enabling buyers and sellers to determine the appropriate price vs. quality tradeoff.

- **Lack of Standardization:** The marketplace is diffuse, with relatively few major entities and several smaller entities (including registries) representing projects both large and small all over the world. Unlike the compliance markets, there are no unified registry services, regulations, or overarching standards, creating all sorts of challenges in assessing credit quality, including double-counting emissions reductions. While efforts are underway to address some of these challenges and drive some form of standardization (e.g., Science Based Targets Initiative or SBTi, Voluntary Carbon Market Integrity Initiative or VCMI), these are in their infancy.

Other challenges span ensuring that the development of market infrastructure keeps pace with the growth in the size of the market (e.g., transaction simplification, risk management, robust trading / post-trade infrastructure, etc.).

Challenges persist on the supply side as well. The major challenges here are as follows:

- **Demonstrating quality:** The burden-of-proof on demonstrating quality is increasingly shifting to the supply side of the market (Shell & BCG, 2023; Widge, 2021). Quality evaluation criteria tend to include considerations like additionality, permanence, leakage, lifecycle impacts, and co-benefits (e.g., biodiversity, soil quality, air quality, and impacts on local communities).
- **Long lead times:** Project developers face long lead times between the initial investment and eventual sale of offsets (Widge, 2021), stemming from several friction points, such as developing appropriate registry methodologies, siting and permitting for projects, regulatory/ standards uncertainty securing appropriate capital.
- **Energy use:** This challenge is specific to technology-based solutions that use some form of energy, generally electricity, to fuel the CO_2 capture and storage processes. Securing access to large amounts of clean and relatively affordable energy is a particularly acute challenge, which feeds into the other two challenges above.

Together, these challenges are contributing to a situation where supply (particularly high-quality supply) cannot keep pace with demand growth, translating to increasing prices.

Within this broader market context, removal credits are becoming particularly important and in high demand. Over half of the respondents to the Shell & BCG (2023) survey reported that they expect removal credits to comprise upwards of 60% of their portfolios by 2030, especially if price reductions evolve in line with forecasts, and 7% noted that they expect 100% of their portfolios to be made up of removal credits. In a market where assessing quality is a large and growing challenge, removal credits are increasingly perceived as a proxy for higher quality. MRV is also perceived as less complex for removals, which is a significant demand driver. As supply shortages abate and price improvements continue, there is a forecast shift in the market mix: removal credits are expected to grow from ~20% to 35% of supply in a rapidly growing market by 2025, with continued growth thereafter.

Carbon Registries

Carbon registries are organizations that track and record emission reduction and removal projects in a unified system. Carbon registries are used to support climate policies and programs, such as cap-and-trade systems, that aim to reduce emissions and mitigate the impacts of climate change. Carbon registries have exploded in popularity in recent years as firms and institutions have sought to validate and track their emissions reduction pledges. The major players in the carbon registry market vary widely, from boutique non-profit operations to tech-heavy solutions.

Nonetheless, all carbon registries share a similar general structure:

1. Each registry has a set of approved methodologies that establish carbon projects' guidelines and allow registration of carbon removal and/or mitigation projects to generate carbon credits. Registries establish a database of verified emissions information for each project to be able to trade, transfer, and retire carbon credits.

2. Registries track and verify emission reductions and/or removals as well as any other requirements specified in each methodology. Depending on each registry and methodology, project developers have to follow a methodology's guidelines and report on a project's progress and operations.
3. Registries enable carbon marketplaces by providing mechanisms to allocate and transfer carbon credits that are usually bought and sold as tools for reducing emissions.
4. Registries aim to provide a transparent interface about market conditions to enable the public to understand the provenance of carbon credits.
5. Lastly, most registries have mechanisms to develop new methodologies or modify existing ones. Each registry has its own rules and procedures to create and approve new methodologies.

Carbon registries are a response to the explosive growth of the VCM. Due to a mix of public awareness of the consequences of climate change and pledges made as a part of corporate ESG governance, many industries, governments, and other institutions have begun to offset their emissions even though it is not required by law. Demand for voluntary offsets is particularly concentrated in consumer-facing industries such as fashion, airlines, consumer packaged goods, and food, where there is a major incentive to make consumers feel good about the environmental impacts of their choices.

It is important to reiterate that the compliance carbon market operates under specific legal and regulatory guidelines. The VCM, on the other hand, allows more experimental emissions reduction projects and can serve as a testing ground for new carbon reduction initiatives. VCMs lack the same level of safeguards and uniform standards as the compliance carbon market, which can sometimes lead to emissions reduction projects of lesser or questionable quality.

In response to the lack of standardization in the voluntary carbon market, registries and third parties seek to develop rigorous MRV processes that will enforce tight rules on how projects get established and operate. The carbon registry landscape is rapidly evolving. However, a select few entities have distinguished themselves with their reach and methodologies. These include:

- Verified Carbon Standard (Verra)
- Gold Standard Impact Registry (GS)
- American Carbon Registry (ACR)
- Puro.earth (Puro Registry)

Carbon Registries Overview and Comparison

	Voluntary Carbon Standard (Verra)	Gold Standard (GS)	American Carbon Registry	Puro Registry
Geographic eligibility	Global	Global	Global, some sectors only United States	Global
Project eligibility by sectors	All CDM sectoral scopes	RE; EE; Industrial Waste handling and LULUCF	Fuel combustion, industrial processes, land use, land use change and forestry, carbon capture and storage, livestock, waste handling and disposal	Biochar, Wooden Building Elements, Soil amendment, Carbonated building element, Carbonated building material
Baseline setting	Mostly project-to-project basis	Mostly project-to-project basis	Project-to-project basis	All CDR suppliers must demonstrate additionality and counterfactual analysis based on baselines that shall be project-specific
Methodologies	CDM, CDM-based, new methodologies and CAR (except for forest protocols)	CDM, CDM-based and new methodologies	CDM-based and new methodologies bottom-up and top-down	CDM-based
New Methodologies Development	Allows submissions of ideas for new and revised methodologies paid by the methodology developer	Allows for new methodology development based on their guidelines paid by the methodology developer	Allows for new methodology development	Unclear if new methodology development is allowed

Life Cycle Assessment (LCA) considerations	Only some methodologies have LCA requirements	Only some methodologies have LCA requirements	Only some methodologies have LCA requirements	Removed carbon is the sequestered carbon minus the emission that is calculated as part of the product or processes' LCA. CORCs only consider net-negate emissions from Negative Emissions Technologies (NET)
Monitoring	Defined in each methodology	For GHG uses UNFCCC standards. Sustainability defined in GS Project Passport	Defined in approved methodologies	Defined in each methodology
Reporting	Monitoring reports, no specified frequency	Monitoring report (including GHG and sustainability aspects)	Monitoring reports, no specified frequency	Monitoring report and data records (including GHG, LCA, evidence of permanent storage, and evidence of no double-counting and claiming). No specified frequency
Verification	VCS approved auditor and staff	DOE and GS Secretariat	Third-party verification by ACR-approved validation and verification bodies	Verification by independent, accredited third-party validation and verification bodies

Source: Author's compilation; NEFCO, 2019; Puro Earth, n.d.

Carbon Registry Methodologies

Methodologies provide a baseline estimation of how much carbon a project will either remove or avoid emitting during its duration. For a given project, the actual carbon mitigation may fall short of, match, or exceed the baseline determined in the methodology. A methodology will also calculate what emissions would have occurred if the project never happened at all. The MRV is completed based on the methodology, which is a foundation upon which each project is built.

Carbon registries have established methodologies for given project types. Because transparency and uniformity are so important to carbon markets, methodologies are published and made available for peer review. Registries will often make new or edited methodologies available for public comment prior to their publication. However, there will inevitably be projects that exist outside the boundaries of existing methodologies. Major registries include the ability to create a new methodology for a given project. Registries also offer the option to modify or revise existing methodologies to fit a given project.

For a methodology to be created, an applicant for a carbon credit must first establish the project boundaries. Boundaries are the parameters that will be considered for the project and are generally split into two categories: physical/spatial and temporal. Physical boundaries are generally considered broadly rather than narrowly to provide a full accounting for a business-as-usual scenario. The physical boundaries must also consider the various actors committing emissions within the bounds of the project.

Temporal boundaries include those of the project itself and the crediting period. Many project types have long time horizons until they are fully implemented. This is especially the case for large-scale nature-based solutions, such as afforestation, or a carbon storage facility that may be receiving carbon from an array of sources. These types of specificities are determined by methodologies. The advantage of peer review and public comment for methodologies is that the details can be standardized across different registries.

The temporal boundaries must also address the period during which the credits will be issued. As many projects are long-term, they will seek the maximum crediting period. A typical crediting period for carbon projects is 10 years (this is the standard for CDM, GS, ACR, and others). During this ten-year period, strict accounting must be kept about the status of the project, and what emissions were achieved relative to the expected reductions. After the period ends, the project will be re-analyzed through the same methodology. However, the registry will likely have updated the methodology in that time frame.

After the project boundaries are defined, the baseline emissions and project emissions are established. As stated, the baseline emissions are the business-as-usual case. The project emissions are those that come about within the established boundaries. Given the baseline and expected project emissions, the data collection plan can be established. Data collection covers measurement techniques and the frequency of measurement. This section will include the MRV plan of the project data. MRV plans are highly detailed in methodologies, as the actual accounting for the credits relies upon the data collected through MRV. Data plans will also account for leakage, or emissions that "leak," or move from the project into the broader market the project exists in as a result of the market perturbation provided by the project.

Because carbon removal is a nascent market, methodologies for these project types are not well-established. In fact, most major registries have either one established CDR methodology or no methodologies for CDR at all. For example, ACR has 16 total approved methodologies listed on its website. One of those methodologies is for CDR, and it deals with CCS storage in geological reservoirs. However, it applies only to enhanced oil and gas recovery projects (American Carbon Registry, n.d.). Gold Standard lists a few methodologies one of which is "Carbon sequestration through accelerated carbonation of concrete aggregate" (Gold Standard, 2022). In the near future, Verra will start offering CDR methodologies developed through their partnership with the CCS+

Initiative (CCS Plus, n.d.). On the other hand, there are new players in the market, such as Pure Registry, that specifically focus on removal projects and only offer CDR methodologies (Puro Earth, n.d.).

Why Do We Need to Evaluate CDR Technologies?

The establishment of a registry methodology, which can take years to get approved, is one of many possible hurdles for CDR projects. If no existing methodology fits a project, there is a risk that this project may fail simply because its methodology was not approved in time. Beyond registry methodologies, MRV, storage pathways, investment landscape, environmental impacts, and other factors can pose risks to technology's implementation.

As a nascent market, CDR is rapidly growing. With rapid growth come risks and uncertainties. To be able to navigate this emerging landscape, it's crucial to evaluate whether or not a CDR technology is ready for deployment. This practice can help project developers, investors, and other stakeholders create risk mitigation strategies and plan accordingly for potential challenges or uncertainties.

PART 4. ASSESSMENT FRAMEWORK

Introduction

The framework to assess readiness to scale CDR technologies (hereinafter referred to as the framework) serves as a mechanism to identify sources of risk to the use of individual technologies to generate carbon credits. The output of this framework is an indicator of maturity in the CDR market and may be used to identify technology-specific roadblocks to scale.

The primary audience for this framework is CDR technology developers, CDR project developers, and financiers, as well as carbon credit buyers. The framework is also relevant for other stakeholders including corporates, registries, methodology developers, non-governmental organizations, innovation incubators, and other market intermediaries.

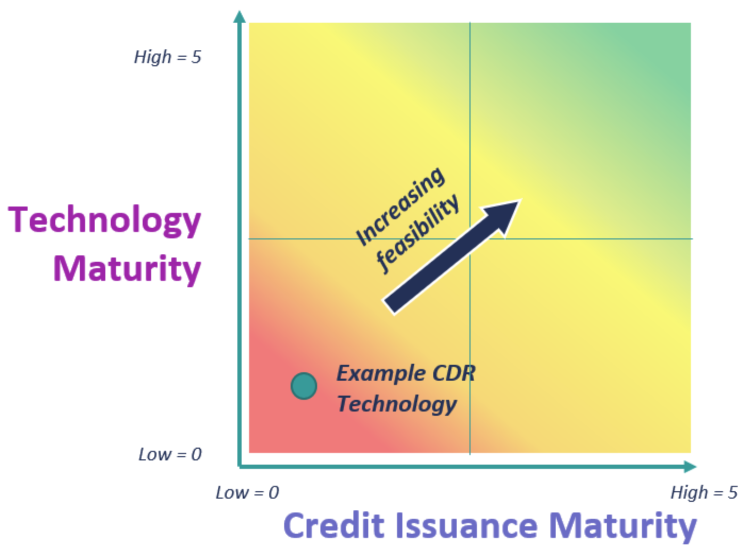
The framework is intended to assess and compare different non-nature-based CDR technology types. It is not designed to evaluate projects. Technology is defined as a distinct pathway for carbon removal that is characterized by its removal type, capture or conversion mechanism, and storage mechanism (as defined in Part 2). In this scenario, a project is a subset of a technology that has unique characteristics such as location, resource availability, and other factors. For example, biochar pyrolysis is a technology pathway whereas the use of pulp and paper mill waste in Georgia to create biochar products and compost blends is an example of a CDR project (Wakefield BioChar, 2023).

The framework is comprised of ten criteria, which capture different sources of risk for an ability of a CDR technology to generate carbon credits. Several criteria build off existing work to map CDR technologies across their lifecycles, from development and deployment to commercialization. Each criterion can be viewed as an exposure to risk. The criteria of the framework should be assessed in present-day terms, not through long-term forecasting or future projections (i.e., the framework assesses technologies as they stand today).

Two separate (albeit overlapping) sources of risk for CDR technologies were identified during the research process – technology risk and credit issuance risk. The former is the risk linked to whether the technology reaches the appropriate stage of maturity to generate carbon credits, and the latter is the risk to the actual issuance of carbon credits using the technology (irrespective of its technological maturity). Each criterion of the framework was bucketed as either a technology risk or a credit issuance risk. Some criteria could be applied to both risk types, which are specified in the criteria descriptions of the criteria below.

Once the criteria scoring is completed, the results are mapped to a matrix using the technology risk as the y-axis and the credit issuance risk as the x-axis (Figure 4). The approach to translating the consolidated scores into x and y coordinates on a matrix is discussed later in the section. The idea behind this matrix is to produce a visual tool that allows an easy reference to the relative positioning of the different CDR technologies.

Figure [4]: Summary Output Matrix for the Assessment Framework



Source: Capstone Team's Schematic

While this framework does not address risk mitigation tactics, it is important that framework users consider entities responsible for mitigating risks associated with each criterion. The key question is: can the barrier be dismantled through a CDR technology developer or project developer's operational choices or R&D efforts, or does it require coordination with the broader system (e.g., infrastructure, scientific communities, registries, etc.)? Risks that a technology developer could mitigate may be easier to overcome versus risks that the wider ecosystem (e.g., financiers, policymakers, etc.) must address. This logic may influence how framework users weigh each criterion, which is discussed in the following section.

Assessment Framework Criteria

The framework consists of ten assessment criteria separated into two categories – technology and credit issuance risks, shown in Figure 5. Each criterion is rated from 0-5 except for capital availability and MRV. In these cases, the rating is normalized to a 0-5 scale. For both technology and credit issuance risks, the sum of criteria ratings is divided by the total number of points available (i.e., 25 points for each technology and credit issuance risks). The results determine the y- and x-axis positions, respectively, as shown in Figure 4.

Individual framework users can weigh one criterion more or less heavily depending on their purpose. In this report and the case study presented below, the weighting for each criterion is set to 1. However, framework users can modify the weight of each criterion in the Excel-based tool accompanying this report, which will change the output scores for technology and credit issuance risks.

Figure [5]: Overview of Assessment Criteria and Scoring Ranges

	Assessment Criteria	Rating Scale	
Technology Risk	Technology Readiness Level	0 to 5	
	Cost per ton	0 to 5	
	Capital Availability	0 to 7	*Normalized to 0-5*
	Storage / Use	0 to 5	
	Measurement, Reporting and Verification	1 to 3	*Normalized to 0-5*
Credit Issuance Risk	Carbon Registry Methodologies	0 to 5	
	Additionality	0 to 5	
	Durability	0 to 5	
	Lifecycle Analysis	0 to 5	
	Environmental and Social Impacts	0 to 5	

Source: Capstone Team's Schematic

I. Technology Readiness Level

Description

Technology Readiness Levels (TRL) are a form of a measurement system that provides a scale against which to assess technological maturity. A TRL rating is assigned based on the evaluation of specific parameters and typically ranges from 1 to 9 with 9 being the most mature. In the 1970s, NASA developed the TRL, which has since been implemented by the U.S. Department of Defense, the European Space Agency, the European Commission, and the International Organization for Standardization (ISO) through the publication of the ISO 16290:2013 standard. While primarily used to assess space station hardware, according to ISO 16290:2013, the TRL scale can apply to various technologies.

Each level is generally defined as follows (Mankins, 1995; Zimmerman et al., 2022):

- TRL 1 Basic principles observed and reported

- TRL 2 Technology concept and/or application formulated
- TRL 3 Analytical and experimental critical function and/or characteristic proof of concept
- TRL 4 Component and/or system validation in laboratory environment
- TRL 5 Laboratory scale, similar system validation in relevant environment
- TRL 6 Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
- TRL 7 Full-scale, similar (prototypical) system demonstration in a relevant environment
- TRL 8 Actual system completed and qualified through test and demonstration
- TRL 9 Actual system operated over the full range of expected conditions

Straub (2015) advocates for a modification to the TRL to include a level 10 by providing five use-cases for TLR 10, which justify the need to discriminate between "tested-and-true and used-once technologies." In assessing CDR technologies' readiness to generate carbon credits, there is also a need to differentiate technologies based on longer-term performance characteristics.

While in the short-term, many carbon removal technologies will lack the documented performance data needed to reach TRL 10, the longer-term monitoring of performance characteristics such as failure conditions, incident levels, and frequency of troubleshooting and repair is relevant since carbon removal technologies will be operational over long periods of time. TRL 10 better captures the range of CDR maturity.

It is important to note that TRL alone is insufficient to evaluate CDR technologies' readiness. Other performance characteristics that fall outside the scope of TRL, such as cost or the maturity of measuring and verification systems, must also be considered. These other criteria, and the justifications for their inclusion, are explored in the subsequent sections of this report.

Justification for Inclusion

TRL provides a well-understood method of communicating readiness from a purely technical standpoint and is commonly used in academic and non-academic literature. The rating scale allows for a comparable way to assess technologies at different stages of development, an essential point for CDR, which spans a wide range of maturities. TRL can also inform a projection of time and cost, making the analysis a worthwhile pursuit to inform the Return on Innovation Investing and guide much-needed investment as CDR technologies are currently very high-cost (Gogerty, 2021).

Along the TRL scale, the primary risk to the ability to generate carbon credits is the risk of uncertainty in the performance of the technology. A lack of demonstration of technological maturity parallels high technology risk (e.g., high cost, low MRV performance) and high credit issuance risk (e.g., low permanence, inefficiency in carbon usage through LCA). The project is primarily responsible for addressing this risk through operational choices and R&D efforts.

Rating Scale

For this criteria, it is assumed that TRL is comprised of 9 to 10 levels. The rating for the assessment framework maps the TRL levels to a scale of 0-5 based on similar defining characteristics/identifiers of TRL levels. This concept is further explored in Appendix A, which gives a general description of each TRL and example threshold exit criteria for advancement.

- 0: no TRL score available
- 1: “Concept phase” (generally aligns with TRL 1-2)
- 2: “Exploration mode” (generally aligns with TRL 3-4)
- 3: “Prototype mode” (generally aligns with TRL 5-6)
- 4: “Build mode” (generally aligns with TRL 7-8)
- 5: “Ton mode” (generally aligns with TRL 9-10)

Potential Limitations

As stated by Zimmerman et al., 2022, “TRL identification does not guarantee that a technology meets expectations in an application; TRL is solely a measure of maturity.” TRL scales are often generic and do not provide much guidance on specific requirements at each level of development, opening the door to subjectivity. Without a globally agreed-upon robust scale specific to CDR technologies, Appendix A provides example threshold criteria to guide end-users. Further resources are available to support TRL evaluation, such as the International Energy Agency’s TRL analysis of CO_2 capture and storage technologies relevant to the clean energy transition (International Energy Agency, 2020).

II. Cost ($/t$CO_2$)

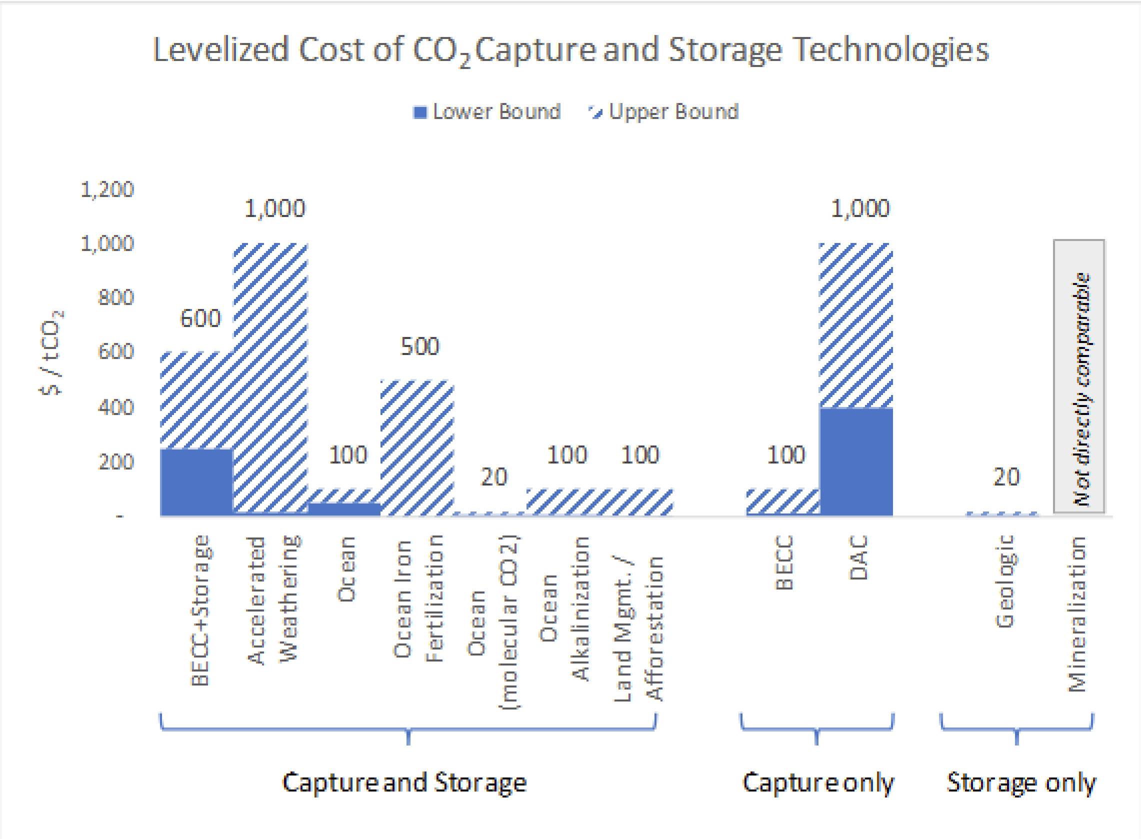
Description

The cost of a given CDR technology typically refers to the levelized $ per ton cost of CO_2 removal and storage associated with the technology. Since it is ‘levelized’, this cost includes capital costs of the machinery and operating costs, including energy for both capture and storage, maintenance, and consumables.

Cost is a commonly used KPI typically estimated via a techno-economic assessment. Technology developers should be able to provide guidance on a range within which costs should lie. That said, it is important to understand how these estimates are produced. For example, there is a rich discussion in the literature about the relevant time horizon to assess costs. To support an apples-to-apples comparison, the framework focuses on the current estimated or realized costs of capture and storage rather than forecasts costs in the future. Similarly, cost estimates can also include the impact of policy incentives, which vary by jurisdiction. While this is a valuable consideration, evaluating costs on an absolute basis without incentives is crucial to enable a more fair comparison between technologies and consider the impact of incentives in the ‘Capital Availability’ criterion.

Costs are expected to be significantly higher for technologies that capture CO_2 from diffuse atmospheric sources rather than more concentrated point sources (e.g., flue streams). Capital costs are also significant and a large source of uncertainty for technologies requiring large plants, especially since many existing deployments of these technologies are relatively small. For example, DAC is yet to be demonstrated at greater than 1 Mt/CO_2 capture per year (IEA, 2022). Finally, factors such as the energy intensity of both capture and storage (e.g., geological storage involves compressing CO_2 at high pressure) and any need for regular replacement of consumables (e.g., sorbents for solid DAC) are additional variables that can markedly influence costs.

Figure [6]: Summary of the Levelized Cost of CO_2 Across Different Removal and Storage Technologies



Source: IEA, 2022; National Research Council, 2015; IEAGHG, 2022

The figure above provides an overview of the range of estimates for different technologies, including some that are beyond the scope of this paper. The literature today suggests capture costs can vary widely between $15-1,000+ /t$CO_2$, with BECC and DAC at the lower and upper bounds of the range, respectively (IEA, 2022; National Academies of Sciences, Engineering, and Medicine, 2019). It is important to note that pathways such as 'prevented deforestation' or 'improved forest management', which generate carbon avoidance credits are not fair comparisons for technologies that generate removal credits, for which the market is willing to pay a cost premium (Shell & BCG, 2023). Nonetheless, these avoidance credits can cost as little as $1-100/t$CO_2$, with an average price of $10/t$CO_2$ (IEA, 2022; National Research Council, 2015). In terms of storage, these can range from $10-100/t$CO_2$ and need to be added to capture costs for technologies where this is relevant.

There is wide consensus in the literature that $100/t$CO_2$ is the ceiling for economic viability for CO_2 capture and storage and the medium to long-term target for costs for a relevant technology (National Academies of Sciences, Engineering, and Medicine, 2019; IEA, 2022; Keith et al., 2018; CarbonPlan, 2022).

Another consideration for analyzing cost is whether or not the captured CO_2 can be leveraged to generate additional revenue streams. This is especially relevant for solutions that store CO_2 for use in secondary products (e.g., building materials, fuels, etc.). This factor is not considered here and instead features in assessing criterion VII 'Additionality.'

Justification for Inclusion

Cost is an essential consideration for CDR technologies, especially in a world without a universal carbon price. Emitters view this cost base as a waste management cost associated with doing business rather than a source of incremental revenue; consequently, carbon credit purchasers and/or emitters are incentivized to choose the lowest cost technology that satisfies their needs. Therefore, to assess technology risk, it is important to consider the capture and storage costs, as these can be leading indicators of the underlying economic viability of a technology.

Ultimately, costs are partly a function of the design and technology choices of the developer and partly a function of input prices. This risk is impacted by external forces and factors inherent to the technology, though it is primarily the developer's responsibility to manage appropriately.

Rating Scale

Unlike TRL, this is a qualitative assessment scale. Based on existing literature on current capture costs associated with more mature CDR technologies (BECC, DAC), incentives created via regulation, for example, the U.S. Inflation Reduction Act (IRA) of 2022, and forecast evolution in capture costs. DAC is widely acknowledged as the most expensive of the different CDR technologies, given the relatively low atmospheric concentration of CO_2 (IEA, 2022). As a result, we have used DAC costs today as the outer bound of acceptable costs, with more affordable technologies as the inner bound of the scale.

Score the current capture and storage cost per tonne associated with the CDR technology pathway being assessed:

- 0: No current capture and storage costs (in $/tCO_2$) noted OR costs > $1,000/tCO_2$
- 1: Between $600-1,000/tCO_2$, since current DAC and storage projects can comfortably deliver within this range today. For example, Climeworks' Project Orca in Iceland operates at $600-800/tCO_2$ (Birnbaum, 2021).
- 2: Between $300-600/tCO_2$, which is below costs today for established DAC+S projects (IEA, 2022) but above the long-term target costs of the technology
- 3: Between $100-300/tCO_2$, which is within the range of target costs for DAC+S over the next decade but above the long term economic viability ceiling of $100/tCO_2$
- 4: Between $80-100/tCO_2$, since $100/tCO_2$ widely viewed in the literature as the long-term ceiling for the economic viability of CDR technology
- 5: <$80/tCO_2$, which is the upper bound of the $15-80/tCO_2$ achievable today via BECC (IEA, 2022), with which other CDR technologies will likely have to compete.

A score of 0 means that the CO_2 captured via a specific technology is unlikely to be captured in an economically viable manner, posing a risk to the future development of this technology. Conversely, a score of 5 means that the CDR technology has a line of sight to a cost-base below the long-term ceiling for economic viability and will continue to appeal to investors and/or technology and project developers.

Potential Limitations

Nascent CDR technologies will likely not have estimates of the levelized cost of CO_2 capture today, especially since many may not yet have pilot projects in place of which to estimate costs. Moreover, when layered with uncertainties linked to storage/use pathways (discussed in criterion IV) and the associated costs, assessing the all-in cost associated with specific applications of CDR technology + storage/use becomes challenging.

One solution to this challenge might be to consider target costs, but this is a future-looking metric that may not accurately represent the actual cost performance of a given technology. For example, Climeworks' reported levelized costs for its first-generation commercial plant are $600/t$CO_2$. However, it forecasts these will decline by 66% to $200/t$CO_2$ by the mid-2030s without a clearly defined route to cost-down (Washington Post, 2021).

Finally, several factors typically influence cost estimates, which can often vary by location and jurisdiction (e.g., energy, transport, and weatherization costs). As with many other criteria, the costs associated with a specific project are typically less abstract than those associated with a specific technology. This limitation will likely diminish over time as technologies and costs mature. However, there is no shortcut to side-step this limitation in the near term, which is worth considering when using this framework.

III. Capital Availability

Description

Capital availability spans the opportunity technology developers have to access both public and private pools of funding and/or incentives to support either the development of the technology or its rollout in the form of CDR projects.

Honegger et al. (2021) identify five types of public policy activities that mobilize CDR development: (1) research and development (R&D) activity-oriented subsidies; (2) mitigation results-oriented subsidies; (3) regulatory mandates; (4) fully-fledged carbon pricing; and (5) ancillary instruments. Of these, (3) to (5) cover 'soft' policy instruments such as emissions standards and targets, carbon taxation, and CDR standards. These are extremely valuable tools but are not directly applicable to assessing public capital availability. In contrast, (1) and (2) are specifically focused on capital.

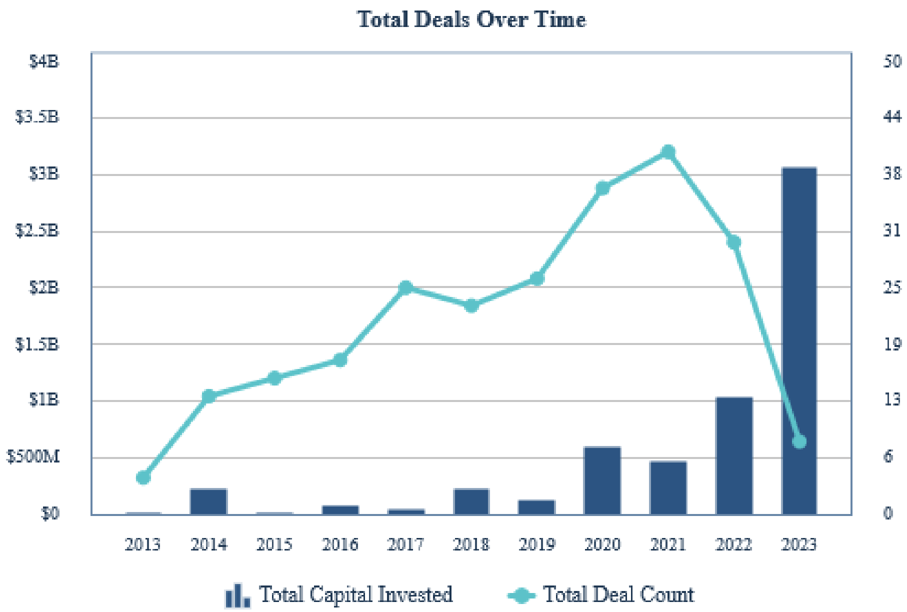
(1) points to the availability of capital to "enable or accelerate CDR research, design, development, or demonstration" (Honegger et al., 2021). These types of programs are not strictly tied to carbon abatement results. Instead, the purpose of these is to foster technology advancements and early-stage learning, but they are not suitable for funding post-pilot phase projects and, therefore, not alone sufficient for scaling CDR. The EU Innovation Fund, which aims to support commercial demonstration of innovative low-carbon technologies, is a good example of such a program.

(2) points to the availability of capital for "scaled implementation and initial operation" and could take the form of direct grants, tax credits, concessional loans, or contracts for difference. In contrast to (1), mitigation-results-oriented subsidies are typically focused on the expected or achieved tons of CO_2 removed. The purpose of these programs is to support and accelerate the cost-down trajectories of new technologies, as evidenced by similar support offered to renewable technologies (Honegger et al., 2021). The 45Q tax break is an example of such a program.

Both (1) and (2) stem from the growing government support for CDR. Appendix B includes a recent snapshot of publicly funded initiatives supporting CDR in some major markets (North America, the UK, Europe, and Japan), highlighting the increasing role public capital pools can play in this space.

Similarly, private capital pools available for CDR technologies are also growing. Pitchbook, a third-party data platform focused on private and public markets investment activity, reported (Figure 7) that almost $7bn of private capital has been invested in carbon capture technologies across ~300 transactions since 2013. It is worth noting that the 2023 data for Figure 7 is based on only four months of data and <10 megadeals representing ~$3bn in capital invested. This represents a ~200x increase in capital deployed vs. 2013 ($17m total), with eight months of the year still to go.

Figure [7]: Overview of the Capital Flowing Into Carbon Capture Technologies Between 2013-2023



Source: Pitchbook, 2023

Unlike policy, which is geared towards the outcomes described above, private capital is typically aligned to an assessment of risk associated with a technology developer or its project. Typically, these can be divided into the following categories based on the risk profile: (1) angel investors, (2) venture capital, (3) preliminary customer agreements, (4) philanthropic activity, (5) strategic partnerships / corporate investors, (6) growth and private equity, (7) public markets equity, (8) debt financing, and (9) project financing. Without going into the specific nuances of each of these types of investors, these pools have been broadly listed in order of risk appetite, with investors operating across (1) typically having the highest risk tolerance and willingness to invest earlier in a company's lifecycle (e.g., early-stage R&D) and (8) having the lowest risk tolerance, generally investing in the roll-out of established technologies. That said, there are instances where investors deploy capital beyond the risk profile typical with their stage of investing, especially in nascent and fast-growing spaces such as CDR.

Some examples of prominent private sector investors specifically operating in the CDR space include Carbon Direct Capital, Breakthrough Energy Ventures, Prelude Ventures, and Lower Carbon Capital. They invest in early-stage start-ups developing CDR technologies, preliminary customer agreements (also called advanced market commitments, i.e., AMCs) offered by organizations like Frontier, philanthropic programs such as the XPRIZE Carbon Removal and Breakthrough Energy's Catalyst Program, and corporate investors such as Oxy Low Carbon Ventures and Chevron Technology Ventures.

Justification for Inclusion

Since most CDR technologies are capital intensive, accessing appropriate funding pools to support development is pivotal to the success and maturation of the technology (e.g., to fund continued R&D, operating costs for technology developers, and development of projects). As a result, we consider capital availability a key factor in assessing the technology risk associated with a given CDR pathway.

Rating Scale

This rating scale is also qualitative and aims to score the capital pools a given technology can access. Unlike the other sliding scales, i.e., from worst to best, that have been discussed thus far, this scale is cumulative. Further, accessing public capital pools has been given higher importance in the scoring, as these can signal a positive macroeconomic and policy environment that may streamline downstream roadblocks to the technology maturing (e.g., siting, permitting, etc.).

Data to support the assessment is not as neatly centralized and must be collected across multiple and evolving sources. For example, the IEA's CCUS Policy Database is a good source of information to analyze public capital availability. Similarly, third-party platforms such as Pitchbook and Crunchbase provide a good overview of private capital pools.

Please add a point for each capital pool that can be accessed. The final score for this criterion will be the sum total of all these points, ranging from 0 to 7. This score will be normalized using the formula presented below to a scale of 0 to 5 to make this score comparable with those of other criteria.

- 0 points: No reliable public / private funding pathways - i.e., limited policy incentives and little to no private capital, such as venture capital funding, accelerator programs (e.g., The EU's EIT Climate-KIC's ClimAccelerator), etc.
- 1 point: Add 1 point for each of the two capital pools below available to fund technology development, i.e., research, design, development, or pilot demonstration, etc.
    - Access to private capital, including institutional equity or debt capital (e.g., venture capital or private equity funding, venture debt, etc.), capital from large strategic companies (e.g., Shell, Exxon, Maersk etc.), advance market commitments (e.g., Frontier), or capital from accelerator programs (e.g., the XPrize, etc.)
    - Access to public capital such as R&D activity-oriented grants or subsidies, public accelerators (e.g., The EU EIT Climate-KIC's ClimAccelator), etc.
- 2 points: Add 2 points for access to private capital (as listed above, but including project finance) to fund First-of-a-Kind (FOAK) projects and / or subsequent and / or Nth-of-a-kind (NOAK) projects
- 3 points: Add 3 points for access to public capital in the form of mitigation results-oriented subsidies (e.g., direct grants, tax credits, concessional loans or contracts for difference).

Once the total score (x_i) had been calculated, the formula below should be used to normalize this value to produce a final score (z_i) ranging from 0 to 5:

$$z_i = (\frac{x_i - min(x)}{max(x) - min(x)}) * Q$$

where, min(x) = 0, max (x) = 7, and Q = 5.

For example, a score of 5 based on the scoring above normalizes to a final score of 3.57, since $z_i = ((5 - 0)/(7 - 0)) * 5$.

Potential Limitations

While capital availability is a helpful assessment criterion, it does not necessarily take into consideration the ability of a company to successfully access the requisite financing to develop its technology or operations. There are several other factors that can influence this as well. For example, private investors will typically assess factors like product-market fit, the competitive landscape and a technology's relative positioning, its commercialization strategy, and the quality of its team before allocating capital to a given company and its technology. Similarly, public capital pools may also be contingent on additional factors; for example, to access the tax credits available to electric vehicles under the IRA, a certain percentage of the vehicle's components must have been sourced locally. In the interest of analytical parsimony, the framework does not consider these factors, though these are nonetheless important to consider in subsequent assessments of a given CDR technology.

Similarly, the framework does not consider the quantum of public and/or private capital available for deployment against a given technology. This is partly due to the nascency of many of the technologies and the high degrees of uncertainty in understanding the cumulative capital needs of any given technology of scale. It is also partly due to the significant data-access challenges that would arise if this lens was considered. Therefore, in the interest of user convenience, the assessment of capital availability is broader and less focused on this specific lens. Again, this is a potential limitation that should be kept in mind for subsequent assessments.

IV. Storage & Use Pathways

Description

While the acronym CDR explicitly refers only to 'removals,' the value of the underlying CDR technology is directly linked to the potential CO_2 storage or utilization pathways that a given removal technology can access. Unless the captured or removed CO_2 is not safely sequestered, there is a risk that it can leak into the atmospheric system and continue to contribute to climate change. The higher the number and the quality of potential storage/use pathways a CDR technology can use for the CO_2 it captures, the more attractive it is.

Justification for Inclusion

We consider the storage/use pathways available to a given CDR technology as a technology risk, though note that this can also impact the issuance of carbon credits. This is a technology risk because not all CO_2 capture technologies are created equal. There can be differences on several fronts, for example, the purity of the CO_2 stream captured and the types/concentrations of impurities, the target size and location of potential projects that could be developed using a given technology. These factors influence the types of storage/use pathways and the associated cost of storage/use a given CDR technology will be able to leverage to sequester its CO_2.

While the storage/use pathway is closely related to the durability of storage, this specific criterion focused on evaluating the likely storage/use pathways that will be available to a given CDR technology considering its inherent characteristics.

Without storage/use options that are viable (economically and technologically) and acceptable to the market, the CDR technology may face challenges on many fronts, such as (1) uncompetitive costs per tonne, (2) constrained access to capital, (3) lower market demand given perceptions about storage/use quality. This risk is both a function of the design choices of the technology developer and a function of external factors such as available storage, transport infrastructure, policy/economic incentives, geology-related constraints, and more that are outside the control of the technology developer.

Rating Scale

This is also a qualitative and relative assessment scale, where the number and quality of available storage/use pathways, as per the literature, influence the score a CDR technology receives for this criterion. Lower-scoring use pathways are less desirable since these are typically less 'durable' and typically carry reversal risk, i.e., all or some of the captured CO_2 returns to atmospheric reservoirs over time.

Score based on the following scale, which gives an additional point for each incremental storage/use pathway potentially available:

- 0: the only pathways available involve storage/use in a short-lived product (e.g., chemicals, fuels, etc.) OR terrestrial biological storage, i.e., plants, soil, etc.
- 1: non-geologic ocean storage pathways are also available
- 2: no scoring, to reflect the large gap between the lower and higher durability storage/use types
- 3: geologic storage without mineralization (e.g., in saline aquifer/sedimentary rock) pathways are available
- 4: above ground mineralization pathways available, including in long-lived products (e.g., concrete)
- 5: geologic storage and mineralization pathways available

A score of 0 means that the CO_2 captured via a specific technology can only be stored/used in short-lived products. Given the CDR taxonomy, this is an unlikely score for the technologies reviewed. A score of 5 means that the CDR technology could theoretically access geologic storage and mineralization. The assumption here is that this technology requires the highest-purity stream of CO_2, such that if this pathway is available, so will the others listed above.

Potential Limitations

This criterion may seem abstract when applied to a CDR technology rather than a specific project developed using the technology. Further, for low TRL technologies that have not been used outside laboratory settings, it might be difficult to ascertain some of the factors that are used to develop an informed view of the available storage/use pathways. Without this information, it might be challenging to determine the appropriate scoring for this criterion. That said, in such an instance, data points such as the target CO_2 concentration of the technology might be used to map it to an appropriate score.

V. Measurement, Reporting, and Verification

Description

MRV refers to the multi-step process undertaken by carbon removal technology and project developers to account for the net impacts of a project. This includes the quantification of net greenhouse gas emissions. MRV assures that the technology is effective and safe and lends credence to durability claims. Information collected and reported as part of the MRV process forms the basis for the issuance of carbon credits, although it is distinct from a registry's methodology. A methodology outlines criteria for credit issuance, although activities undertaken for MRV may go beyond the scope of the methodology, including more routine monitoring or the publication of leak detection reports. It is worth noting that MRV is also referred to as monitoring, verification, and accounting or measurement, monitoring, and verification in the literature (Monea et al., 2009; Ma et al., 2022); however, the fundamentals are the same.

Justification for Inclusion

A robust MRV process establishes a technology as a viable solution for greenhouse gas mitigation (Monea et al., 2009). The application of a mature MRV process specific to a technology also signals a high likelihood of public acceptance, which is favorable in the pursuit of credit issuance. It may also open new streams of capital. Certain technologies, such as DAC, lend themselves more easily to monitoring and verification, but others struggle, such as offshore geological injection and storage. Some enhanced weathering projects have used the EPA Class VI well requirements to build their MRV processes. Understanding unique MRV needs for each technology, and assessing the barriers to system monitoring provides critical evidence of maturity in the path toward carbon credit generation.

This criterion is a strong identifier of the risk of public acceptance. Projects with unverified claims of carbon capture and storage that is safe and effective are highly unlikely to succeed. Public reporting of MRV results builds confidence and trust with the public, which is critical, especially for novel technologies (Cox et al., 2020). The risk of low-quality MRV processes endangers a technology's social license to operate.

This is considered a technology risk since the maturity of MRV influences the ability of a technology to reach the appropriate stage of maturity to generate carbon credits. Notably, MRV builds the foundation for permanence/durability; therefore, it is also closely related to credit issuance risk. Projects with high permanence risk may be filtered out by credit issuers (and credit buyers) or may be approved, but the risk is reflected in the credit value. Primary responsibility to address this risk is likely on the project level due to the requirements of MRV programs to adequately capture technology-specific criteria.

Rating Scale

The rating scale is qualitative, and the scoring will likely be based on literature review. The scale spans from 0-3 based on the maturity of MRV processes.

- 0: no MRV processes
- 1: nascent MRV processes with none or few instances of application in relevant environments
- 2: mature MRV processes with some instances of application in relevant environments
- 3: tried and tested MRV processes with documented success

Once the total score (x_i) had been calculated, the formula below should be used to normalize this value to produce a final score (z_i) ranging from 0 to 5:

$$z_i = \left(\frac{x_i - min(x)}{max(x) - min(x)}\right) * Q$$

where, min(x) = 0, max (x) = 3, and Q = 5.

For example, a score of 2 based on the scoring above normalizes to a final score of 3.33, since $z_i = ((2-0)/(3-0)) * 5$.

Potential Limitations

Taken alone, the MRV rating is not a comprehensive indicator for technological efficacy. That is, a monitoring plan can be in place, but it is not to say there are also appropriate maintenance plans in place to address reported findings or recourse to address discovered issues such as leakage. While MRV maturity is a signal or source of risk associated with public acceptance and the relevant outcomes along the path toward credit issuance, it is not the only driver of this risk. Additionally, it is unclear how much impact the maturity of the MRV processes for CDR technologies will have on public acceptance, which is an intangible quality of the enabling environment for the development of climate change mitigation strategies in general.

VI. Carbon Registry Methodologies

Description

Carbon registry methodologies are frameworks that outline parameters and quantifications required to generate carbon credits. Each methodology is designed for a specific type(s) of carbon offset or removal and defines qualifying practices for each project. This includes establishing a baseline, monitoring requirements, and assuring that emission reductions or removals are real, verifiable, quantifiable, and additional. Those rules are used to validate GHG reductions or removals. Once a project is registered, the credits can be traded, tracked, and retired (OffsetGuide, n.d.).

Once approved by a registry, methodologies are public knowledge and can be used by other project developers to generate carbon credits. In addition to using existing methodologies, project developers can propose a new methodology or modify existing methodologies at their own cost. Various registries allow for new methodology development; however, the process can be time and resource-consuming.

Justification for Inclusion

The existence of an approved methodology to generate carbon credits is a direct path to projects' commercialization. Developing or modifying new methodologies is another crucial aspect of generating carbon credits when a project does not qualify for an approved methodology. The only way to issue and trade carbon credits is through registering projects with a carbon registry. Thus, including carbon registry methodologies is an essential criterion of the assessment framework.

While carbon registry methodologies are designed to generate accurate and trusted carbon credits, there are many associated risks. In some cases, methodologies are developed by entities determined to use them to generate credits from their own projects. Some methodology developers can tailor the frameworks to fit specific project requirements, which can result in bias and conflict of interest for methodology development. Carbon registry methodologies require independent verification. However, there is always a risk of verifiers not being fully objective and independent. Carbon projects must demonstrate permanence and additionality of removals or reductions, which can always pose a risk of over or underestimation of carbon credits.

Additionally, if a methodology needs to be developed or revised, it can take a substantial amount of time and resources, which can slow down project implementation, affect capital distribution, and in the end influence ROI. This type of risk is also included in evaluating this criterion and is accounted for in the rating scale.

Some of these risks can be mitigated by robust and established MRV practices, due diligence of methodologies, as well as enhanced verification processes from registries and the existence of "buffer pools" of issued credits.

Rating Scale

This qualitative assessment scale is based on research on carbon registry methodologies and projects associated with those methodologies to generate carbon credits.

- 0: no approved methodology and none under development
- 1: no approved methodology, but one or more under development

- 2: no approved methodology, but one or more are available for public review
- 3: one or more approved methodology but no registered projects (others may/may not be under development)
- 4: one or more approved and/or under development methodology with registered projects
- 5: multiple approved methodologies across different registries and approved projects

Potential Limitations

While there are existing methodologies for CDR technologies covered in this project, carbon registry methodologies alone are not enough to ensure a CDR technology potency and commercialization success. Different registries and methodologies can have different approaches to the same CDR technology type, verification practices, and accounting methods. To this date, there is a limited number of registered technological CDR projects as this is an emerging and developing industry.

VII. Additionality

Description

Additionality is a concept to ensure that CDR removes CO_2 from the atmosphere that wouldn't have otherwise been removed without the financial incentive provided by carbon credits. This is particularly relevant for many nature-based carbon sequestration projects, which need to prove the activities related to reducing deforestation or degradation would not have taken place without carbon finance.

Additionality is relevant for CDR technologies because in some cases there are alternative uses for biochar, compressed carbon, and other products of carbon removal processes. For example, biochar can be sold as a soil amendment, and types of DAC that create building materials, such as concrete, have other revenue-generating uses. For a credit to be issued, it needs to be proved that the process would not have taken place without financing for the production of a carbon credit.

Justification for Inclusion

Additionality is important to evaluate at the project level, but also has some correlation with the CDR technology used. For example, biochar inherently has a by-product that has valuable agricultural uses and therefore a financial market. This criteria can provide a basis for highlighting what CDR technologies will be easier or more difficult to prove additional. Since additionality was frequently listed as a requirement for registries, it is relevant to evaluate.

The main risk around additionality is reputational risk. If carbon removal credits are found to not have been additional, this will expose the credit issuer to greenwashing claims and negative press.

Non-additional CDR will not result in any impact on climate change, so this risk of supporting non-additional CDR technologies is diversion of climate funding to initiatives that will not actually impact the climate.

Rating Scale

Many registries require that projects be additional. Therefore, the following rating scale is based on a score of 0 (not additional) to 5 (very likely additional). To calculate the score, a series of questions around financial additionality and incentives will be asked.

- Does this technology have a use case outside of CO_2 sequestration?
    - If yes - 0 points
    - If no - 1 point
- Is this technology financially viable and attractive without carbon credit revenues?
    - If yes - 0 points
    - If no - 1 point
- Are there byproducts of this technology that have possible revenue-generating uses? For example, concrete, soil amendment, etc.
    - If yes - 0 points
    - If no - 1 point

- Are there current or proposed regulations in other jurisdictions that mandate the use of this technology? For example, methane capture at waste processing facilities.
    - If yes - 0 points
    - If no - 1 point
- Are there current or proposed incentives that fully cover the cost of this technology? For example, as part of the IRA or other tax rebates.
    - If yes - 0 points
    - If no - 1 point

Take the sum of all points.

- 0: Not additional
- 1: Likely not additional
- 2: May be additional
- 3: Likely additional
- 4: Very likely additional
- 5: Additional

Potential Limitations

This process is a highly rough approach for considering additionality. However, it should prompt the type of due diligence necessary to evaluate additionality and highlight its nuance. One interviewee mentioned that with a single revenue stream, DAC is absolutely additional, but acknowledged that it gets more complicated with multiple revenue streams (M. Avery, personal communication, April 10, 2023). While typically thought of as binary (additional or not additional), it is helpful to think of additionality more as a sliding scale. For example, when solar was substantially more expensive than natural gas, it was considered additional. As the price of solar has dropped and with the help of government incentives, solar is now not considered additional in most circumstances due to its financial viability.

VIII. Durability

Description

The 'durability' of CO_2 storage refers to the varying ability of the stored/used CO_2 or the material it is stored in to withstand pressure or wear and tear that may result in the CO_2 eventually escaping or 'leaking' back into the atmosphere or other ecosystems. The more secure the CO_2 storage, the lower the risk that some or all of it leaks back into the atmosphere over a given period of time. Storage 'permanence' is a related concept and refers to the ability of alternative CDR pathways to safely and securely store CO_2 over different timescales, ranging from a few weeks to 100+ years. The duration of CO_2 storage outside the atmosphere directly impacts the climate benefit of CDR, as the benefit of these technologies lies not only in the volume of CO_2 removed but also in how long the CO_2 is prevented from returning to the atmosphere (Wilcox et al., 2021). In summary, the more durably CO_2 is stored and the longer the time horizon over which it is stored, the higher the quality of the CDR solution.

For the technologies in scope, the durability of the pathway is driven by the storage/use solution that the removal technology is paired with. For example, CO_2 storage in biological systems (e.g., soil ecosystems, oceans) is generally over shorter horizons and is far less durable than geologic storage or mineralization. This reflects in the high price that market participants are willing to pay for more durable pathways; for instance, one of the interviewees the team spoke to developing CDR storage technology noted that buyers are willing to pay up to $1,000 per tonne for CO_2 captured via DAC and stored via mineralization (C. Nelson, personal communication, March 8, 2023).

Eventually, this may also result in a higher relative market demand for these types of credits, especially from the quality-focused corporate segment of the voluntary carbon market. This may influence how the registries prioritize developing methodologies, with higher-durability methodologies being developed before lower-durability ones.

That said, not all shorter-term or less durable storage is bad. Given the time value of carbon and the cost associated with higher durability and permanence storage/use pathways, Hoglund (2022) argues that there is a role for less durable (to an extent) storage routes to play. Assuming that the cost of durable storage falls in the future, it is arguably more valuable to store the carbon today and replace the expiring storage in the future when prices are lower. While scientifically and economically, this is an interesting argument; it is uncertain how this will reflect in the methodologies registries develop. In fact, given some of the scrutiny about methodologies in recent years (Greenfield, 2023; Take, 2022; Shifflett, 2022), we suspect registries may have a low appetite to engage with unconventional approaches such as this.

Justification for Inclusion

Durability is a key factor carbon registries use in developing methodologies, based on which CDR projects are assessed, and carbon credits are issued, especially for carbon removal credits (Streck et al., 2021). Therefore, there is some degree of overlap between this criterion and criterion VI (Registry Methodology). However, given the nascency of the CDR space and the low number of technologies with established methodologies, this criterion allows this framework to avoid penalizing technologies that may have high durability but still need an established methodology.

Low durability poses a risk not only to the issuance of the carbon credit but also to the value of the carbon credit. This risk would likely be addressed by the technology developer, who has some agency over some factors that influence the permanence linked to the CO_2 the technology captures. However, there are several other factors that influence durability.

Rating Scale

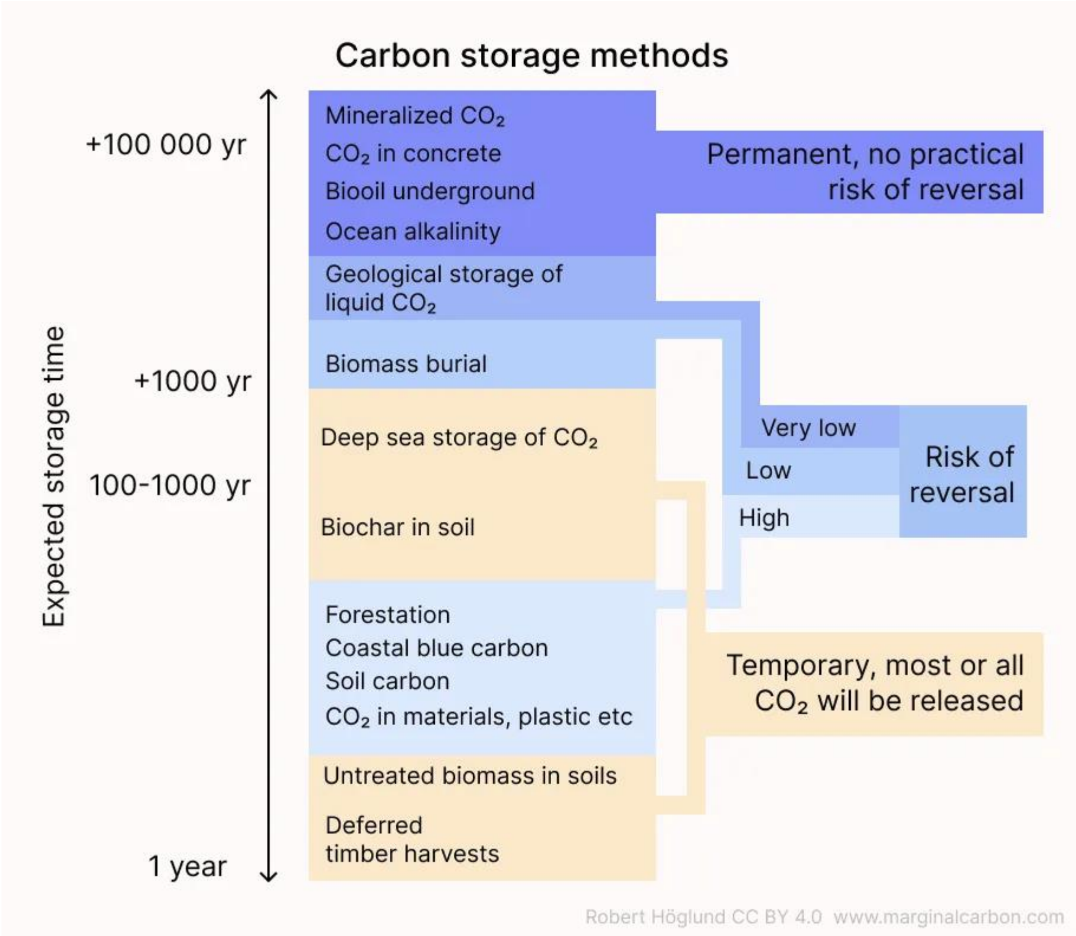
This is a qualitative rating scale based on storage durability, as presented in the figure below from Hoglund, 2022. The scoring is built on the risk of reversal, which captures the expected likelihood that some or all of the captured CO_2 will release back into atmospheric reservoirs over time.

Map the storage/use solution to the risk of reversal below and score based on the following:

- 0: Temporary storage, high risk that most or all CO_2e will be released from storage
- 1: High risk of reversal and no strategy to either “replace” expiring storage or manage leakage (e.g., buffer pools, insurance, etc.)
- 2: High risk of reversal but has a strategy to “replace” expiring storage and risk mitigation in place to manage leakage
- 3: No scoring, to reflect the strong divide between technologies with high and low to no risk of reversal
- 4: Low to very low risk of reversal
- 5: Permanent with no practical risk of reversal

A score of 0 means that the CO_2 captured via a specific technology will remain out of the atmosphere for a short duration and is not durable, as is the case with some of the less sophisticated nature-based approaches. A score of 5 means that the CDR technology could theoretically durably sequester CO_2 over a millennium time frame with a low risk of reversal, keeping it out of the atmosphere where it risks causing warming and other effects.

Figure [7]: Map of Storage Durability and Permanence



Source: Taken from Hoglund, 2022

Potential Limitations

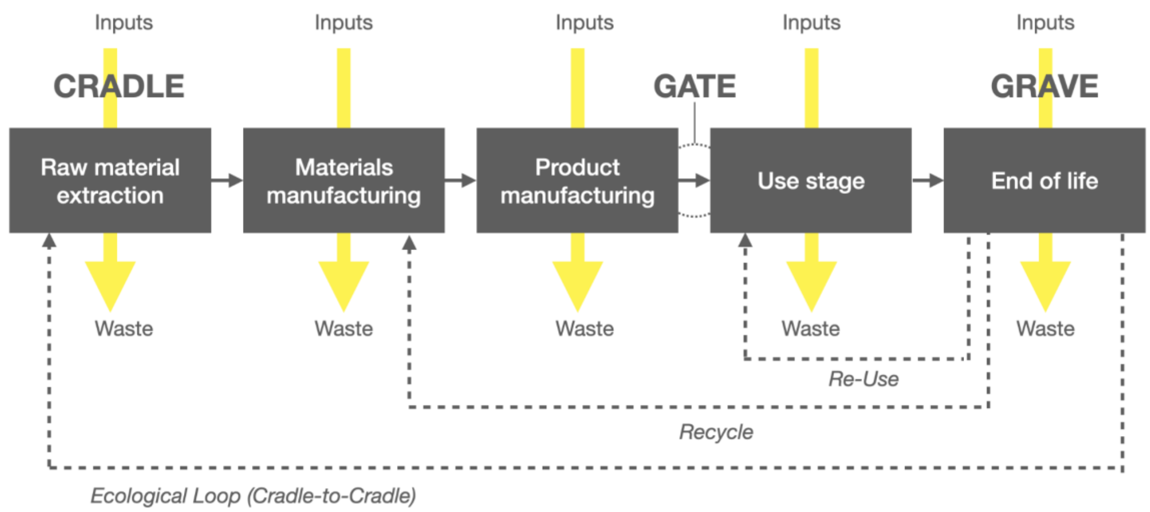
As with one of the limitations associated with criterion IV (Storage/Use Pathways), when applied to a CDR technology rather than a specific project developed using the technology, this criterion may seem abstract. However, the suggestion for overcoming this challenge is similar to that for criterion IV (i.e., determine the target CO_2 concentration of the technology, map that to the potential storage pathways, and map these to the appropriate durability score).

IX. Life Cycle Impact

Description

LCA is a systematic analysis to quantify the potential environmental impacts of a product or process, considering all stages from raw materials extraction to end of life. LCA methods are defined by the International Organization for Standardization (ISO) 14040 series (ISO 2006a; ISO 2006b). Performing an LCA involves the identification of a functional unit or a basis of normalization to report results against, drawing a boundary, which defines what steps in the life cycle are included, and allocating all activities within the boundary to determine the impacts. The ISO 14040 series outlines which LCA impacts should be measured and reported. Typical LCA impacts reported include global warming potential, eutrophication potential, resource consumption, and ozone layer depletion, among others.

Figure [8]: Lifecycle Stages Captured in LCA



Source: Capstone Team's Schematic

Justification for Inclusion

An emerging carbon removal technology's potential is directly related to its ability to sequester carbon in a way that is as close to "net zero" emissions as possible. That is, the global warming potential impact of the life cycle operations of a technology should, at the very least, not be greater than the quantity of CO_2 emissions captured. Assessing which technologies can remove the most carbon from the atmosphere while minimizing the release of emissions through the life cycle is an important criterion of consideration. Mendoza et al. 2022 argue that LCAs of CCUS technologies help account for the value of a technology in the marketplace and are an indicator of competitiveness (i.e., worthiness of credit generation). Additionally, LCA measures other environmental impact indicators beyond global warming potential, which allows for assessing potential tradeoffs.

Reporting the results of a "full" or "net" LCA of GHG emissions is recommended in the literature (National Academies of Sciences, Engineering, and Medicine, 2019) with a preference toward following the ISO 14040 series (Mendoza et al. 2022; U.S. DOE, 2022). Carbon credit methodology developers and carbon removal and storage project developers also use LCA to evaluate technologies. In an interview with the President of one of the largest DAC projects in the world, it was also noted that buyers of credits desire full LCAs of projects and see them as an indicator of integrity.

Additionally, in 2022 Puro.earth released its biochar methodology, which dictates that "the producer must demonstrate net-negativity with results from [LCA] or carbon footprint" (Puro.earth, 2022). DAC and underground storage companies Climeworks and Carbfix have published the full LCA results of their technologies on the basis of 1 mass unit of CO_2 captured or captured and stored (Deutz, S., & Bardow, A., 2021; Terlouw et al., 2021).

This criterion indicates the ability to generate carbon credits for two primary reasons: LCA may be a barrier to entry for some registries, and the LCA results may inform the credit generation's financial viability. To the first point, the carbon credit registries are likely to be the ones to define LCA as a requirement of CDR technology methodologies. This is already being observed, as per the Puro.earth biochar standard mentioned above. Secondly, performing an LCA will give the technology developer a sense of the financial return a carbon credit will provide. An LCA closer to net negative provides the greatest return (i.e., the most carbon is captured with the least emissions output in the process will result in more credits or more expensive credits generated). There may be a point of diminishing returns that is a risk to pursuing the generation of credits.

Rating Scale

There are two risks associated with LCA that should be reflected in a rating scale: how developed the LCA is and how good the results of the LCA are. Because of the lack of standardized LCA rules for CDR technologies (for example, a Product Category Rule), the latter risk is challenging to capture in a rated scale. As the practice of performing CDR LCAs develops, this scale may need to be adjusted to reflect global warming potential barriers at each level, similar to what was done for the cost indicator. For now, the following levels are defined:

- 0: no LCA has been performed

- 1: an LCA has been performed, but with a limited scope (i.e., some exclusions of inputs or stages of the full life cycle, for example, without the modeling of end-use pathways); the majority of data may or may not be primary
- 2: an LCA has been performed but with a limited scope (i.e., some exclusions of inputs or stages of the full life cycle and the majority of data is primary)
- 3: an LCA has been performed without exclusions, and the majority of data is primary; a publicly available LCA report with documentation of data sources, assumptions, and results has been published
- 4: an LCA has been performed without exclusions, the majority of data is primary, and the LCA followed an ISO-based procedure defined by a publicly available source (for example, a Product Category Rule); a publicly available LCA report with documentation of data sources, assumptions, and results has been published
- 5: an LCA has been performed without exclusions, the majority of data is primary, the LCA followed an ISO-based procedure defined by a publicly available source (for example, a Product Category Rule), and the results of the LCA reveal a lower global warming potential than some pre-defined baseline or industry average; a publicly available LCA report with documentation of data sources, assumptions, and results has been published

It's worth noting that primary data refers to data collected based on the performance of the technology at the present time at its current technological stage. Primary data could refer to measured data from pilot scale operations or in situ scaled-up testing. Data collection at all stages of the technology scale is important to assess environmental impacts and reflects the risks associated with a technology as it is today. Forecasting LCA impacts based on assumed operating conditions at scale should not be used where possible. If this is the only available data (i.e., no pilot scale operations have taken place), then the technology will not be able to score higher than a 1. Lastly, "majority" as it relates to primary data means that all inputs that could be reasonably filled with collected/measured data are used. This is up to the opinion of the LCA practitioner.

Potential Limitations

The calculation of LCA impacts may be challenging for nascent technologies, specifically for the LCA stages, which fall outside the company's operational control. Some resources already exist to support this work, including the AssessCCUS platform from the Global CO_2 Initiative, which hosts resources for the life cycle and techno-economic assessment of CCUS technologies. The U.S. Department of Energy has also published best practice guidelines for performing LCAs on DACS systems (U.S. DOE, 2022).

A "full" LCA may also be called cradle-to-grave, although what exactly is encompassed within each stage may differ for each technology or product being evaluated. To avoid confusion, program operators develop product category rules to standardize how LCAs are conducted. Program operators include UL, EPD International, EPD North America, and ASTM. Currently, there are no product category rules for carbon removal technologies. Therefore, it is likely that different methodologies or funding bodies will prescribe their own methods and boundaries, usually based on the ISO 14040 series. This could create confusion when comparing different technologies. All assumptions made when conducting the LCA should be transparently disclosed. Carbonplan's CDR Verification Framework provides a useful tool for visualizing the system boundaries of different CDR technologies and could be a helpful resource for developing LCAs or their underlying rules.

X. Environmental and Social Impacts

Description

Environmental impacts describe potential harm to the environment, natural ecosystems, biodiversity, and wildlife habitat. Social impacts refer to possible community threats, which can result in human rights violations, inequity, economic, health, and other consequences.

Justification for Inclusion

While evaluating each CDR technology, it is important to consider the environmental and social impacts of each solution. Buyers often assess environmental and social impacts to limit potential liability and/or maximize the economic value of their investment (Environmental Defense Fund et al., 2015).

To fully understand CDR technology impacts, environmental and social considerations during technology development, deployment, implementation, and operations need to be evaluated. Land use, energy intensity and sources, air, water, and noise pollution, soil quality, upstream and downstream activities, community health, safety, well-being, and employment opportunities are among some of the criteria that should be considered to assess each CDR technology. Some of these criteria can be technology and/or project-specific and need to be further evaluated on a project-by-project basis.

This criterion focuses exclusively on evaluating risks. However, it's strongly recommended to engage local communities, ensure living wage compensation, promote economic opportunities, and other benefits in each project. The "criteria for high-quality carbon dioxide removal" developed by Carbon Direct and Microsoft can be a valuable resource to evaluate environmental justice and other principles of CDR technologies and projects. From a consumer perspective, co-benefits such as community involvement, biodiversity, support of low-income populations, and other factors can be prioritized and evaluated on a project-level basis.

Because of the relative novelty of the carbon removal credits space and the subjective nature of determining environmental and social impacts, uncertainties are included in evaluating this framework criterion. As the industry continues to develop, more identifications and eventual outcomes of CDR technologies will be available. In turn, as more data is collected, the uncertainty level of environmental and social impacts will be less prominent.

Additionally, beyond GHG reductions, some carbon registry methodologies include environmental and social risk guidelines, such as the C-Capsule methodology on distributed biochar production (Clarke, 2023). They are usually evaluated at a project level; however, it is worth considering potential impacts from a technology perspective, as some CDR solutions can pose more or less risk to the environment and communities.

Environmental and social impacts can pose immediate risks to ecosystems and communities, and the environment as a whole. They can result in biodiversity loss, hazards that affect air, water, and soil quality, increased inequality and poverty levels, and other consequences. These risks are not limited to local parameters but can also apply to downstream activities like resource extraction and associated community impacts.

Adverse environmental and social consequences can affect multiple parties, such as technology developers, registries, and project developers. Reputational damage also carries over to buyers who support these types of technologies and projects.

Rating Scale

The rating scale represents the severity of a CDR technology's impacts on the environment, natural ecosystems, local communities, and their well-being in combination with the uncertainty level of each risk. This criterion is evaluated on a scale from 0 to 5, with 0 being the most significant impact and 5 being the least significant impact, as shown in the table below.

The scale provides some examples that help benchmark associated environmental and social outcomes. This criterion can be evaluated alongside LCA as it helps capture all relevant activities involved in each CDR technology.

- *Catastrophic Risk:* This category describes environmental and/or social risks associated with CDR technology that may have irreversible or long-lasting impacts on the environment and people. For example, the technology may involve the release of large amounts of toxic pollutants, long-lasting soil, and water contamination, or have significant impacts on climate or global ecosystems. The technology may also have extreme social impacts, such as forced displacement or health hazards. These types of risks are impossible or very costly to prevent and minimize.

- *Critical Risk:* This category describes environmental and/or social risks associated with the CDR technology that may have drastic impacts on human health, ecosystems, or communities. For example, the technology may involve the use of hazardous materials at any point during downstream or upstream activities, or it may have long-lasting impacts on ecosystems, biodiversity, and people. The technology may also have significant social impacts, such as displacement of indigenous communities or violations of human rights. These types of risks are very hard to impossible to mitigate and may require a substantial amount of time and resources.
- *Major Risk:* This category describes environmental and/or social risks associated with the CDR technology that may be difficult to manage or mitigate. For example, the technology may involve large-scale land use changes or negatively impact biodiversity. Or the technology may be energy intensive, which could result in extensive GHG emissions. These risks can be minimized by utilizing renewable energy sources, but they can be costly and time-consuming to implement. Social impacts such as job displacement, economic disruption, or resource reallocation from local populations may be difficult to address through traditional mitigation measures.
- *Moderate Risk:* This category describes moderate environmental and/or social risks associated with the CDR technology, but these risks can be managed and mitigated with appropriate measures. For example, the technology may require the use of certain chemicals or materials that pose low environmental risks if properly managed, or it may have minor social impacts that can be addressed through stakeholder engagement or community outreach. These risks can be mitigated with proper management and resources.
- *Negligible Risk:* This category describes insignificant environmental and/or social risks associated with this CDR technology. This means that the technology should have no negative impact on ecosystems, biodiversity, natural resources, or human health. It also implies that the technology does not contribute to social inequality, human rights violations, or other social risks during upstream and downstream activities.

The uncertainty level represents a combination of track records, previously acquired knowledge, literature review, and/or potential outcomes from a CDR technology implementation.

To determine a proper rating scale from 0 to 5, social and environmental impacts need to be cumulatively assessed to match the severity scale of a CDR technology's impacts. Once the impacts' severity is determined, uncertainty levels of those impacts need to be evaluated (i.e., how likely is it that those impacts will occur?). For example, some technologies use highly toxic metals that can contaminate groundwater and soil, but the technology is designed to mitigate this type of risk. Thus, based on a combination of severity and uncertainty factors, social and environmental impacts can be evaluated using the table below.

Risk of Negative Environmental and/or Social Impacts

		Uncertainty			
		Unlikely	Possible	Likely	Almost certain
Severity	Negligible	5 - Insignificant	5 - Insignificant	5 - Insignificant	5 - Insignificant
	Moderate	4 - Low	4 - Low	3 - Medium	2 - High
	Major	4 - Low	3 - Medium	2 - High	1 - Very high
	Critical	3 - Medium	2 - High	1 - Very high	0 - Significant
	Catastrophic	2 - High	1 - Very high	0 - Significant	0 - Significant

Potential Limitations

This approach focuses on evaluating the cumulative social and environmental impact from a technological perspective. To determine more specific risks and outcomes, each

CDR project must be assessed individually, considering location, required resources, communities affected, and other factors. Some technologies may pose hundreds of social and environmental risks that may be difficult to assess cumulatively. This criterion can be too broad to estimate real impacts; however, it remains a valuable part of this framework, especially as more buyers consider this criterion.

The complexity of these risks is another limitation since their assessment often entails subjective interpretations and judgments. The objectivity of evaluating these risks can be biased or incomplete as there is no universally accepted standard to assess environmental and social risks. The uncertainty factors such as natural disasters or social unrest should also be considered. However, they can be difficult to predict, especially when evaluating CDR types from a technological standpoint.

Perhaps, one of the most important limitations is limited data availability. For some technologies, such as DAC, there is simply not enough data to accurately assess and measure short and long-term impacts. Assessment of these risks can be incomplete and inconsistent since there is a limited number of projects for some CDR types, and some technologies are relatively new to develop a comprehensive understanding of associated environmental and social impacts.

Limitations and Interdependencies of the Framework

The framework criteria are not mutually exclusive or exhaustive. This limitation can be grouped into three categories: inter-dependencies within the framework, technology-specific factors that constrain criteria within the framework, and other relevant factors that shape the enabling environment. It is important to understand how the framework functions within the decision-making ecosystem, its limitations, and its relationships with other criteria as technologies are scaled.

First, inter-dependencies exist between criteria within the framework. For example, LCA is related to some extent to cost. Minimizing energy input also lowers costs. Second, there may be cases in which technology-specific constraints outside the framework's scope influence the assessed criteria. For example, enhanced weathering has geographical constraints that may have implications for market friendliness or access to clean energy. While location is not assessed within the framework, the influence of this choice is represented in the framework as other criteria, such as capital availability and LCA.

Third, there may be cases in which other factors relevant to users of the framework are not identified in or necessarily influenced by the framework. These factors define the enabling environment within the technology development and credit generation ecosystem and cannot be influenced by specific projects, therefore were excluded from the framework. For example, an uncontrolled factor to consider may include the timeline to issue carbon credits, including the credit issuer's timeline for credit pay-out and registry backlog. A controlled factor may be a project developer's limitations on technologies to engage with.

It is also important to note that the inputs to this framework will all be self-reported by the framework user. Therefore, there are inherent risks associated with data quality that should be kept in mind when interpreting the results. It is also critical to re-emphasize the fact that this framework only assesses technologies and does not assess projects. Important variables like the policy environment, location, and transport infrastructure also influence risk. Since these are only captured at the project level, leaving them from the framework means there are elements of risk it is not able to address.

PART 5. CASE STUDY - CARBON TO STONE

Carbon to Stone is a CO_2 removal and storage startup that combines DAC with mineralization to create carbonates that can be used in building materials. The technology is included in Frontier's portfolio of CDR technologies available for advanced market commitments. The Carbon Dioxide Removal Purchase Application from Fall 2022, available in a publicly available GitHub folder, and the company's website were used to perform the analysis.

Naming based on taxonomy: DAC + Mineralization

Carbon to Stone uses liquid DAC to capture carbon dioxide and mineralization to store the carbon dioxide in cement.

Assessment Overview

Carbon to Stone was assessed against each of the ten criteria developed for the framework, each weighted equally (i.e., with a weight of 1). The results are summarized in the table that follows.

Assessment Summary

Risk	Criteria	Score	Rationale
Technology Maturity **(2.5 score)**	Technology Readiness Level	2	Carbon to Stone lists its TRL as 4, which correlates with a 2 on the rating scale.
	Cost	0	No pilot operations at present though the levelized price of CO_2 sold to Frontier is priced at ~$393/t$CO_2$; target costs of $83-126/t$CO_2$.
	Capital Availability	5	Access to public and private capital pools (e.g., Frontier AMC, 45Q eligibility).
	Storage & Use Pathways	4	Planned storage in solid Ca- and Mg-bearing carbonates, potentially for use in construction materials
	Measurement, Reporting, and Verification	1.67	Nascent MRV processes with none or few instances of application in relevant environments, only in laboratory setting.
Credit Issuance Maturity **(3.2 score)**	Carbon Registry Methodologies	3	There are several approved methodologies among several registries for DAC projects; however, no DAC projects are currently registered under either carbon registry.
	Additionality	4	Carbon to Stone could store carbon in cement and generate revenues from this secondary product
	Durability	5	Carbonate minerals are very stable over long time frames, provided they are not heated or put in very acidic environments. While the application includes several storage routes with varying durabilities, the underlying process is durable enough to reward a 5.
	Life Cycle Impact	1	An LCA has been performed, but the scope is unclear, and the quality of data (primary or non-primary at the pre-pilot stage) is not explicit.
	Environmental and Social Impacts	3	The project states that heavy and toxic metals such as chromium, manganese, and nickel can be released into drinking water supplies and soil. The project aims to mitigate this risk by locking these metals into the solid carbonate matrix.

Score Summary Matrix

Figure [9]: Summary of the Excel Output Scoring Carbon to Stone

CDR Technology Assessment Framework

CDR Technology Name: Carbon to Stone

<< input the name of the technology assessed here

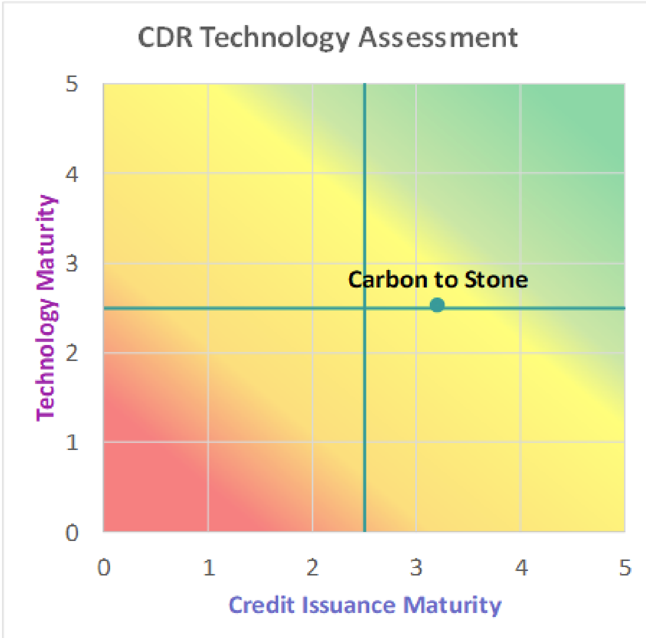
		Assessment Criteria	Rating Scale	Raw Score	Normalized Score	Weight
Technology Risk	1	Technology Readiness Level	0 to 5	2	2.00	1
	2	Cost per ton	0 to 5	0	0.00	1
	3	Capital Availability	0 to 7	7	5.00	1
	4	Storage / Use	0 to 5	4	4.00	1
	5	Measurement, Reporting and Verification	0 to 3	1	1.67	1
Credit Issuance Risk	6	Carbon Registry Methodologies	0 to 5	3	3.00	1
	7	Additionality	0 to 5	4	4.00	1
	8	Durability	0 to 5	5	5.00	1
	9	Lifecycle Analysis	0 to 5	1	1.00	1
	10	Environmental and Social Impacts	0 to 5	3	3.00	1

Total Technology Maturity Score	2.53
Total Credit Issuance Maturity Score	3.20

Cumulative scores will be auto-caluclated here and plotted on the matrix

Input raw scores here - use report for guidance on scoring

Input weights (if any) here - default weight is 1 for all criteria



Source: Capstone Team's Excel Tool

Assessment Explained

Carbon to Stone's technology is only at laboratory scale. At the time of their application (Fall 2022), they had only stored 2 kg of carbon with their technology. The laboratory scale is considered a TRL of 4 (which Carbon to Stone self-identified as in their application). That correlates to a **TRL** score of 2 in this framework.

Given that this is an incipient technology, certain parts of their application were underdeveloped relative to what the framework designates as industry standards. For instance, its two lowest scores were in **cost per ton** and **LCA**, where it scored 0 and 1, respectively. Carbon to Stone's application did not provide a current estimate for cost per ton – it only contained a forecast for future cost. This framework assesses all criteria in the present, so the lack of data caused Carbon to Stone to score a 0 on cost per ton. Carbon to Stone was likely capable of producing an estimate of the current cost, but it was not explicitly asked for in the Frontier application. In this instance, the lack of data harmed their score. Similarly, their LCA was underdeveloped, possibly because it is a laboratory-scale project. The scope of the LCA was unclear and limited. Carbon to Stone could likely provide clarity on aspects of their LCA, but the data was not available at the time of evaluation.

Carbon to Stone also did not have a well-developed **MRV** process. The process relies primarily on self-published academic articles based on laboratory-scale experiments and data with many assumptions. A better-developed MRV that addresses the scale the project hopes to achieve would be better, but MRV received a raw score of 1, which translated to a normalized score of 1.6 because of this nascency.

Carbon to Stone scored well on storage and use pathways (4), additionality (4), and durability (5). For **additionality**, DAC+mineralization scored "no" on four out of five questions (Does this technology have a use case outside of CO_2 sequestration? Is this technology financially viable and attractive without carbon credit revenues? Are there regulations in other jurisdictions that mandate the use of this technology? Are there incentives that fully cover the cost of this technology?). Each answer of "no" scored a point. The only question it scored a "yes" on was about byproducts with use cases, which mineralization has. With a score of 4 in additionality, this technology is listed as “very likely additional.” To that end, one of the main use cases of mineralized carbon is inside construction materials. This is a viable pathway that is already commonplace. Because of this use pathway and the highly durable storage of mineralization, this project scored a 4 in **storage and use pathways** for, “above ground mineralization pathways available, including in long-lived products (e.g., concrete).”

The storage mechanism is very safe - unlike their silicate counterparts, carbonate minerals do not involve CO_2 in the chemical reaction as they weather. That is to say, when a silicate mineral weathers, it stores CO_2. When a carbonate mineral weathers, it does not release that CO_2. The carbon is only released if the carbonate minerals are in a highly acidic environment (pH below 2) or the minerals are heated above several hundred degrees Celsius, both unlikely scenarios for most storage mechanisms or uses. Thus, Carbon to Stone earns a 5 in **durability** for being permanent with no practical risk of reversal.

The fact that Carbon to Stone’s pre-pilot stage technology was funded by Frontier (a funding mechanism supported by Alphabet, Meta, and McKinsey, among others) is an example of its promising potential for capital. This technology is eligible for and plans to acquire tax credits via the Section 45Q Tax Credit for Carbon Sequestration. Its availability of public and private funding and tax incentives earns it 5 points for **capital availability**. This tracks as other major DAC projects are being launched, such as 1PointFive, which has secured pre-purchase of removal of 400,000 tons of CO_2 from Airbus (Oxy, 2022).

Another sign of the viability of DAC is the fact that there are published **methodologies** for DAC in major registries, but none are currently generating projects. This will change soon, as DAC is a technology that is seeing a good deal of funding (as noted in capital availability). This earns it a score of 3.

Among the lines of evidence considered for **environmental and social impacts** is the materials used and generated in the process of using the technology. For instance, does the technology use or emit persistent organic pollutants as defined by the Stockholm Convention? Are chemicals present on-site that can create health risks? Does the technology use water, and does that use come with the potential for contamination?

This technology utilizes alkaline wastes which are rich in heavy metals. These would otherwise be landfilled, causing harm to human health. The technology aims to lock these heavy metals into carbonate matrices, a safer alternative than would otherwise happen. This earns it a score of 3, as an event of major severity is possible. The data acquired for this case study self-reported their main risks, but it will be a challenge to know the risks of newer and less-known technologies and apply them to the scoring matrix.

Overall, Carbon to Stone's scores of **2.5 for technological maturity** and **3.2 for credit issuance maturity** align with our expectations for a technology belonging to the DAC+S family. However, this particular company's technology, however, is not as well-developed as some of its counterparts. The funding provided by Frontier is meant to give technologies the ability to move quickly through developmental stages and become projects that can safely and effectively remove carbon from the atmosphere. This technology currently has middling scores on the framework but may score much higher.

A good test for this framework would be to apply it to technologies at several stages of development as they mature both from a technological perspective and a credit issuance perspective. This could lead to understanding certain thresholds above which a technology may be a good enough candidate for creating carbon credits.

Learnings from the Case Study

Overall, the case study provides a good litmus test for the framework. The positioning of the technology in the yellow band in Figure 9 (medium technology risk and medium credit issuance risk) aligns with the reality of the development of liquid DAC + enhanced weathering technologies. Both are more mature than other CDR technologies, and Carbon to Stone was ranked within a range that is "feasible to pursue" but has limitations, primarily due to the nascency of the project (inhibiting cost and LCA scoring, in particular).

Most of the criteria were simple to assign a score following the framework's guidance. The fact that Fronter's application asks for many of the pieces of information needed to use the framework is a good sign that much of this information will become available as projects continue to develop. The primary challenge was the evaluation of environmental and social impacts. Besides what Carbon to Stone disclosed as a risk, the team was limited in understanding other technology-specific risks that might be relevant. This is likely to be less of a problem for other framework users who will be more familiar with the technology types or would have more access to resources to identify the risks, such as discussions with project developers.

In future studies, the framework could be tested against a wide range of different technology types to ensure alignment with reality. While it would be useful to also run historical data to see how technologies performed and how they were rated using the framework, the CDR space is so new that this likely does not exist. Instead, running the assessment framework multiple times with the same technology along its development cycle would be interesting to determine if the framework adequately reflects maturity. Lastly, it would be a good exercise to feed the assessment framework a set of slightly different technology types (sub-sets of one technology type) to test its sensitivity.

CONCLUSION

Given the pace of emissions reductions and removals needed to keep global warming limited to 1.5°C, demand for CDR technologies is expanding rapidly, particularly in the VCM. The nascency of CDR means it is challenging to name and compare technologies to prioritize rapid development while mitigating risk.

This report provides a proposed naming taxonomy for CDR technologies and explains the development of an assessment framework to evaluate readiness to generate carbon credits against ten risk criteria. The team developed assessment criteria that pose risks to either the technology development process or the credit issuance process. Next, we proposed granular scoring scales for each criterion, building on academic and industry literature and interviews with select industry participants. The guiding principle in developing scoring scales was usability and ease of scoring and had, as far as possible, included guidance on where and how to approach the data required to assess each criterion. Finally, we developed an algorithm to aggregate scores for the five technology risk criteria and the five credit issuance risk criteria and map these to a matrix to help visualize the relative balance of technology and credit issuance risk. This work was summarized in an Excel-based tool, which facilitates easy scoring, aggregation, and visualization of the scores.

The naming taxonomy and the assessment framework were tested using a case study of a nascent company developing DAC + mineralization technology. Both the taxonomy and the assessment framework had limited user friction. The results of the assessment aligned with general expectations of this technology's maturity and sources of risk as they stand today. It's recommended to test the taxonomy and framework on a range of different technologies across different maturity levels. This can help reveal further sensitivities and/or biases in the framework.

APPENDICES

APPENDIX A

Technology Readiness Level category buckets for framework scoring

TRL	Framework scoring	Identifiers for framework scoring	Description*	Threshold exit criteria*
1	1	Technology is in "concept phase". The concept is being researched and is identified to be feasible and beneficial in a specific application.	Technology Research – Basic principles observed and reported	Peer reviewed publication of research underlying the proposed concept/application.
2			Technology Concept – Concept and/or application formulated	Documented description of the application/concept that addresses feasibility and benefit.
3	2	Technology is in "exploration mode", with experiments and testing in a lab-scale environment.	Proof of Concept – Analytical and experimental critical function and/or characteristic proof-of-concept	Documented analytical/experimental results validating predictions of key parameters.
4			Technology Demonstration – Generic design demonstrating concept-enabling performance consistent with potential applications	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	3	Technology is in "prototype mode" and a system design is developed or complete. Results of testing are in agreement with analytical	Conceptual Design and Prototype Demonstration – Performance requirements, definition of relevant environments and conceptual design complete – Performance, permance/durability "robustness"	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling

		predictions and there is documented thought put toward scaling requirements.	in critical environments validated by analysis – Components and subassemblies with new technology or moderate to significant engineering development validated in newly developed areas using stand-alone subassembly-level prototypes of approximate size, mass, and power and built with parts and materials tested in a laboratory environment at extremes of conditions (if relevant)	requirements.
6			Preliminary Design and Prototype Validation – Preliminary system design complete – Multiple assemblies or subassemblies incorporating new technology or moderate to significant engineering development validated in newly developed areas using engineering models (integrated form, fit, function prototypes) of the correct size, mass, and power, built with parts and materials tested in a laboratory environment over the range of expected conditions	Documented test performance demonstrating agreement with analytical predictions.
7	4	Technology is in "build mode". The final design is complete and tests have been performed across a range of operating conditions such that constraints are known and documented. Based on this, procedures for operation and testing have been built.	Detailed Design and Assembly Level Build – Final assembly, subsystem, and system design, performance, and constraints documented – Production capability and/or parts availability, and vendors' current capability validated – Near operational assemblies pass stress tests that demonstrate significant margins operating at extremes over a range of expected environments – System successfully passes function/ performance validation tests	Documented test performance demonstrating agreement with analytical predictions.

8			Subsystem Build and Test – All parts of the system fabricated, integrated, and functionally tested – Build and test procedures qualified in the laboratory – System built and functionally tested – Identical/actual system environmentally tested	Documented test performance verifying analytical predictions.
9	5	Technology is in “ton mode”. The system is functional in the range of operating scenarios identified and is reliable. Over time, performance is documented, as well as any incidents of failure, to create a record of proven operations.	System Operational – System build and test procedures qualified in a facility – System integrated and functionally tested against requirements and operating scenarios – System environmentally tested	Documented operational results.
10			Proven Operations – The technology has been used without incident (or with incident levels within an acceptable range) for a protracted period of time – The technology has been certified (if applicable) via appropriate technology-type certification mechanisms through evaluation of repeated operations and other means – Failure rates for the technology are known and failure conditions and their causes are understood – The technology/system operates without unacceptable levels of unplanned troubleshooting or repair being required	Documented use of technology without incident for a protracted time period, documentation of certification, documentation of failure rates, known failure conditions and assessment of acceptability of troubleshooting/repair requirements.

**Modified from Straub, 2015*

APPENDIX B

Major publicly funded CDR initiatives by region (IEA, 2022) - *not exhaustive*

Programme/ instrument	Description
Canada	
Climate Action and Awareness Fund	The fund is investing CAD 206 million (USD 164 million) to support projects that will reduce Canada's GHG emissions, including efforts to understand the potential for, and implications of, carbon removal technologies including DAC.
Net Zero Accelerator	Part of the Strategic Innovation Fund, this initiative was announced in December 2020 and further enhanced by Canada's Budget 2021 to provide a total of CAD 8 billion (USD 6.4 billion) over seven years to support the decarbonisation of the industrial sector. DAC with CO_2 use is eligible as a climate-neutral CO_2 feedstock to produce low-carbon products.
Clean Fuel Standard	The standard will require liquid fuel suppliers to gradually reduce the carbon intensity of the fuels they produce and sell. Low-carbon-intensity fuels include those made from sustainably sourced biomass and DAC.
Budget 2021	The budget included CAD 319 million (USD 254 million) over seven years for Natural Resources Canada to fund RD&D to improve the commercial viability of CCUS technologies, including DAC.
European Union	
Horizon Europe	DAC projects are eligible for support under Horizon Europe, the main EU funding programme for research and innovation, with a total budget across all areas of EUR 95.5 billion (around USD 113 billion).
Innovation Fund	The EUR 10 billion (USD 11.8 billion) fund was launched in 2020 to support innovation in low-carbon technologies and processes, including CCUS and DAC.
Communication on Sustainable Carbon Cycles	The communication, released in December 2021, sets out a strategy to increase removals of carbon from the atmosphere. It suggests that 5 Mt of CO_2 should be removed annually by 2030.
United Kingdom	
DAC and GHG Removal Competition	This competition, announced in 2020, will provide funding for technologies that enable the removal of GHGs from the atmosphere. Total budget is up to GBP 100 million (USD 137 million).
Net Zero Strategy	The strategy identifies a need for 75-81 $MtCO_2$ of engineered carbon removals via DACS and BECCS by 2050. DAC may also benefit from announced funding of GBP 180 million (USD 248 million) to support production of sustainable aviation fuels.

Programme/ instrument	Description
United States	
45Q tax credit	This tax credit (introduced in 2008 and expanded in 2018) provides USD 35 per tonne of CO_2 used in enhanced oil recovery and USD 50 per tonne of CO_2 stored. The credit is available for DAC only if the capture capacity of the plant is above 100 000 tCO_2/year. There are a number of proposals to increase the value of the 45Q tax credit, including in the Build Back Better Act, which would provide USD 180/tCO_2 for DACS.
California Low Carbon Fuel Standard	DAC projects anywhere in the world are eligible to receive LCFS credits, provided the projects meet the requirements of the Carbon Capture and Sequestration Protocol (including 100 years of storage monitoring). The LCFS credits traded at an average of around USD 200/tCO_2 in 2020.
Infrastructure Investment and Jobs Act	Almost USD 12 billion in CCUS support was included in this act, which was enacted in November 2021. This includes USD 3.5 billion in funding to establish four DAC hubs (1 $MtCO_2$ per year and above) and related transport and storage infrastructure. DAC projects are also eligible for additional CCUS funding support included in the act of around USD 0.5 billion. A DAC Prize programme was also fully funded by the infrastructure package, with USD 100 million for commercial-scale projects and USD 15 million for pre-commercial projects.
Carbon Negative Shot	This was announced during COP26 in November 2021 as a call for innovation in technologies and approaches that will remove CO_2 from the atmosphere and durably store it at meaningful scales for less than USD 100/tonne of CO_2-equivalent, including DAC.
DOE funding programmes	Multiple funding programmes specifically for DAC were announced in March 2020 (USD 22 million), January 2021 (USD 15 million), March 2021 (USD 24 million) and October 2021 (USD 14.5 million).
Japan	
Moonshot Goal 4	The Moonshot Goal 4 (a subset of the Moonshot R&D Program, launched in 2019 with a total budget of YEN 100 billion [USD 1 billion]) focuses on "the realisation of a sustainable resource circulation to recover the global environment by 2050". In order to reach this goal, the Moonshot Goal 4 includes R&D funding of YEN 20 billion (USD 200 million) for multiple innovative technologies, including DAC.

Notes: GHG = greenhouse gases; DOE = Department of Energy.

APPENDIX C

Scoring Framework Example with Instructions and Calculation Logic

CDR Technology Assessment Framework

CDR Technology Name: Example CDR Technology << input the name of the technology assessed here

		Assessment Criteria	Rating Scale	Raw Score	Normalized Score	Formulas	Weight
Technology Risk	1	Technology Readiness Level	0 to 5	2	2.00	=F6*1	1
	2	Cost per ton	0 to 5	3	3.00	=F7*1	1
	3	Capital Availability	0 to 7	5	3.57	=((F8-0)/(7-0))*5	1
	4	Storage / Use	0 to 5	3	3.00	=F9*1	1
	5	Measurement, Reporting and Verification	0 to 3	1	1.67	=IF(F10="",0,((F10-0)/(3-0))*5)	1
Credit Issuance Risk	6	Carbon Registry Methodologies	0 to 5	3	3.00	=F11*1	1
	7	Additionality	0 to 5	4	4.00	=F12*1	1
	8	Durability	0 to 5	5	5.00	=F13*1	1
	9	Lifecycle Analysis	0 to 5	2	2.00	=F14*1	1
	10	Environmental and Social Impacts	0 to 5	3	3.00	=F15*1	1

Total Technology Maturity Score	2.65
Total Credit Issuance Maturity Score	3.40

Formulas

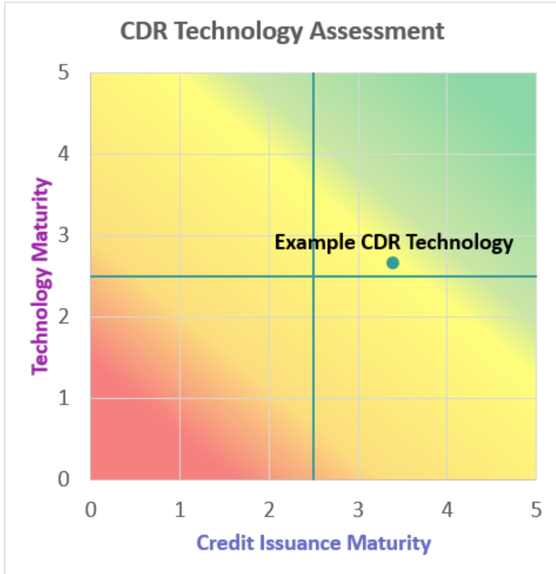
=SUMPRODUCT($G$6:$G$10,$I$6:$I$10)/SUM($I$6:$I$10)

=SUMPRODUCT($G$11:$G$15,$I$11:$I$15)/SUM($I$11:$I$15)

Cumulative scores will be auto-caluclated here and plotted on the matrix

Input raw scores here - use report for guidance on scoring

Input weights (if any) here - default weight is 1 for all criteria; N.B. all weights should be positive numbers



Source: Capstone Team's Excel Tool

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