مؤسسة دبي للمستقبل
DUBAI FUTURE FOUNDATION

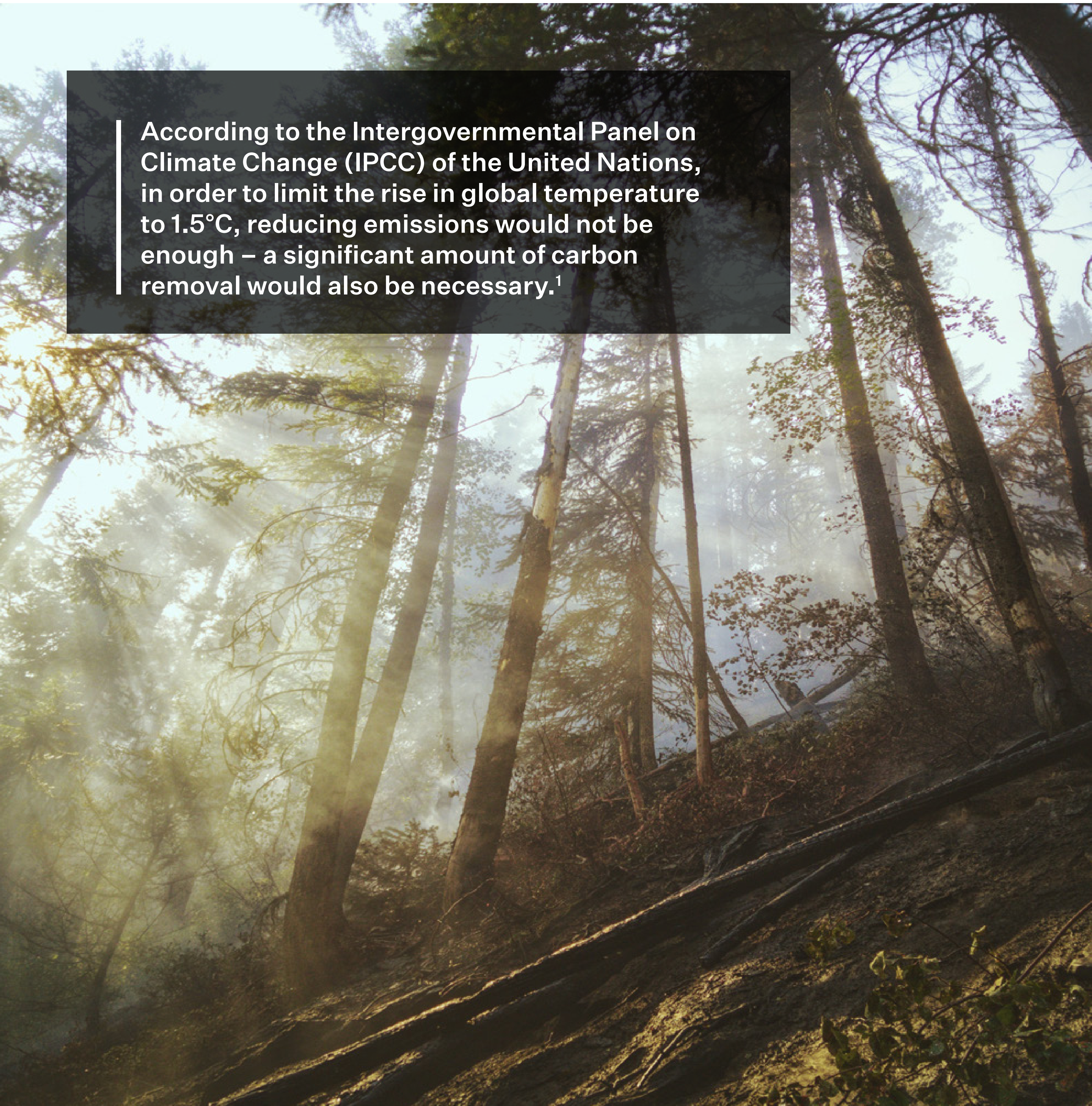
MAY 2023

HOW CARBON COULD BE A **$15 TRILLION INDUSTRY OF THE FUTURE**

Contents

Executive Summary 01

Since the first Industrial Revolution, anthropogenic emissions amounting to approximately 1 trillion tons of excess carbon dioxide have accumulated in our atmosphere, resulting in an increase in global temperature of approximately 1°C so far.



According to the Intergovernmental Panel on Climate Change (IPCC) of the United Nations, in order to limit the rise in global temperature to 1.5°C, reducing emissions would not be enough – a significant amount of carbon removal would also be necessary.[1]

Driven by this urgent need to mitigate climate change, innovators and entrepreneurs are seeking ways to address this catastrophic challenge through natural and engineered carbon removal initiatives. If successful, developers of such initiatives can be compensated for the successful removal of carbon through the issuance and sale of carbon credits. Each carbon credit represents 1 ton of carbon emissions removed. As of November 2021, the average price of carbon credits related to carbon removal was more than $15/ton,[2] potentially making carbon removal a $15 trillion industry of the future.

There are myriad carbon removal approaches that could be implemented, including enhanced weathering, enhanced photosynthesis and chemical solutions, some of which are covered in this report. The approaches vary widely in terms of cost, market readiness, ease of deployment, storage potential and permanence. There remains an opportunity to improve existing carbon removal methods and to drive down their costs. There also remains room for R&D to develop novel approaches to carbon removal.

The captured atmospheric carbon can either be sequestered or utilised. Depending on the application, utilising the captured carbon could prove to be more viable than sequestration. There are several emerging applications for captured atmospheric carbon. Some of the immediately impactful applications include the production of clean synthetic fuels that can be used in existing internal combustion engine vehicles around the world, as well as production-enriched concrete, which has the potential to decarbonise an industry responsible for more than 7% of the world's carbon dioxide emissions.[3] It must be noted, however, that applications such as the combustion of synthetic fuels result in carbon dioxide returning to the atmosphere.

Dubai is well positioned to become a global hub for carbon removal and a net exporter of carbon credits because of its abundant year-round solar resources, its focus on innovation, its established entrepreneurial ecosystem and its proximity to geological formations suitable for long-duration carbon dioxide sequestration. Specific recommendations are provided in this report to incentivise carbon removal in Dubai.

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Earth's Atmosphere 02

Changing Conditions

Earth's atmosphere is composed primarily of nitrogen (78%) and oxygen (21%) and also contains small amounts of argon (0.93%) and other gases (0.04%) such as carbon dioxide, neon and helium.[4]

The world benefited from unprecedented economic growth during the 19th and 20th centuries. However, this economic growth came at the cost of climate change and rising global temperature. In fact, our planet's average surface temperature has risen by around 1°C since the late 19th century.[5] Scientists have linked this rise in global temperature to human activity.[6]

The economic growth during the 19th and 20th centuries was fuelled by the burning of fossil fuels across the world's industrialising countries, resulting in significant amounts of greenhouse gas (GHG) emissions, which trap heat and cause rises in global temperature. In fact, we have emitted so much carbon dioxide since the beginning of the Industrial Age that the concentration of carbon dioxide in the atmosphere has almost doubled: it hovered at around 280 parts per million (ppm) during the warmer interglacial periods prior to the first Industrial Revolution in the late 18th century[7] and, as of August 2022, now stands at over 425 ppm.[8]

Excess Carbon

Between 1850 and 2019, approximately 950 billion tons of excess carbon dioxide were emitted due to human activity such as the burning of fossil fuels.[9]

In an effort to mitigate climate change, governments, intergovernmental organisations, non-governmental organisations and the private sector around the world are attempting to prevent the emission of more GHGs and are seeking ways of removing carbon from the atmosphere. Indeed, carbon reduction and carbon removal are being incentivised through policies, regulations and voluntary funding. Such incentives are driving innovation in the field, resulting in novel ways of capturing carbon and the introduction of new applications for captured carbon, as discussed later in this report.

Value of Carbon 03

Carbon Markets

Voluntary funding, environmental policies and regulations have created demand for carbon reduction and carbon removal projects around the world. Carbon reduction projects include technologies that reduce the amount of emissions occurring at polluting sources. Carbon removal projects are those that remove or absorb carbon dioxide from the atmosphere and store it permanently. On the supply side, people developing such projects can be compensated for their efforts through carbon markets. In carbon markets, carbon reduction and removal efforts are traded in the form of carbon credits. Each carbon credit represents 1 ton of carbon dioxide reduced or removed.

Carbon Credit Quality

Several factors impact the quality of carbon credits. Factors known as additionality, double counting and permanence are among those with the most impact:

01 Additionality
A carbon offsetting project is considered additional if that project would not have existed in the absence of revenues or benefits from the sale of associated carbon credits.[10] The purpose of carbon credits is to encourage additional carbon reduction and removal initiatives. Carbon reduction or removal projects that have had their additionality verified by credible independent organisations are considered higher quality projects and their associated carbon credits achieve higher prices.

02 Double Counting
Although ownership of carbon credits can be easily verified, the risk of double counting cannot be ignored. Under no circumstances should the same carbon credit be sold to multiple entities at the same time. Carbon reduction or removal projects that are on the registries of credible independent organisations are considered higher quality projects and their associated carbon credits achieve higher prices.

03 Permanence
Permanence refers to the amount of time the carbon reduction or removal lasts. For carbon offsetting to be effective, the carbon dioxide should not return to the atmosphere after a short period of time. Carbon reduction or removal projects that ensure the carbon dioxide is not returned to the atmosphere for a long time are considered to be higher quality projects and their associated carbon credits achieve higher prices. This is often referred to as the ‘permanence premium’.

Carbon Offsetting

Carbon offsetting is when an individual or company responsible for emitting carbon dioxide directs money towards initiatives that reduce or remove carbon dioxide from the atmosphere in an effort to negate their own emissions. For instance, a person travelling on an aircraft can choose to offset the emissions related to their flight by paying an additional fee on their ticket, which the airline would put towards carbon removal or reduction initiatives. Another example could be a technology company that owns and operates data centres. If the source of their electricity is not clean, they could offset emissions related to its production by funding a carbon reduction or removal project.

The Controversy

Carbon offsetting could be considered controversial because it allows carbon dioxide emitters to continue emitting while purchasing carbon credits. This could be a concern because some emitters may be inclined to purchase low-quality carbon credits because of their lower prices, which may not be effective in negating their emissions. For this reason, carbon emitters are encouraged to reduce emissions wherever possible and to offset only the emissions that cannot be reduced. Furthermore, in order to ensure that only high-quality carbon credits are purchased for the purpose of offsetting emissions, appropriate regulations should be implemented.

Carbon as a Commodity

Given that there exists a market and demand for carbon and that carbon has value, carbon could be viewed as a commodity. With this in mind, in addition to the environmental benefit, mining carbon from the air could also be seen as an economic opportunity.

At present, the price for carbon credits is over $5 per metric ton of carbon dioxide reduced[11] and over $15 per metric ton of carbon dioxide removed,[12] and prices could increase rapidly due to the need for urgent climate action.[13] It must be noted that these are average prices and that prices may vary depending on the technology used and the quality of carbon credits. Carbon credits could maintain their value until the world has removed enough excess carbon dioxide to reverse the increase in global temperature. At today's prices, **the world needs to remove the equivalent of $15 trillion** (almost 1 trillion tons of carbon dioxide) to return the atmosphere to its condition prior to the first Industrial Revolution, potentially reversing human-induced climate change. Once that goal is achieved, an amount equivalent to our annual emissions would need to be removed annually in order to maintain a net-zero carbon cycle.

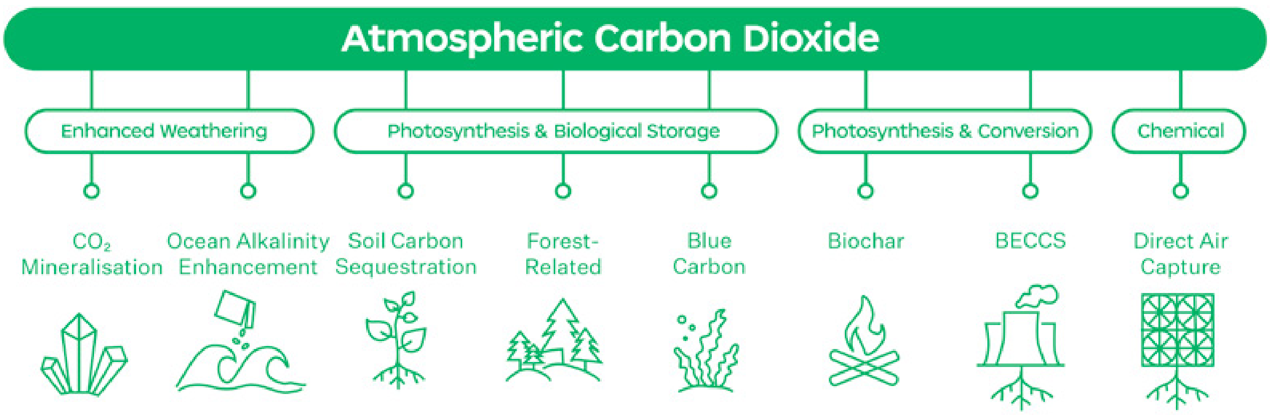
Carbon Removal Methods 04

The Natural Carbon Cycle

Until the first Industrial Revolution, our planet had mostly maintained a stable cycle of carbon dioxide absorption and release. The world had been at equilibrium with a net-zero carbon cycle in which carbon dioxide that had been naturally released into the atmosphere was subsequently absorbed by the oceans and the land. There were nevertheless times when more carbon dioxide was released by natural processes thus upsetting the balance. But now the balance is being disrupted due to human activity. Since the first Industrial Revolution, significant amounts of human-activity-induced (anthropogenic) emissions have been introduced, altering the delicate state of our ecosystems. The accumulated emissions are causing our planet to absorb more carbon dioxide than it used to, contributing towards harmful changes in our ecosystems, such as the acidification of our oceans.[14] While more carbon dioxide is added to the atmosphere than the oceans and the land can absorb, the natural carbon cycle will not be net zero, and the oceans and land will continue to absorb ever larger amounts of carbon dioxide, perpetually altering our ecosystems.

Human-Induced Carbon Removal

Since the natural carbon cycle is no longer at equilibrium, there now exists an urgent argument for inducing carbon removal. Carbon removal can be induced through enhanced weathering, enhanced photosynthesis and chemical solutions, among other methods. Although not comprehensive, the following diagram covers the most common methods.[15] An overview is provided for each method, including respective cost estimates and the potential risks and challenges of each.



	CO_2 Mineralisation	Ocean Alkalinity Enhancement	Soil Carbon Sequestration	Forest-Related	Blue Carbon	Biochar	BECCS	Direct Air Capture
Cost-USD/ tCO_2	20-100	70-160	20-100	1-20	18-29	30-130	20-288	150-100
Storage Capacity-($GtCO_2e$)	60,000,000	1,000+	5/year	4-12/year	2.4-4.5/year	1.1-3.3/year	1.2-5.2/year	Limited by CCS
Permanence	High	High	Low	Low	Low	Medium	High	High

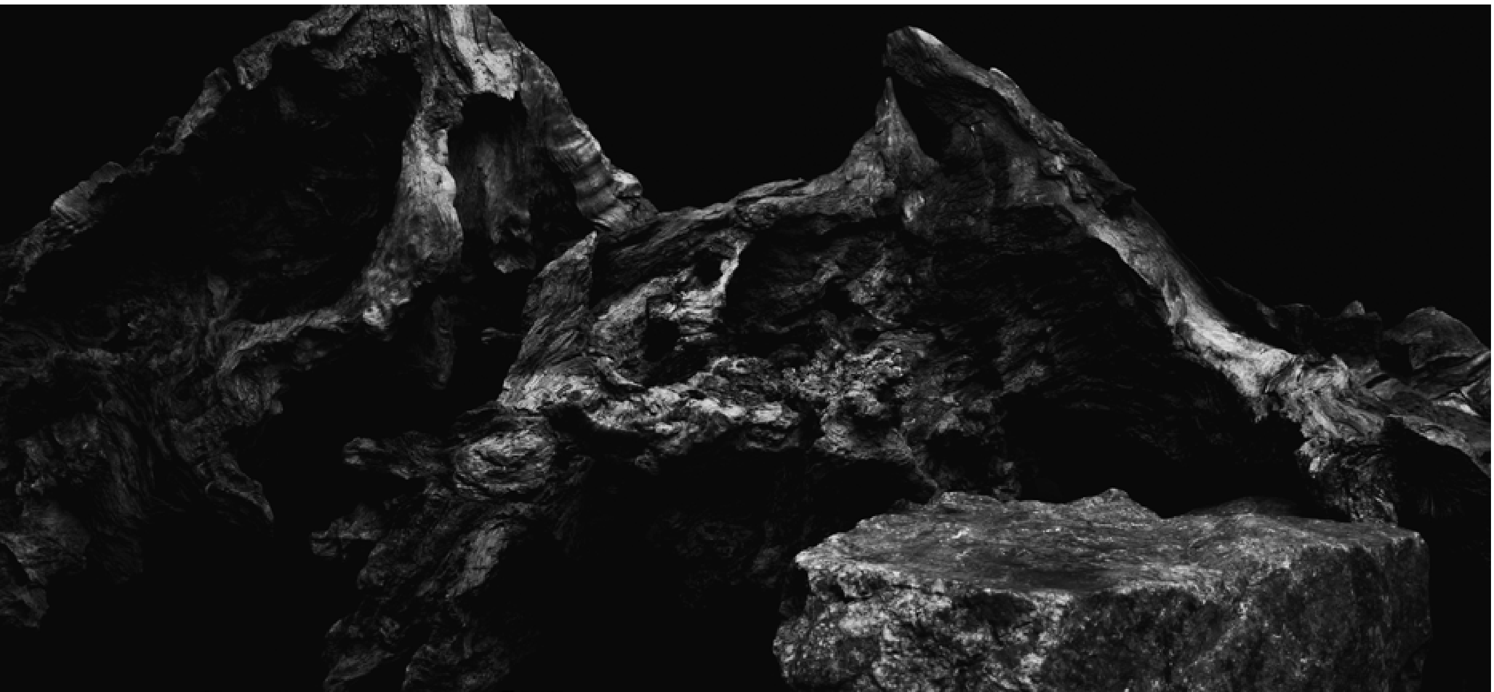
Carbon Dioxide Mineralisation

Mineralisation is a process by which carbon dioxide reacts with an alkaline material to form a solid carbonate rock. The process occurs naturally in alkaline environments such as rocky areas rich in magnesium or calcium, like basalt (volcanic) or peridotite formations, and can be accelerated for carbon dioxide removal (CDR) or carbon capture and sequestration (CCS). According to the CCS company 44.01, peridotite appears uniquely on the surface in large quantities in the UAE and Oman, significantly reducing the cost of access. In total, the company states that peridotite in the region has the capacity to mineralise approximately 10 trillion tons of carbon dioxide. **Enhanced carbon dioxide mineralisation can be achieved in three ways:**[16]

Surficial Alkaline mine tailings or alkaline rocks are left on the Earth's surface to react with atmospheric carbon dioxide, potentially enhanced by crushing the reactive material to increase atmospheric exposure.

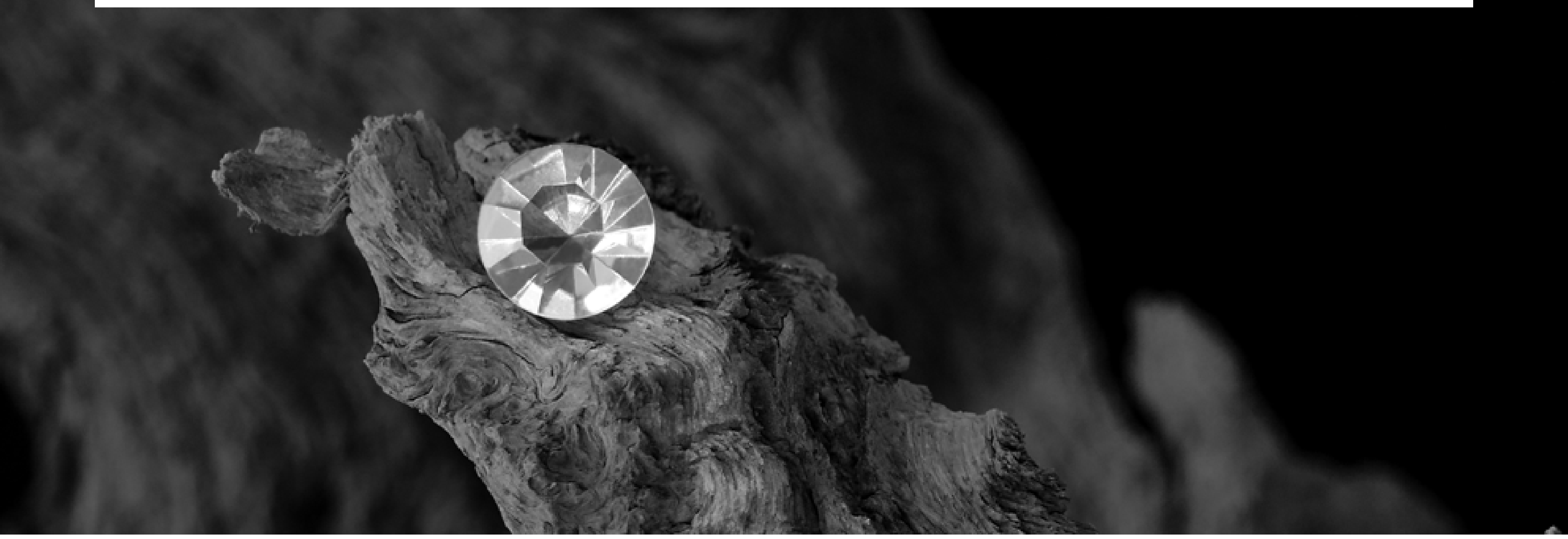
In situ Carbon-dioxide-enriched fluids are sent underground to react with alkaline material below the surface.

Ex situ Minerals are mined, ground and exposed to atmospheric carbon dioxide, often under higher temperatures and pressures to accelerate the mineralisation process.



Diamond company, De Beers, is exploring carbon sequestration at its mines in Canada and South Africa. Kimberlite rock, which is an ore known for containing diamonds, also has the potential to store large volumes of carbon. De Beers stores previously mined waste rock in tailings dams above ground at its mines. According to De Beers, each mine has the potential to offset 10 times its annual emissions using its on-site tailings.[17]

In situ pilot projects, in which carbon dioxide is captured, dissolved in water and injected underground, are being explored in Oman by the CCS company 44.01[18] and in Iceland by Carbfix.[19]



Risks and Challenges

The primary concerns specific to carbon sequestration methods, such as in situ mineralisation are its potential for leakage, which would return the sequestered carbon dioxide back into the atmosphere or affect nearby water supplies, and potential human-induced tremors caused by the build-up of pressure underground. Research is currently underway in Spain to determine the potential risks from carbon sequestration.[20]

Costs

Costs are estimated to be $20–$100 per ton of atmospheric carbon dioxide (tCO_2) with mine tailings at the lower end but with significantly smaller storage potential.[21]

Ocean Alkalinity Enhancement

The ocean absorbs carbon dioxide by dissolving it to form carbonic acid, which breaks down into anions (positively charged ions) including bicarbonate and carbonate. These are normally balanced by cations (negatively charged ions) formed of calcium, magnesium, sodium and potassium, but the high concentration of carbon dioxide in the atmosphere has led to ocean acidification from an overabundance of carbonic acid. Ocean alkalinity enhancement (OAE) – making the ocean more alkaline (less acidic) by adding reactive substances like sodium hydroxide, sodium carbonate or limestone – could enable the ocean to absorb more atmospheric carbon dioxide and store it as dissolved bicarbonate and carbonate, while offsetting acidification.[22] The process is similar to carbon dioxide mineralisation, except the carbon dioxide is sequestered in a dissolved state in the ocean rather than in a mineral state on or under the land.

Risks and Challenges

The part of the ocean being 'enhanced' could become too alkaline and damage ecosystems. There are also risks from a legal perspective, since large volumes of reactive material would simply be dumped into the ocean.[23] Challenges include energy input costs, dispersion challenges and carbon removal measurement. Furthermore, OAE can be considered a form of geoengineering, which is often considered controversial because long-term impacts have often not been studied and the impacts affect several countries, posing geopolitical risks as well.

Costs

Costs are estimated to be $70–$160 per tCO_2, with ocean liming using dolomite on the lower end of the cost spectrum and limestone on the upper end.[24]

Soil Carbon Sequestration

Soil carbon sequestration involves changes in land management that lead to increased carbon storage in soil organic matter, which results in net removal of carbon dioxide from the atmosphere.[25] Forestry, the ploughing of prairies and standard agricultural practices have resulted in an estimated 133 gigatonnes of carbon dioxide being released from the soils over the past 12,000 years.[26] The process of soil sequestration seeks to rebuild the carbon content of soils through climate-smart agricultural practices and soil management techniques.

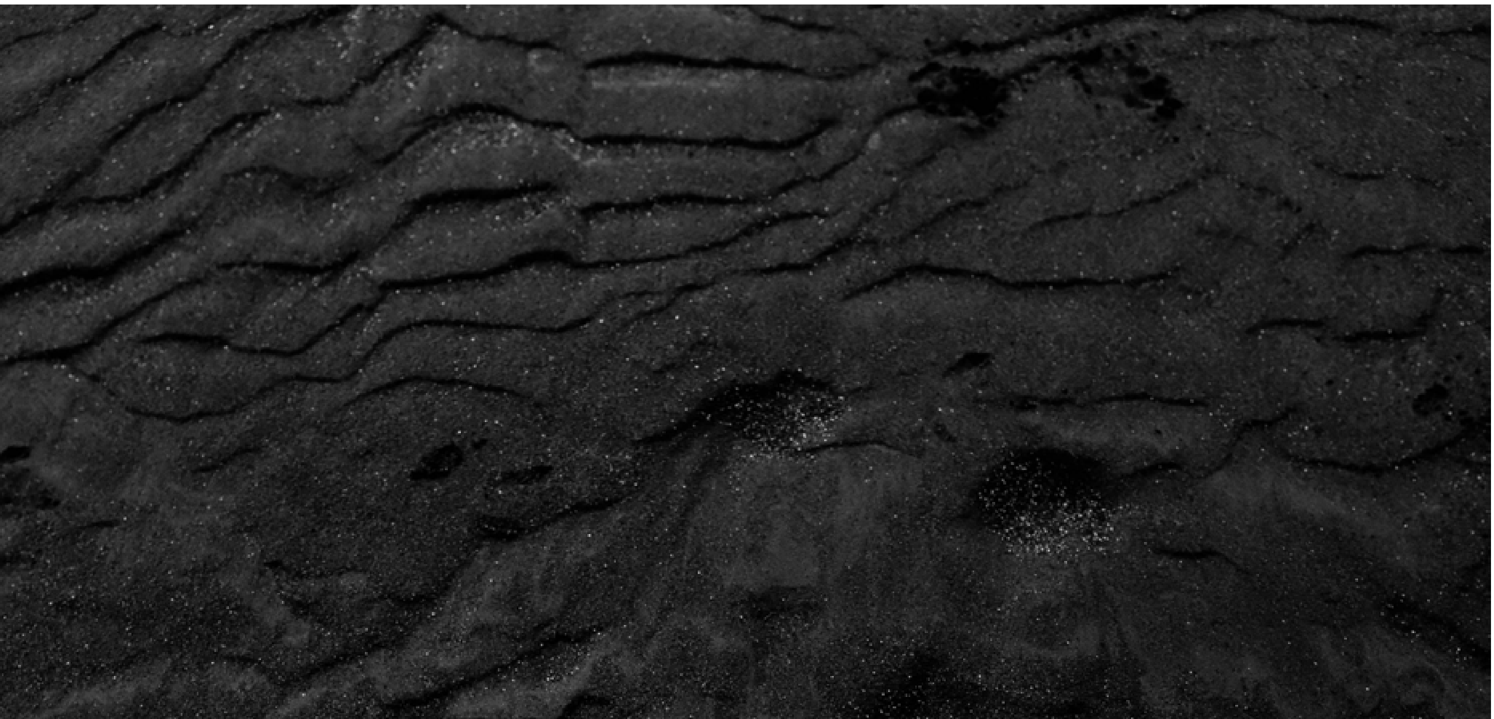
Such practices include minimising erosion and enhancing soil carbon. Erosion is reduced through low-till or no-till agriculture or by planting cover crops. Soil fertility is enhanced by applying composts to the soil, enriching soil with biochar and leaving leaf litter and agricultural wastes on farmland. The effectiveness of these techniques varies widely across different ecological zones, crop types, agricultural practices and soil depths.

Risks and Challenges

Risks include guaranteeing the permanence of sequestered carbon and difficulties related to necessary policies and regulatory measures that encourage soil carbon sequestration.

Costs

Soil sequestration costs vary, with some studies showing a positive return on investment.[27] It is estimated that 1.5–2.6 gigatons of carbon dioxide could be sequestered annually at carbon prices of \$20–\$100 per tCO_2.[28]



Improved Forest Management, Afforestation, Reforestation and Agroforestry

As trees grow, they sequester atmospheric carbon in their roots, trunks and branches and through soil sequestration as leaf litter decomposes and increases soil carbon content. **There are four main ways forests can contribute to human-induced CDR:**

Improved Forest Management Changes to forest practices that increase forest biomass and carbon storage. For actively managed forests, this includes longer timber harvesting schedules to enhance their carbon storage potential, better fire management and improved tree plantation and understorey management.[29]

Afforestation Planning new forests on land where forests have not recently existed. It often involves monoculture planting, which limits biodiversity.[30]

Reforestation Replanting forests in recently cleared areas or regenerating damaged forestland.[31]

Agroforestry Planting trees on agricultural land. Trees, crops and animals can be integrated into the same agricultural plots and generate greater financial returns than if they were cultivated separately.[32]

Risks and Challenges

There are several risks associated with using forests for human-induced CDR, primarily permanence, competition for land and additionality concerns. Permanence is threatened by potential reversals through forest fires, disease or future land conversion. Competition for land is especially acute for afforestation programmes where the land was not recently a forest. Additionality is challenging to ensure because the counterfactual (what might otherwise have happened) is uncertain; for example, would cleared land have turned into a forest in the absence of an intervention? Ensuring additionality is also challenging because the time boundary between changes in land use is subjective; for example, how much time would need to pass between forest clearing and reforestation for the new forest to count as an additional carbon reduction initiative?

Costs

Costs of forestry interventions vary considerably but are generally quite low, in the range of \$1–\$20 per tCO_2.[33, 34]

Blue Carbon

Blue carbon refers to organically stored carbon in coastal ecosystems, including mangroves, marshes, wetlands, seagrasses, tidal zones and the wider ocean.

Coastal areas tend to be very fertile and produce biomass quickly, but there are uncertainties regarding how much carbon rejoins the carbon cycle and how much is permanently sequestered.[35]

Where air encounters the ocean surface, carbon dioxide is transferred from the atmosphere to the water through molecular diffusion. The ocean's ability to absorb carbon dioxide is enhanced by the wind, which stimulates the movement of the water, creating waves, and the mixing of the surface layers, helping carbon dioxide to enter the different layers of the ocean. Furthermore, marine ecosystems, such as macroalgae, microalgae and corals, play a significant part in carbon dioxide absorption, with research indicating that microscopic plants on the ocean's surface alone absorb 10–20 billion tons of carbon dioxide every year.[36] Like land plants, underwater plants, such as phytoplankton and seaweed, extract the dissolved carbon dioxide from the ocean as they obtain their energy through photosynthesis, which also helps to deacidify the water.

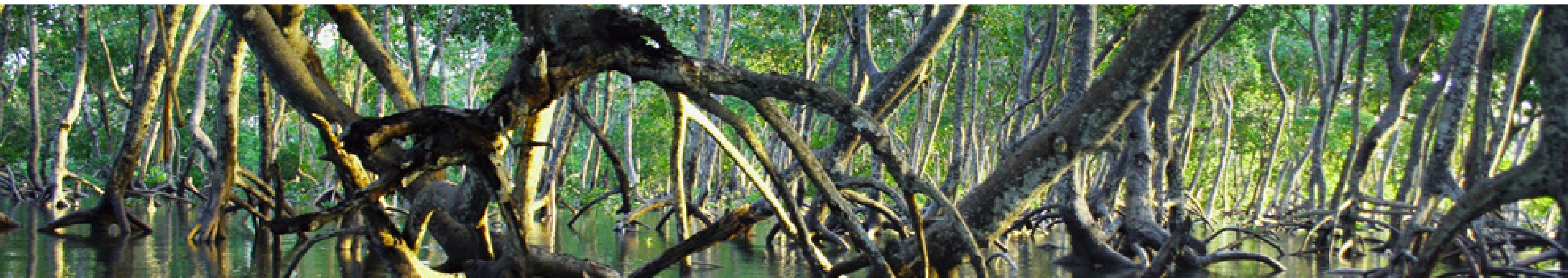
Blue carbon human-induced CDR methods include nature-based coastal resilience projects, replanting mangroves, managing new wetland opportunities as sea levels rise and changing fishing practices to encourage healthy underwater ecosystems. As the role of oceans in balancing carbon dioxide in the Earth's atmosphere becomes better understood, there are also new geoengineered solutions being pursued in the form of ocean fertilisation, which involves adding nutrients to the upper layers of the ocean to stimulate increased phytoplankton activity in an attempt to reduce atmospheric carbon dioxide levels. Phytoplankton is responsible for most of the transfer of carbon dioxide from the atmosphere to the ocean. Carbon dioxide is consumed during photosynthesis and the carbon is incorporated into the phytoplankton, just as carbon is stored in the wood and leaves of a tree.

Risks and Challenges

Blue carbon sequestration risks include eutrophication, pollution, overfishing, sea level rise, sea temperature change, competition for wetland resources and coastal infrastructure development. The volume of sequestration in different blue carbon methods is difficult to measure and monitor and its permanence is not guaranteed.[37] Furthermore, similar to OAE, ocean fertilisation is a form of geoengineering with potential long-term effects on our ecosystems that are uncertain. In fact, fertilising the ocean using iron or other minerals to promote phytoplankton growth and remove carbon dioxide from the atmosphere was banned in 2013 by the London Protocol, which is a global convention with 53 parties that aims to reduce marine pollution.[38] There are efforts being undertaken today to lift this ban through scientific studies that will determine whether the ocean fertilisation efforts can be managed and their benefits demonstrated unequivocally.

Costs

Costs for blue carbon projects on the voluntary carbon market are in the range of $18–$29 per tCO_2.[39]



Biochar

Biochar is a carbon-rich solid made from organic material that has been transformed under high temperatures in the absence of oxygen, a process called pyrolysis. Pyrolysis stabilises organic matter in such a way that carbon is not quickly returned to the atmosphere through decomposition and the carbon cycle. Biochar can be made from different feedstocks, including plants grown specifically for biochar conversion, as well as agricultural wastes and residues like stalks and leaves left over from crop harvests. It is often returned to agricultural soils to enhance their carbon content.[40]

Since biochar degrades much more slowly than untreated biomass, it can be considered a human-induced CDR technology when viewed as part of a system that includes biomass growth.

Risks and Challenges

Risks include land-use competition, biomass transport, uncertainty regarding the net impact of removing biomass and its nutrients from the land and a relatively poor understanding of biochar's persistence in real-world environments, especially when it is incorporated into tilled agricultural soils.

Costs

Cost estimates for biochar carbon removal vary widely, depending on the feedstock, production process, scale and geography, with costs in the range of $30–$120 per tCO_2.[41,42]

Bioenergy With Carbon Capture and Storage

Bioenergy with carbon capture and storage (BECCS) combines biomass combustion with carbon capture and storage. Biomass removes carbon dioxide from the atmosphere as it grows. Biomass can be burned to produce heat and electricity or chemically transformed through fermentation to produce liquid biofuels. Both processes produce carbon dioxide, which can be captured and stored in geological formations or other storage media. BECCS can be used as human-induced CDR, as long as the emissions generated from cultivation, harvest, transport, energy conversion and carbon capture and storage processes are less than the emissions successfully captured and stored.[43]

> Drax Power Limited has launched two BECCS pilot projects in the UK. The first pilot project uses technology from C-Capture and has the capacity to capture up to 1 ton of carbon dioxide per day. The second pilot uses technology from Mitsubishi Heavy Industries and has the capacity to capture around 300kg of carbon dioxide per day to test the technology. Drax Power Limited plans for commercial-scale capture by 2027.[44]

Risks and Challenges

Risks include the limited availability of biomass feedstock and the land required to grow it. When considering direct and proximate land-use change, water consumption and potential biodiversity loss, its net climate and environmental impact is difficult to measure. The implementation of BECCS involves challenges, including the cost of the CCS technology and how to transport the captured carbon dioxide from point sources to centralised CCS storage locations. Furthermore, the environmental impact of transporting the biomass itself must be taken into consideration.

Costs

The cost of BECCS spans a wide range, estimated at \$20–\$288 per tCO_2.[45] Costs depend on the type of biomass feedstock, the energy conversion process and the type of CCS technology used, among other factors.[46]
A key driver of the cost of BECCS is the carbon dioxide capture step: bioenergy processes that produce high-purity carbon dioxide streams are more economically viable than others such as biomass combustion.

Direct Air Capture

Direct air capture (DAC) technology removes carbon dioxide from the ambient air using a chemical process. **Fans push air through a contactor containing a synthetic solid or liquid that chemically reacts with carbon dioxide and removes it from the atmosphere:**

- Solid sorbents use amines or amino groups attached to porous materials (e.g. activated carbon or silica) formed into sheets or beads that are engineered to have a very high surface area to maximise contact with carbon dioxide. Upon contact, the carbon dioxide reacts to form a carbamate bond.

- Liquid solvents use alkaline solutions that are pumped over or through high surface area forms to maximise carbon dioxide contact. The carbon dioxide and alkaline solutions react to form a carbonate bond.

When saturated, the liquid or solid is heated to break the carbamate or carbonate bonds, which releases a high-purity stream of carbon dioxide and reformulates the initial reactive substance. The carbon dioxide can then be sequestered or utilised, and the reactive substance can be reused.

Risks and Challenges

DAC is energy intensive. Clean energy is required for heat, to run fans and to drive pumps. In areas where clean energy is scarce, using that clean energy for other purposes could be more effective in climate change mitigation than using it for DAC.

Breaking chemical bonds with heat requires temperatures of about 900°C for liquid-solvent-based carbonates and about 100°C for solid-sorbent-based carbonates. The lower temperatures required for solid sorbents make them suitable for pairing with renewable heat sources like concentrated solar or geothermal power. For both solid and liquid methods, about 80% of the energy requirement is for heat and about 20% of the energy requirement is for electricity.[47] For DAC to be a net-negative human-induced CDR initiative, its energy supply must come from low-carbon sources.

Costs

Costs for DAC are high, partly because it uses an immature technology with more opportunity for innovation and economies of scale, and partly because of energy demand, with estimates of \$250–\$600/tCO_2.[48] The costs of the facility run by Climeworks, are about \$600/tCO_2[49] and their costs are estimated to fall to \$250–\$300/tCO_2 by 2030.[50] Occidental reports costs of \$400–\$500/tCO_2, falling to an estimated \$200–\$250/tCO_2.[51] Learning, innovation and economies of scale could reduce costs to about \$100/tCO2.[52] Similar reductions in costs have been observed with wind and solar deployment.

Swiss DAC company, Climeworks, recently signed a 10-year carbon removal offtake agreement with Microsoft, in which Climeworks will permanently remove 10,000 tons of carbon dioxide emissions from the atmosphere for Microsoft.[53]

Canadian DAC company, Carbon Engineering, has partnered with Occidental and its subsidiary 1PointFive to build the world's largest DAC plant in the Texas Permian Basin.[54]

Carbon Applications* 05

Existing Carbon Applications

At present, most of the captured carbon from carbon removal projects is sequestered underground or injected for enhanced oil recovery. However, there is an opportunity to extract value from captured carbon by utilising it in applications where the carbon is not re-emitted to the atmosphere or in other applications where there are no viable alternatives to using carbon, resulting in lower emissions overall.

Carbon is a necessary ingredient in several industrial applications today, including in the production of iron, steel and aluminium, where carbon is used in the smelting process. Carbon is also essential for producing graphite, which is used in the production of electric motors, lubricants and even pencils. Carbon is also needed for carbon fibre, which has been increasingly relied on in recent years because of its strength and its light weight. Carbon fibre is widely used in aircraft and sporting goods such as tennis rackets and cars. There are numerous other applications for carbon in our daily lives, such as paints, batteries and tyres, to name a few, and we have an opportunity to switch to clean carbon (sourced from carbon removal projects) wherever possible.

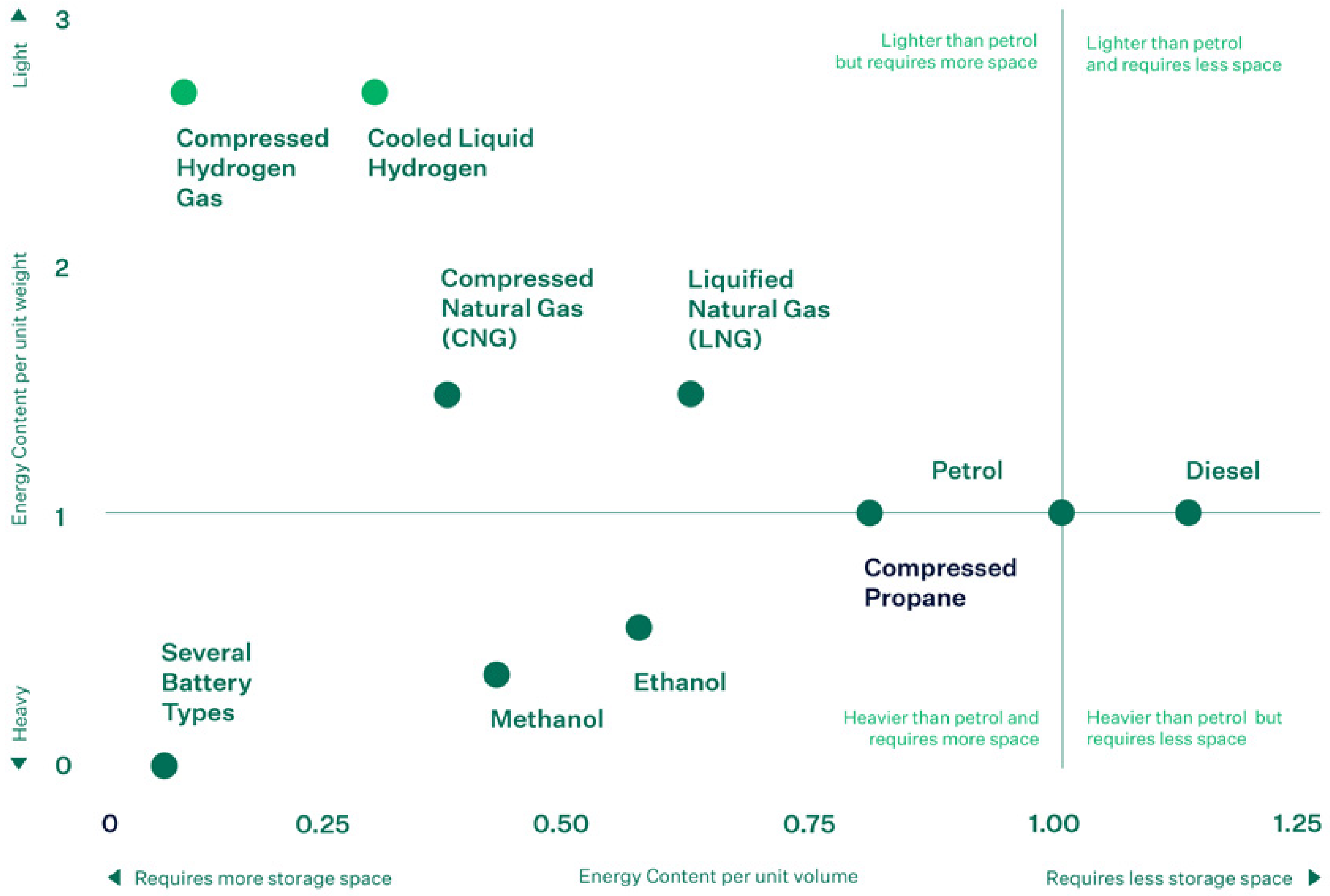
Emerging Carbon Applications

Synthetic fuels

Fossil fuels have enabled significant economic growth and energy security since the first Industrial Revolution. However, this has come at the cost of the accumulation of carbon dioxide in our atmosphere and resulting climate change, due to which several industries are now seeking viable alternatives to fossil fuels. Although most industries are on track towards decarbonisation, certain industries such as heavy transport, shipping and aviation still rely on fossil fuels. The aviation industry alone is responsible for 2.8% of fossil fuel carbon dioxide emissions.[55]

Today's batteries are too heavy for heavy road vehicles, ships and aircraft. Hydrogen fuel cells are often proposed as a clean alternative, but hydrogen (even when compressed or liquefied) suffers from low energy density, requiring a large amount of space.[56]

** Several carbon applications result in carbon dioxide being released back into the atmosphere, in which case they cannot be strictly considered carbon removal initiatives.*



Source: US Energy Information Administration

A transitional solution to this challenge could be synthetic fuels. Low-carbon hydrogen can be combined with captured carbon to produce clean synthetic fuels. Although using this synthetic fuel will inevitably lead to carbon emissions, the process is a carbon-neutral loop, with carbon being recaptured from the atmosphere to produce the cleaner synthetic fuel.

Disadvantages of synthetic fuels include high costs and energy losses resulting from electrolysis, synthesis and the internal combustion engines the synthetic fuels are used in.[57] Although battery electric vehicles are significantly more efficient for road transport when using sustainable electricity, synthetic fuels could provide an immediate solution for transportation without requiring extreme changes such as the need to purchase new vehicles compatible with a new technology. Synthetic fuels can serve as a carbon-neutral transitional solution until other clean technologies are widely adopted.

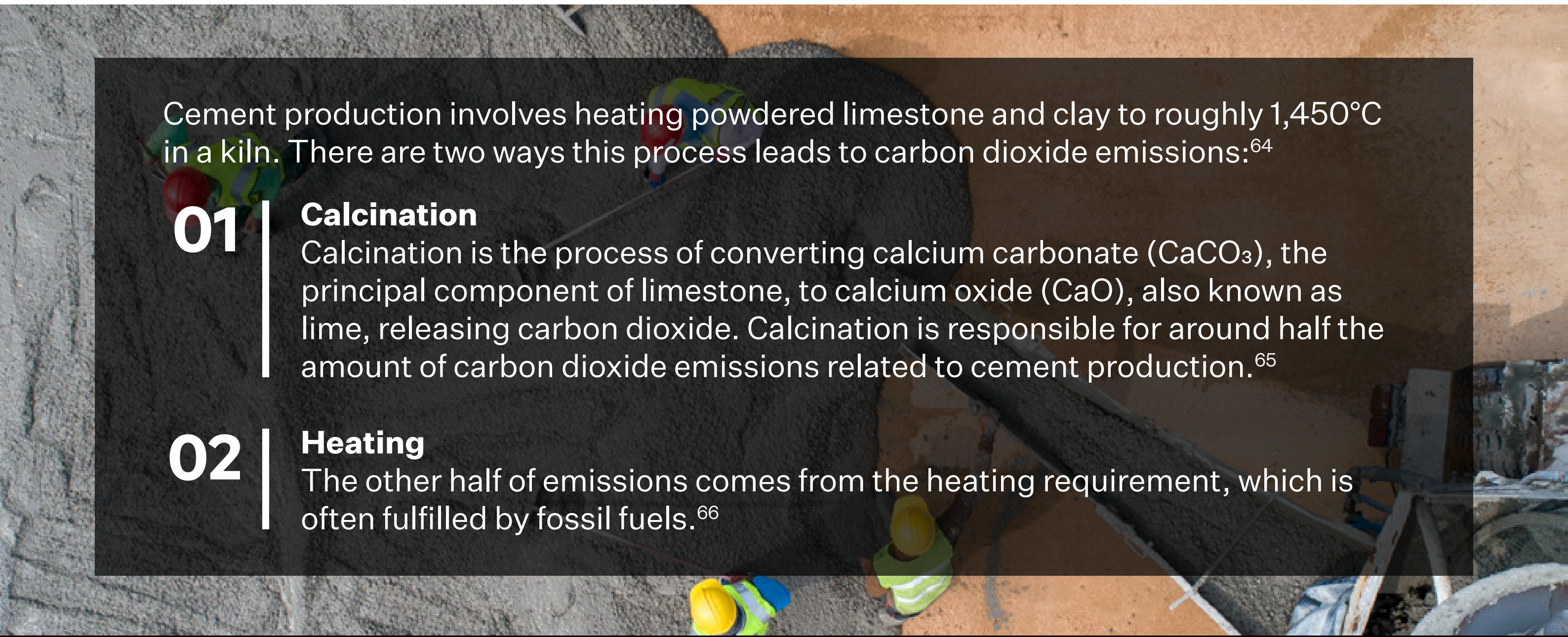
Formula 1 (F1) aims to help develop a 100% sustainable fuel that would be used in F1 races from 2026 onward and then scaled up for wider social use. The fuel will be laboratory created, using components that come from either a carbon capture scheme, municipal waste or non-food biomass. The fuel will meet F1's demanding energy density requirements, making them comparable to current fossil fuel petrols.[58]

Porsche is seeking to save the internal combustion engine through the use of synthetic fuels. The company broke ground at a new synthetic fuel plant in Chile in 2021. It is producing synthetic fuels that will be initially used in motorsport and later in existing unmodified combustion engine vehicles.[59,60,61]

In 2021, KLM made its first regular passenger flight, from Amsterdam to Madrid, fuelled partially by synthetic fuel produced by Shell.[62]

Enriched Concrete

Concrete has been arguably the most essential building material for people around the world, and, until recently, cement has been necessary for binding the ingredients of concrete together. Cement is responsible for more than 7% of the world's carbon dioxide emissions.[63] Finding alternatives to cement, or capturing emissions related to its production, could have a significant impact on tackling climate change. It must be noted that capturing emissions related to the production of cement is considered carbon capture rather than carbon removal.



Cement production involves heating powdered limestone and clay to roughly 1,450°C in a kiln. There are two ways this process leads to carbon dioxide emissions:[64]

01 Calcination

Calcination is the process of converting calcium carbonate ($CaCO_3$), the principal component of limestone, to calcium oxide (CaO), also known as lime, releasing carbon dioxide. Calcination is responsible for around half the amount of carbon dioxide emissions related to cement production.[65]

02 Heating

The other half of emissions comes from the heating requirement, which is often fulfilled by fossil fuels.[66]

CarbiCrete produces carbon-negative concrete. The company avoids using cement, circumventing carbon emissions related to its production, and instead uses steel slag. It then injects carbon dioxide during curing, removing carbon dioxide in the process.[67]

Solidia provides technologies related to sustainable cement manufacturing, reducing emissions by 30–40%, and sustainable concrete curing, in which concrete is cured utilising carbon dioxide instead of water.[68]

CarbonCure injects captured carbon dioxide into fresh concrete during manufacturing, where it reacts with cement to transform into a mineral that in turn strengthens the concrete.[69]

Other Applications

Countless applications are being explored around the world. Aside from road transportation, captured carbon is being used for the production of other transportation fuels, such as jet fuel and rocket fuel.[70] In food and agriculture, captured carbon is being used for the production of baking soda, fish food, proteins, healthy soils and fertilisers.[71] Using captured atmospheric carbon for such applications could prove to be a more valuable alternative to sequestration.

Conclusion 06

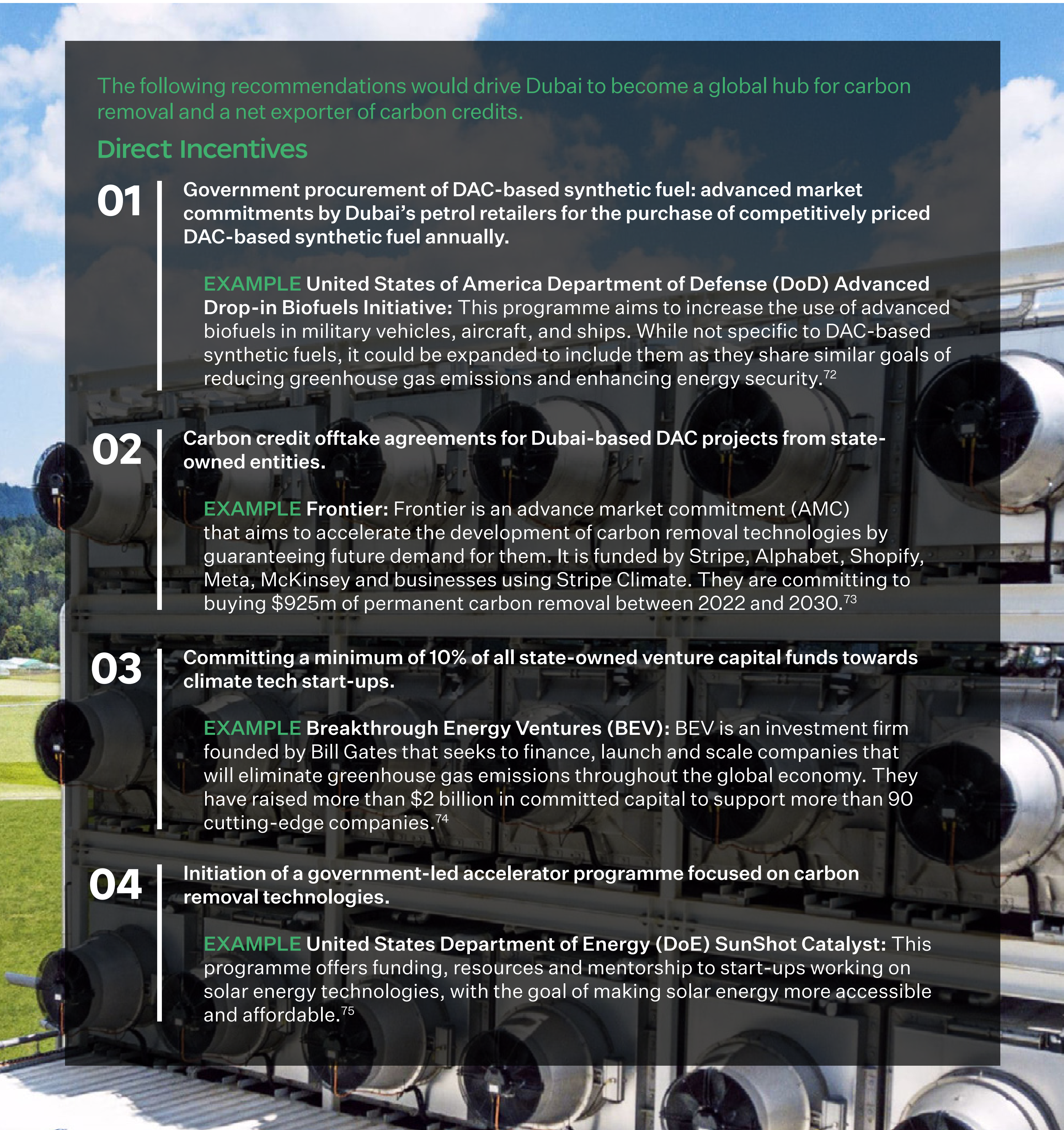
Emissions reductions are needed because of the accumulation of GHGs in the atmosphere and the resulting increase in global temperature and extreme weather events. However, they will not be enough to stop or reverse the effects of climate change. Reducing emissions will only slow down the rate of climate change. In addition to emission reductions, there is a need to remove the excess carbon dioxide that has accumulated in the atmosphere.

Despite the existence of several methods for carbon removal, such as enhanced weathering and enhanced photosynthesis, such methods are often not permanent or their effectiveness or additionality are hard to verify. There is, therefore, significant room for R&D and innovation in high-quality human-induced carbon removal methods, especially for engineered solutions such as DAC where the level of permanence is typically high.

Positive impact on the environment can be maximised by utilising captured atmospheric carbon to replace fossil-fuel-based carbon in industries where alternatives are not viable, such as fuels used for transportation. The scale of this challenge is incredibly large, as is the opportunity for those willing to take action.

Recommendations 07

With abundant year-round solar resources, Dubai has the potential to produce significant amounts of renewable energy. This competitive advantage, together with Dubai's proximity to geological formations suitable for long-duration carbon dioxide sequestration, its focus on innovation and its established entrepreneurial ecosystem, makes Dubai a strong contender to become a successful early mover in human-induced carbon removal.



The following recommendations would drive Dubai to become a global hub for carbon removal and a net exporter of carbon credits.

Direct Incentives

01 **Government procurement of DAC-based synthetic fuel: advanced market commitments by Dubai's petrol retailers for the purchase of competitively priced DAC-based synthetic fuel annually.**

EXAMPLE **United States of America Department of Defense (DoD) Advanced Drop-in Biofuels Initiative:** This programme aims to increase the use of advanced biofuels in military vehicles, aircraft, and ships. While not specific to DAC-based synthetic fuels, it could be expanded to include them as they share similar goals of reducing greenhouse gas emissions and enhancing energy security.[72]

02 **Carbon credit offtake agreements for Dubai-based DAC projects from state-owned entities.**

EXAMPLE **Frontier:** Frontier is an advance market commitment (AMC) that aims to accelerate the development of carbon removal technologies by guaranteeing future demand for them. It is funded by Stripe, Alphabet, Shopify, Meta, McKinsey and businesses using Stripe Climate. They are committing to buying $925m of permanent carbon removal between 2022 and 2030.[73]

03 **Committing a minimum of 10% of all state-owned venture capital funds towards climate tech start-ups.**

EXAMPLE **Breakthrough Energy Ventures (BEV):** BEV is an investment firm founded by Bill Gates that seeks to finance, launch and scale companies that will eliminate greenhouse gas emissions throughout the global economy. They have raised more than $2 billion in committed capital to support more than 90 cutting-edge companies.[74]

04 **Initiation of a government-led accelerator programme focused on carbon removal technologies.**

EXAMPLE **United States Department of Energy (DoE) SunShot Catalyst:** This programme offers funding, resources and mentorship to start-ups working on solar energy technologies, with the goal of making solar energy more accessible and affordable.[75]

Supporting Ecosystem

01 **Implementation of a low-carbon fuel standard in Dubai, supporting carbon utilisation and driving demand for DAC-based synthetic fuels.**

EXAMPLE **California Low Carbon Fuel Standard (LCFS):** LCFS is a regulatory programme aimed at reducing the carbon intensity of transportation fuels. It sets declining annual targets for the average carbon intensity of petrol and diesel sold in California.[76]

02 **Development of a 'Carbon Lab' to develop new carbon products, supporting carbon utilisation and driving demand for carbon removal.**

EXAMPLE **United States Department of Energy (DoE) National Renewable Energy Laboratory (NREL): :** NREL conducts research, development and testing to drive innovative solutions for a sustainable energy future. It partners with other national laboratories, government agencies, academic institutions and private industry partners to accelerate the development and commercialisation of cutting-edge clean energy technologies.[77]

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مؤسسة دبي للمستقبل
DUBAI FUTURE FOUNDATION

About the Dubai Future Foundation

Dubai Future Foundation aims to realise the vision of His Highness Sheikh Mohammed bin Rashid Al Maktoum, Vice President and Prime Minister of the UAE and Ruler of Dubai, for the future of Dubai and consolidate its global status as a leading city of the future. In partnership with its partners from government entities, international companies, start-ups and entrepreneurs in the UAE and around the world, Dubai Future Foundation drives joint efforts to collectively imagine, design and execute the future of Dubai.

Under the supervision and with the support of His Highness Sheikh Hamdan bin Mohammed bin Rashid Al Maktoum, Crown Prince of Dubai, Chairman of the Executive Council of Dubai and Chairman of the Board of Trustees of Dubai Future Foundation, DFF works on a three-pronged strategy: to imagine, design and execute the future. It does this through the development and launch of national and global programmes and initiatives, preparing plans and strategies for the future, issuing foresight reports and supporting innovative and qualitative projects. These contribute to positioning Dubai as a global capital for the development and adoption of the latest innovative solutions and practices to serve humanity.

Dubai Future Foundation focuses on identifying the most prominent challenges facing cities, communities and sectors in the future and

dubaifuture.ae

research@dubaifuture.gov.ae

@dubaifuture