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Assessing the Scalability of Clean Innovations for Net Zero:

Strategic Interventions to Enhance the Economic Viability of Scaling Direct Air Capture Technologies

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Background

Despite significant efforts to reduce carbon emissions through sustainable energy sources and the adoption of lifestyle changes at both individual and organisational levels, a considerable amount of carbon dioxide continues to remain in the atmosphere. Human activities are responsible for generating approximately 35 billion tons of CO2 annually. According to MIT's Climate Portal, even after considering natural processes involving oceans, plants, soil, and other carbon sinks, an additional 20 billion tons of CO2 must still be removed each year. Additionally, when you take into account several industries that are more difficult to decarbonise, such as aviation and shipping, there is a strong need to apply carbon removal techniques (IEA, 2023). Various methods for carbon dioxide removal are available, including bioenergy with carbon capture and storage (BECCS) and natural absorption through forests and soils. However, Direct Air Capture (DAC) has emerged as the most promising solution for large-scale implementation. Nonetheless, the expansion of its deployment has been constrained by its limited economic feasibility.

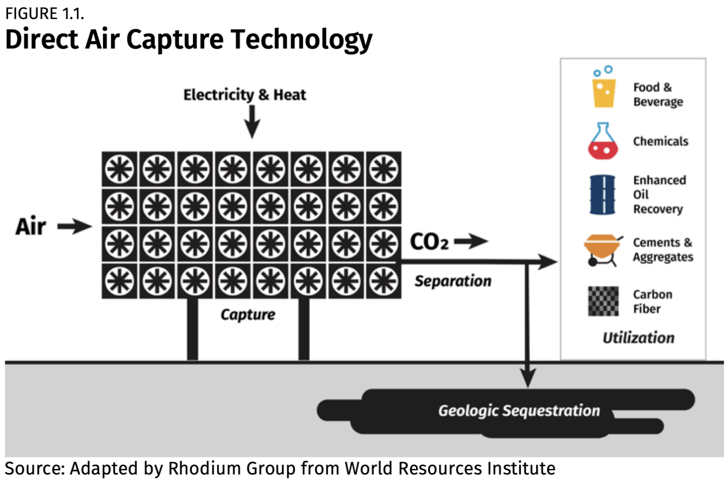


Figure 1

Figure 1 from the World Resources Institute, later adapted by the Rhodium Group, gives a general illustration of DAC technology. DAC extracts CO2 directly from the atmosphere, which can then be stored permanently in geological formations, or used again in a variety of ways ([IEA]). Popular uses include using it to produce concrete, plastic, fuel, or even be sold to use in fizzy drinks.

These processes are referred to as carbon recycling, as they involve returning carbon to the atmosphere. In fact, according to Figure 2 from Carbon180, fuels represent the product with the highest global market value that can be produced using captured CO2. However, the use of fuels results in the release of carbon back into the atmosphere, rendering it counterproductive and an ineffective method for the reutilisation of carbon.

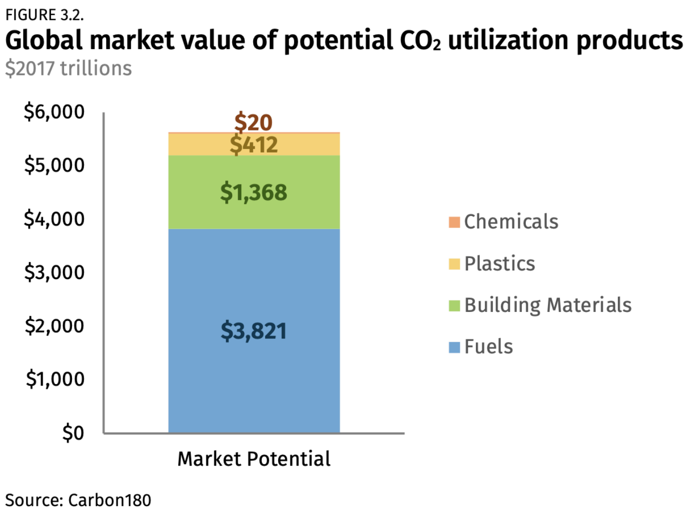


Figure 2

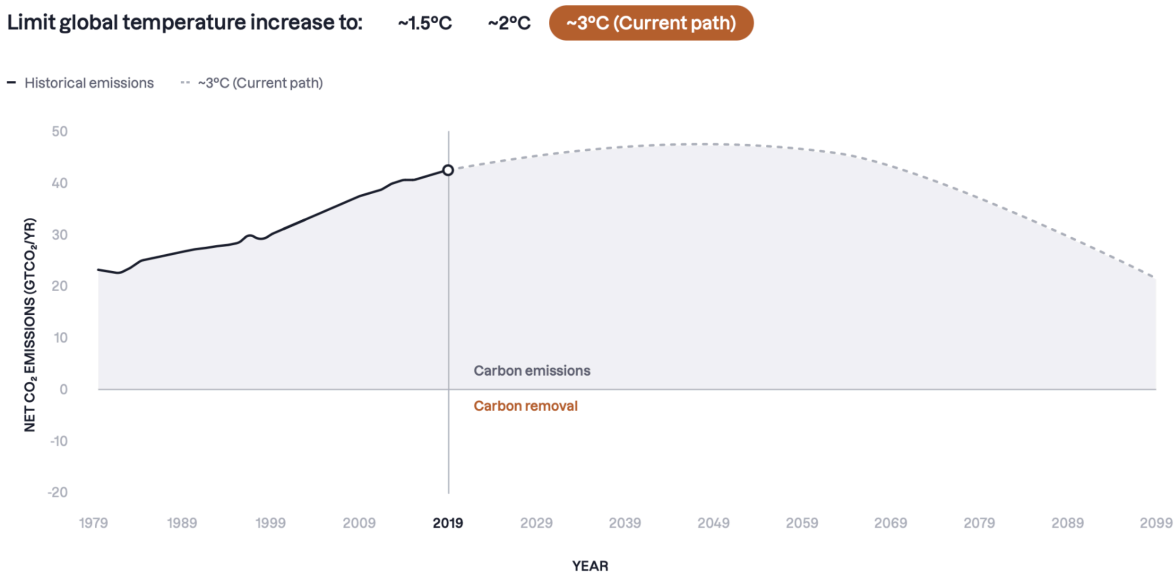
While the prospect of continuing our current consumption and lifestyle trends without adversely affecting the environment is appealing, there are still significant challenges that come with the implementation of Direct Air Capture (DAC). Capturing CO_2 from the atmosphere is one of the most expensive forms of carbon capture compared to other techniques. This is due to the fact that CO_2 released into the atmosphere is more dilute than at its source, requiring DAC to utilise relatively higher energy inputs, which in turn drives up costs (IEA).

Furthermore, the extensive number of DAC plants necessary to process an adequate volume of CO_2 would occupy vast land areas and necessitate additional wind and solar farms for power. According a Professor of Civil Engineering at MIT, there are currently limitations on the amount of carbon that can be removed due to finite land resources. Existing technology suggests that achieving the required scale would involve constructing an estimated 30,000 facilities, all of which would demand substantial resources and generate a significant carbon footprint during their construction, including activities such as mining, building, and manufacturing (Yoshida, 2021). Nevertheless, it is clear that without a significant reduction in carbon emissions, along with the scaling up of technologies to extract carbon from the atmosphere, meeting our net-zero goal by 2050 to limit global temperature rise to 1.5 degrees Celsius will be impossible.

The UN Intergovernmental Panel on Climate Change (IPCC) estimates that Direct Air Capture (DAC) could potentially capture 29 gigatonnes of CO_2 by 2100, positioning it as one of the three key methods for carbon capture, utilisation, and storage (CCUS). DAC offers several advantages compared to other CCUS methods, particularly its locational flexibility, which minimises transportation needs and associated costs (IEF). This flexibility translates to significantly lower land and water usage—up to 30 to 100 times less than alternative methods, such as bioenergy with carbon capture and storage (BECCS) (Yoshida, 2021).

However, the implementation of DAC is not without its challenges. There are concerns regarding resource limitations, the risks of over-reliance, and the costs associated with carbon storage and safety, including potential issues like CO_2 leakage and water pollution. Additionally, the reutilization of captured carbon often proves unsustainable, as it can eventually re-enter the atmosphere. A pressing concern is that without appropriate policies and economic or financial interventions, there is currently “no price for carbon anywhere in the world large enough to make sequestration financially viable” (Yoshida, 2021).

Despite these challenges, the IPCC has emphasised that Direct Air Capture (DAC) technology remains essential to achieve our emission reduction targets. The accompanying dashboard from Frontier Climate (Figure 3) illustrates our annual net carbon emissions. If current business practices and emissions release rates persist, we are projected to experience a temperature increase of approximately 3 degrees Celsius.



Historical Emissions via Global Carbon Project[1], "Current path" shows SSP4-6.0[2,3], removal pathways adapted from CICERO[4]. For simplicity this chart only shows CO_2, though the modeled scenarios account for other greenhouse gas emissions, all of which will need to be reduced.

Figure 3

Consequently, it is imperative to take appropriate actions to limit this temperature increase to 1.5 degrees Celsius, as outlined in the Paris Agreement. Achieving this goal requires not only a reduction in emissions but also an effective carbon removal strategy. A combined approach is projected to significantly lower emissions by 2030, as indicated by Figure 4.

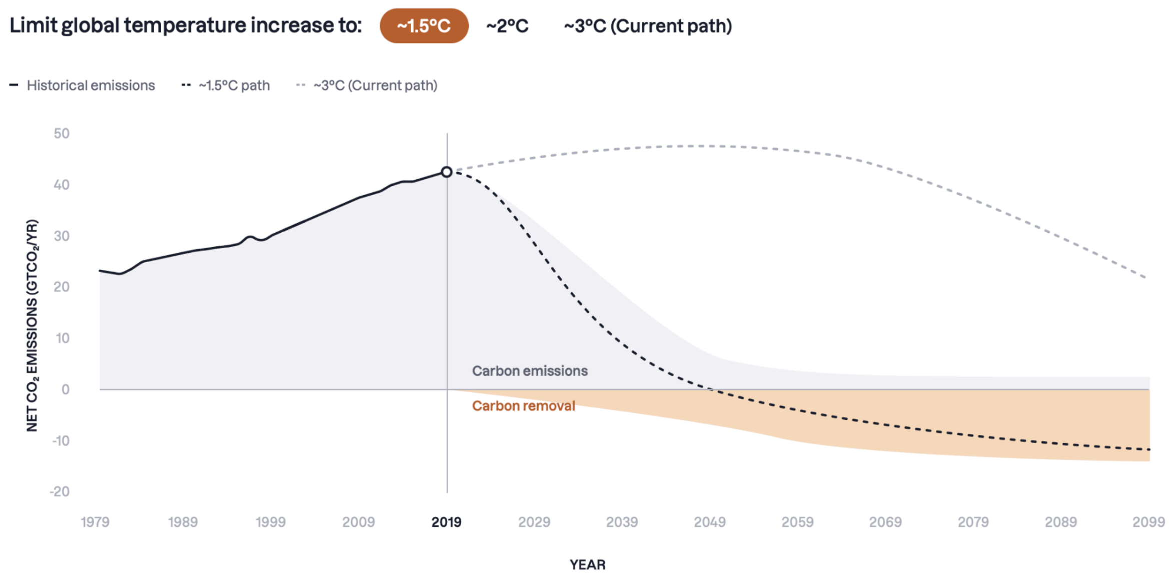


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Figure 4

To effectively scale Direct Air Capture (DAC), the ESG Initiative at the Wharton School, University of Pennsylvania, emphasises the need for the federal government to enhance budget allocations for research and development, increase procurement of carbon offsets, and refine policies that incentivize companies and individuals to adopt this technology.

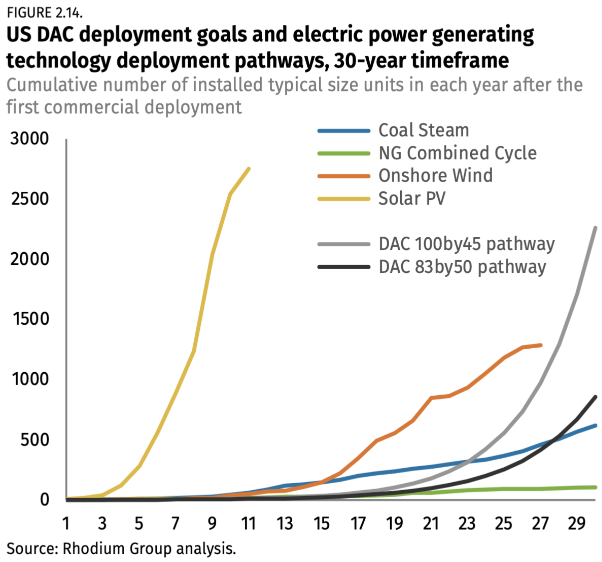


Figure 5

Figure 5 illustrates the projected increase in installed DAC units over a 30-year period. An analysis from Rhodium Group forecasts an exponential rise in installations in later years, likely due to economies of scale, advancements in technology, and a more consistent flow of investments. This surge may also reflect a more comprehensive and serious global approach to addressing climate change (Yoshida, 2021). The key challenge now is identifying the mechanisms and interventions that can effectively trigger and sustain this growth.

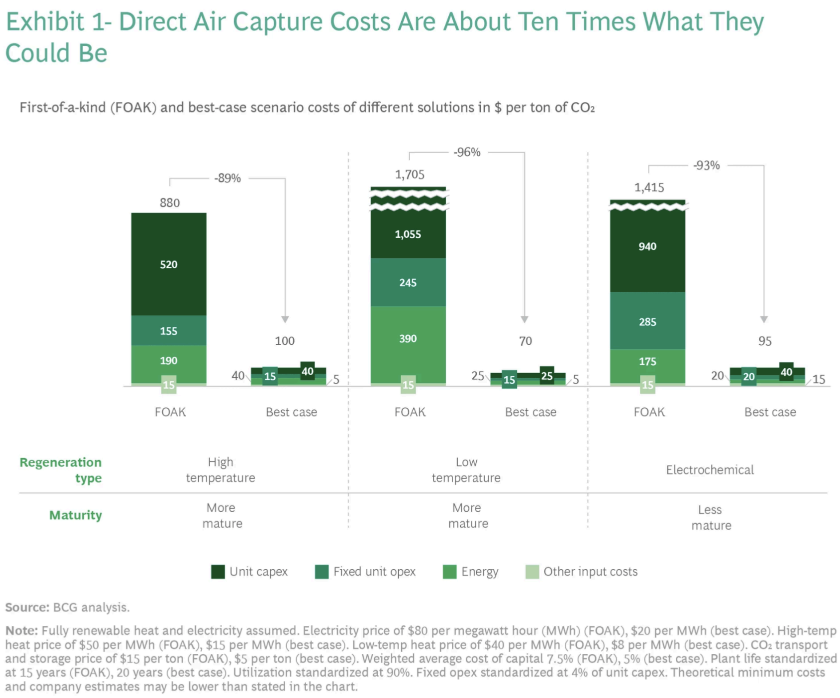
Currently, there are only 19 operational DAC plants worldwide, collectively capturing tens of thousands of tons of CO2 annually, according to the International Energy Agency (IEA). However, the IEA's Net Zero Scenario envisions the need to construct an average of 32 new plants each year, with each plant removing 1 Megaton of CO2 annually. At present, researchers at ETH Zurich estimate DAC costs to range between $230 and $540 per ton of CO2 captured (Elhardt, 2024).

Objectives

1. Elaborate on the current sentiments, progress, investments and outlook of direct air capture technology
2. Identify financial interventions and government policies that can be used to scale direct air capture
3. Analyse and evaluate the different interventions and how effective they have been when implemented in different situations and countries
4. Recommend the best course of action for the United Kingdom to achieve target of net zero

Current Outlook

The Boston Consulting Group has recently released a report titled *Shifting the Direct Air Capture Paradigm,* in which it details "3 Potential Answers to the DAC Puzzle" [(BCG, 2024)](). The IPCC states that by 2050, up to 10 billion tons of CO2 will need to be removed from the air each year. They suggest that the cost of DAC will need to fall from the $600 - $1000 range per ton to $100 - $200 to be widely scaled. This cost is in around the same range as waste disposal in high income countries, which range from $170 - $205 per ton. This fall in cost is needed in order to accelerate demand from the private sector and make this technology generally affordable [(BCG, 2024)]().



BCG has conducted analysis on seven different DAC developers to determine whether or not it was reasonable to estimate cost reductions of over 75%. Their findings show that it was possible, but only through an influx of massive investments, concentrated government support, and higher industry engagement. There is great uncertainty on future demand as there are high barriers to entry, discouraging initial investments.

Figure 7

Suppliers of key components are also not investing enough resources into research and development, while companies are not adopting collaborative approaches to drive more rapid innovation [(BCG, 2024)](). This analysis takes into consideration the experience curve, a concept first introduced by BCG, which essentially indicates that costs decline as volume increases. BCG estimates that the industry requires an investment of about $200 billion to make costs more attractive to investors.

However, there is still significant progress being made. Figure 8 illustrates current private and public investments in major DAC (Direct Air Capture) plants across Western Europe and North America, showcasing the potential of DAC technology. These investments also reflect growing investor confidence in the success and scalability of DAC as a critical tool in addressing climate change. As more resources are directed toward DAC projects, this indicates that both private and public sectors recognize the importance of advancing carbon removal technologies to meet sustainability targets.

Domestic and International Public Sector Investment in Direct Air Capture

United States

The past decade of federal research funding for direct air capture is **less than 1 percent** of the National Academies' recommended cumulative level of $1.8-2.4 billion over the next one to two decades. For reference, since 2009, cumulative federal research funding for direct air capture totals less than **$11 million** – about 4.6 percent of the average *yearly* appropriated research budget for solar energy technologies.[1]

Ways to advance direct air capture: Implementation and potential expansion of 45Q tax credits for carbon capture; Greater federal research and development (via DOE, Department of Defense, NASA, NSF, and others).

Canada

While the total amount of funding the Canadian government has invested in direct air capture technology is not readily available, the government boasts numerous funding mechanisms (such as those supporting Carbon Engineering) that have been or can be leveraged for direct air capture projects, including:

- Business Development Bank of Canada's Industrial, Clean and Energy Technology Venture Fund
- Pan-Canadian Framework on Clean Growth and Climate Change – Low Carbon Economy Fund

European Union

The European Union has clear policy frameworks, such as the Emissions Trading System, and multiple complementary funding opportunities that can support direct air capture projects. Long-term collective policymaking efforts continue to provide greater structure and certainty to carbon capture endeavors.

- Horizon 2020: EU Research and Innovation Program with nearly 80 billion euros in funding available over seven years (2014-2020)
- Innovation Fund: Focused on innovative, low-carbon tech in energy-intensive industries; carbon capture, use, and storage; renewable energy generation; energy storage

Figure 8

Identifying Interventions

This section of the report identifies potential interventions and categorises them into market based mechanisms, market shaping mechanisms, and green finance mechanisms.

1. **Market-Based Mechanisms:**
    a. Carbon Taxes
    b. Cap and Trade Systems / Emissions Trading Systems (ETS)
    c. Carbon Offsets
    d. Sale of CO2 Sourced Carbon
    e. Voluntary Carbon Markets
    f. Contract for Difference
    g. Feed-in Tariffs
    h. Subsidies and Tax Incentives
    i. Concessional / Grant Payments
2. **Market-Shaping Mechanisms:**
    a. Public Procurement
    b. Advanced Market Commitments
    c. Direct Investments
3. **Green Finance Mechanisms:**
    a. Green Bonds
    b. Sustainable Investment Funds

Evaluation / Discussion

A. Market Based Mechanisms

I have selected several widely implemented strategies and analysed their effectiveness, the conditions necessary for their success, and their ease of implementation.

In the case of carbon pricing, specifically carbon taxes and cap-and-trade systems, the outcomes vary significantly between countries, such as Sweden and Australia. Sweden's carbon tax has proven to be highly effective, resulting in a 25% reduction in greenhouse gas emissions. Stable and clear carbon pricing signals in Sweden have successfully attracted investments, and revenues from the tax have been reinvested into clean energy alternatives and subsidies for carbon removal technologies. By contrast, Australia faced public backlash, underscoring the importance of considering socioeconomic factors, like energy affordability, when designing sustainability initiatives. This is especially relevant for the UK, which has historically struggled with rising energy prices. Therefore, it would be wise to include compensatory mechanisms, such as rebates or programs to offset costs for low-income households. A potential solution could be a tiered carbon tax, similar to a progressive income tax, where taxation increases gradually over time, allowing businesses time to adjust to higher energy costs. Additionally, subsidies or incentives for companies that invest in renewable energy or carbon removal technologies could further support this transition.

Cap-and-trade systems have also shown mixed results. The European Commission for Climate Change reported that the EU Emissions Trading System (ETS) successfully reduced emissions by 47% compared to 2005 levels (European Commission). This system establishes a cap on emissions and effectively creates a market value for carbon. The EU ETS has set a gradually declining cap, which ensures ongoing reductions in emissions while providing companies with the flexibility to trade allowances in a market-like environment. However, the success of such systems relies on the robustness and liquidity of the market. Initially, the EU ETS struggled with an oversupply of permits, which led to lower carbon prices and reduced the incentives for companies to cut emissions. By adjusting the cap, the system has since demonstrated its ability to adapt and remain effective as a carbon trading mechanism.

In California, the Low Carbon Fuel Standard (LCFS) tackles one of the most difficult areas to decarbonize: transportation fuels. The LCFS aims to reduce greenhouse gas emissions and decrease California's dependence on petroleum by encouraging the use of cleaner, low-carbon transportation fuels (California Air Resources Board). The system evaluates the "carbon intensity" (CI) of fuels like gasoline and diesel and compares these results to a continually decreasing CI benchmark each year. Fuels with a CI below the benchmark generate credits, while those exceeding it incur deficits. This flexibility ensures that the market maintains an efficient and fair price for carbon, with a cap that limits emissions. High market liquidity makes the system adaptable, but designing an effective cap is critical. If set too high or too low, the system's efficiency could fall. For the UK, implementing sector-specific caps—targeting areas such as transportation, heavy industry, and energy—could lead to more focused emissions reductions. This approach would also help identify sectors that are exceeding or lagging behind in their reduction targets. Additionally, strict oversight would be required to prevent market manipulation or oversupply, ensuring the overall effectiveness of the program.

Another mechanism, Voluntary Carbon Markets, is expected to grow rapidly, driven largely by corporate investments and commitments to achieving net-zero emissions. According to McKinsey, the demand for voluntary carbon credits is projected to continue increasing, reaching up to $50 billion, depending on credit pricing (McKinsey, 2021). These carbon offsets allow companies to invest in carbon dioxide removal (CDR) projects, such as reforestation, clean energy, and community initiatives, to earn carbon credits. However, it's important to note that earning credits can be challenging due to the lack of clear definitions and regulations for positive environmental benefits. Additionally, the process of verifying new credits is time-consuming, and suppliers often face unpredictable demand afterward.

There are also risks of over-crediting, where credits may be issued for reductions that do not actually take place, and companies could use offsets as a way to avoid reducing their own emissions. McKinsey analysts have observed that the voluntary carbon market struggles with low liquidity, limited data, and minimal financing (McKinsey, 2021). Therefore, it's crucial to standardise and tighten verification processes to accelerate credit issuance and ensure fairness. It is equally important to hold companies accountable, preventing them from relying solely on offsets instead of reducing their emissions. Encouraging investment in carbon removal technologies like Direct Air Capture (DAC) could stimulate innovation and scale up the adoption of such technologies.

Carbon Contracts for Difference (CCfDs), as explained by the Canadian Climate Institute, were designed to manage risks when future carbon prices fail to rise as projected (Canadian Climate Institute, 2021). These contracts provide protection for low-carbon projects, which depend heavily on future carbon prices, such as projects involving carbon storage or green hydrogen. By guaranteeing a fixed price, CCfDs increase investor confidence in green projects. For example, the government could set a strike price of $150 per tonne of carbon, with the expectation that the price will rise to $170 by 2030. If carbon prices fail to reach the expected level, the government compensates the project developers. Conversely, if prices rise above the strike price, the project developers pay out (Canadian Climate Institute, 2021).

CCfDs have been effective in reducing emissions by securing a minimum carbon price, making green projects less risky for investors. However, setting prices too high could generate public opposition. Germany's new CCfD program offers another example: it compensates small and medium enterprises (SMEs) and energy-intensive industries for 15 years, covering additional operating and capital expenses, making green technology more appealing for energy-intensive industries for companies who otherwise would not be able to afford it (IEA, 2023).

B. Market Shaping Mechanisms

A relatively recent example of market-shaping mechanisms is Advanced Market Commitments (AMCs). The University of Chicago defines market shaping as the use of economic tools to correct market failures when commercial incentives alone are insufficient. According to their Market Shaping Accelerator, AMCs are a type of "pull mechanism" used to encourage private investment by creating incentives, ultimately bringing solutions to market

(The University of Chicago). AMCs involve a binding promise made in advance to purchase a new product once it is invented. This can include a firm producing the technology agreeing to sell at a price close to cost in exchange for the sponsor committing to purchasing a large volume of the products.

AMCs have demonstrated success in the past. For instance, in 2009, the use of AMCs for pneumococcal vaccines saved 700,000 lives (The University of Chicago). This shows the potential of AMCs to help scale up emerging technologies, such as Direct Air Capture. The Frontier AMC is a notable example of this, illustrating how guaranteeing demand can drive both investment and innovation, even when the technology is still in its early stages. Frontier has committed to purchasing over a billion dollars' worth of initial carbon removal from 2022 to 2030 (Frontier). This initiative is backed by major tech and financial players, including Stripe, Alphabet, Shopify, Meta, and McKinsey.

In addition, government investments in such programs further increase investor confidence, sending a strong signal that solid, long-term demand for the technology can be expected in the future. This creates a supportive environment for emerging technologies like DAC to thrive.

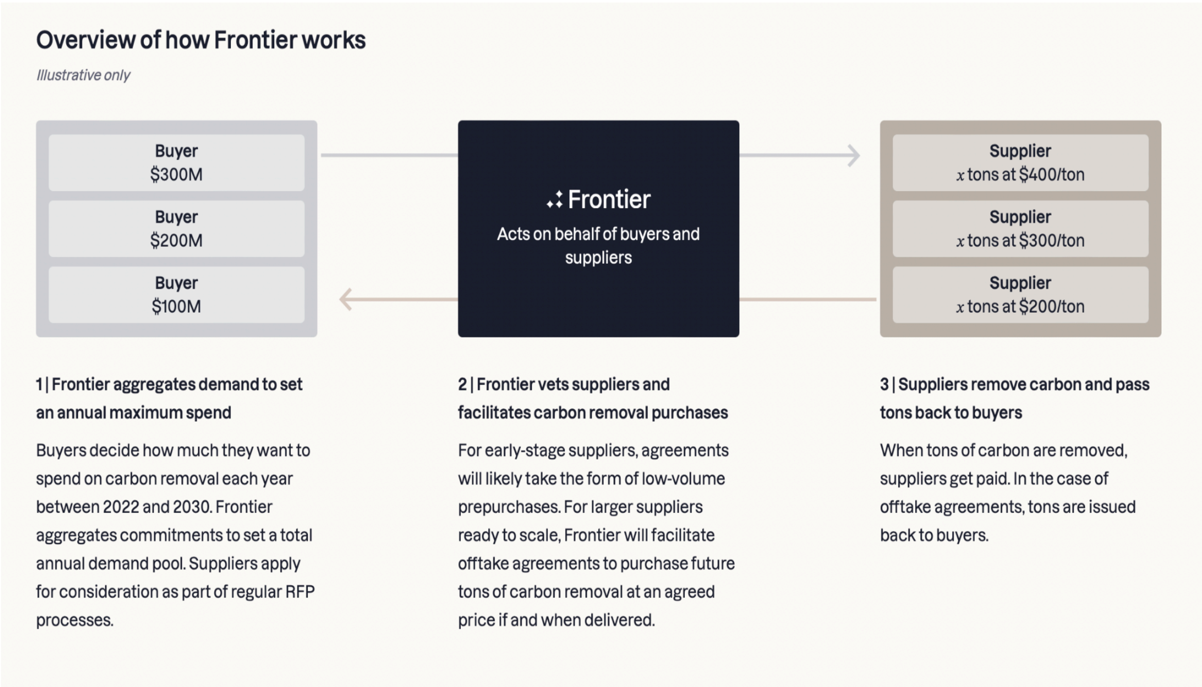


Figure 9

Figure 9 illustrates how Frontier operates, highlighting the two-way relationship between Frontier, buyers, and suppliers. Like other advanced market commitments, Frontier's primary goal is to send a strong signal to entrepreneurs, investors, and researchers that the market for these emerging technologies is growing. Frontier is focused on fostering new carbon removal supply rather than increasing competition over existing supplies.

Frontier's team of experts facilitates purchases from companies with high-potential CDR technologies, driving demand signals in the market without excluding companies that are still in the development phase. However, a careful and strategic approach must be taken when choosing which technologies to support, ensuring that only viable and impactful innovations are incentivized.

To scale essential technologies like Direct Air Capture (DAC) and meet sustainability goals, the UK should consider creating its own AMC to generate demand for DAC or collaborate with existing initiatives, such as Frontier. Early investments and government funding will be critical in scaling DAC quickly and efficiently.

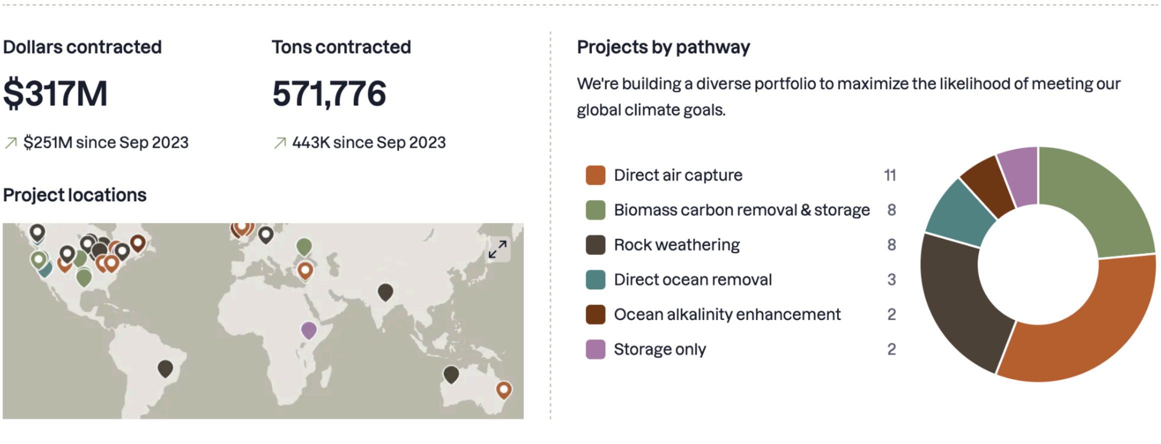


Figure 10

This illustration from Frontier's website depicts the value of contracts it has secured since September last year. As seen in the graph, Direct Air Capture (DAC) currently leads as the top carbon dioxide removal (CDR) method.

C. Green Finance Mechanisms

According to the United Nations Environment Program (UNEP), green financing aims to increase investments from public, private, and nonprofit sectors to fund technologies and initiatives that promote sustainable development. UNEP's key areas of focus include supporting the public sector, advocating for public-private partnerships, and increasing the capacity of small and medium-sized enterprises (SMEs) working toward sustainability through micro-credits.

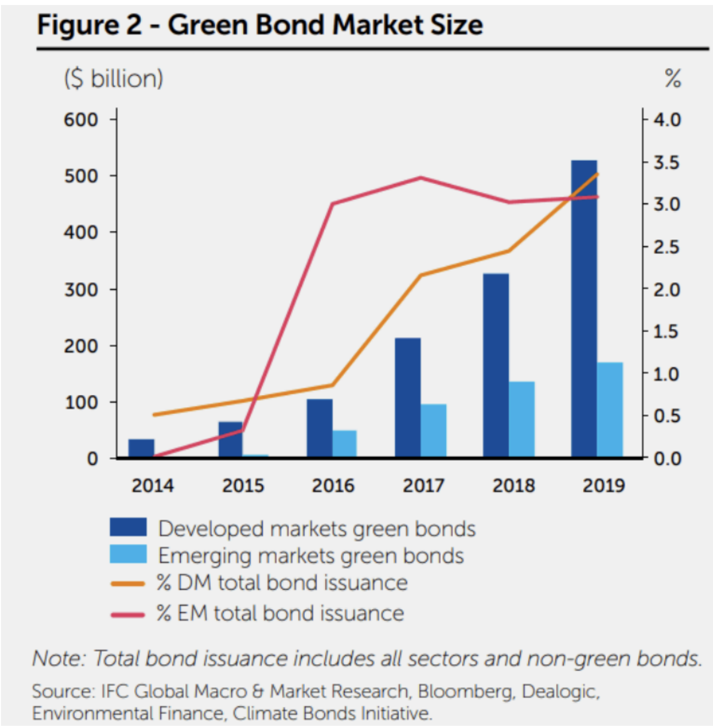
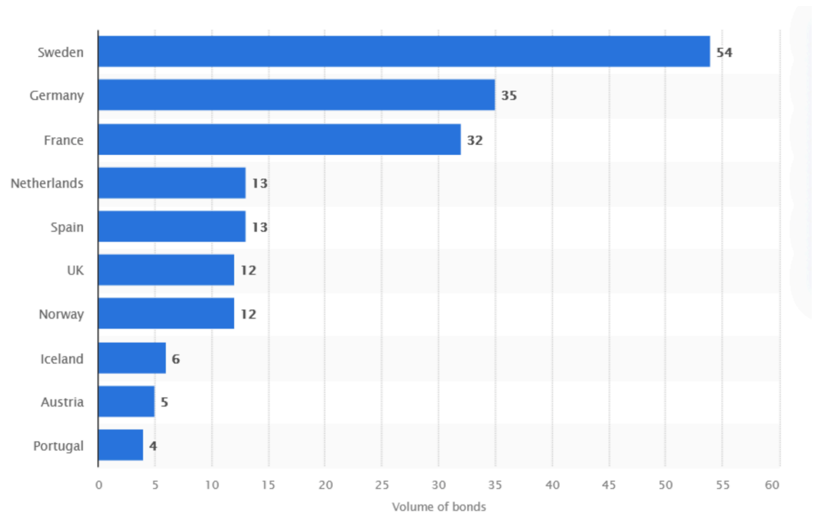


Figure 11

Figure 11 highlights the significant growth in the market size of green bonds. One reason green bonds are attractive to investors is their potential to create positive environmental impacts with reduced risk. As explained by Investopedia, green bonds are a type of fixed-income security that funds projects with environmental benefits. Like traditional bonds, they offer investors a stated return, but the profits are allocated to finance sustainability projects (Segal, 2024). Additionally, the Corporate Finance Institute (CFI) notes that green bonds may offer tax incentives as well.

The green bonds market saw a notable surge in 2021 when the European Union issued $14 billion in green bonds, marking the largest issuance of its kind at the time (World Economic Forum, 2023). This demonstrates the growing momentum behind green financing as a key tool for achieving sustainability goals globally.



Volume of green bonds issuance in selected European countries in 2020. Image: Statista

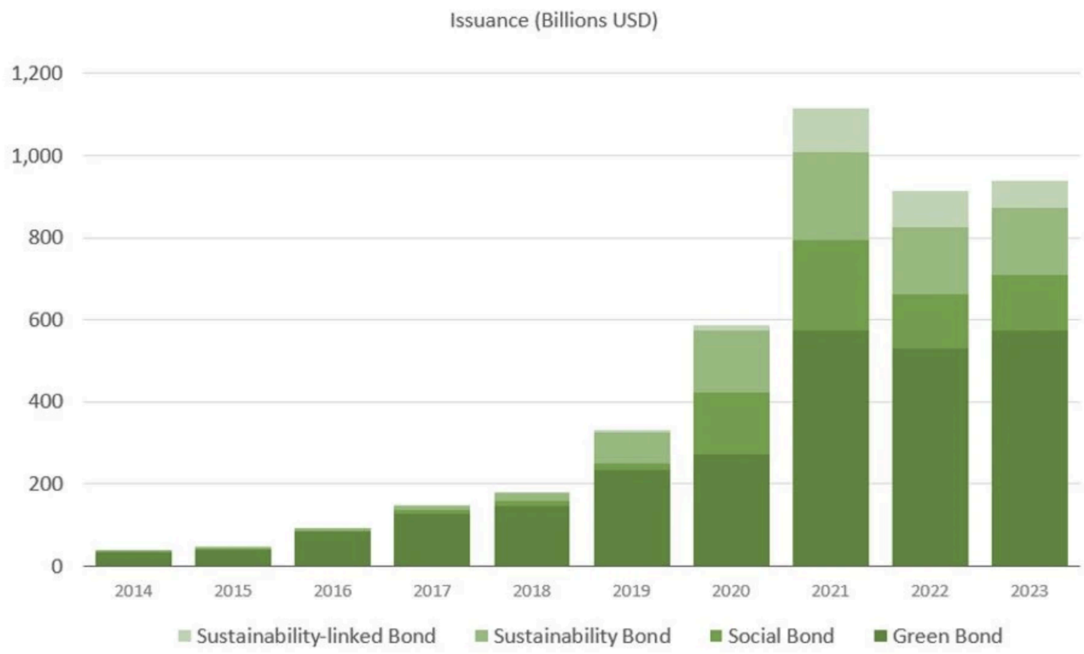
According to Figure 12 by Statista, developed countries in Europe have been leading in the volume of green bond issuances, with the UK ranking sixth. In 2023 alone, $193 billion worth of green bonds were issued globally, as reported by Bloomberg (Bloomberg, 2024).

Figure 12

Moreover, S&P forecasts that sustainable bond issuance could reach $1 trillion this year, a figure that appears very possible when considering historical trends in green bond growth. This indicates a rapidly expanding market as both public and private sectors increasingly invest in sustainable financial instruments to support environmental initiatives.

Despite the positive growth of green bonds, as shown by Figure 13, greenwashing remains a significant challenge. Companies often exaggerate the environmental impact of their projects, and the absence of standardised measurement frameworks across different regions weakens investor confidence. Addressing this issue will be critical to ensuring that green financing continues to grow and support meaningful environmental change.

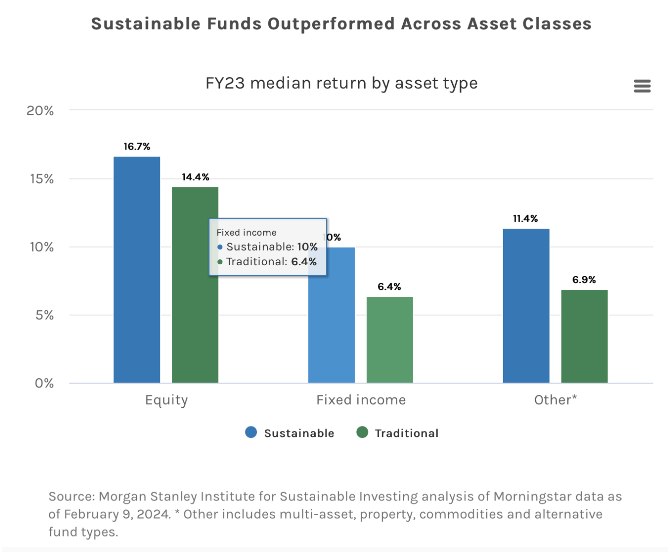
Figure 1.



Note: Data shows yearly supply of impact bonds

Source: Bloomberg

Figure 13



Interestingly, sustainable investment funds have recently outperformed traditional funds across all asset classes. According to Morgan Stanley, sustainable funds generated median returns of 12.6%, significantly outpacing traditional funds, which saw returns of 8.6%. These funds now account for 7.2% of global assets under management, signalling the strong upward trend of sustainable investing. This demonstrates that sustainability-focused investments can also offer attractive financial returns.

Figure 14

To further drive investments, government expansionary monetary policies, along with tax exemptions or reduced rates on income from green bonds, could be beneficial. Additionally, offering tax relief on capital gains from sustainability-linked investments would provide a strong incentive for investors to channel more resources into these areas.

For the UK, one potential measure is to focus on issuing green bonds specifically targeting carbon removal technologies, such as Direct Air Capture (DAC), while ensuring clear and enforceable standards to avoid greenwashing. Encouraging sustainable investment funds and committing to direct government investments would further help scale DAC technologies, which are crucial for meeting long-term climate goals.

Conclusion

This report has identified a total of 15 mechanisms, listed below:

4. **Market-Based Mechanisms:**
    a. Carbon Pricing - Carbon Taxes
    b. Carbon Pricing - Cap and Trade Systems / Emissions Trading Systems (ETS)
    c. Carbon Offsets
    d. Sale of CO2 Sourced Carbon
    e. Voluntary Carbon Markets
    f. Contract for Difference
    g. Feed-in Tariffs
    h. Subsidies and Tax Incentives
    i. Concessional / Grant Payments
5. **Market-Shaping Mechanisms:**
    a. Public Procurement
    b. Advanced Market Commitments
    c. Direct Investments
6. **Green Finance Mechanisms:**
    a. Green Bonds
    b. Sustainable Investment Funds
    c. Sustainability-Linked Bonds (SLB)

In conclusion, there is not one intervention or mechanism that is capable of helping scale DAC to the level that we need it to be to achieve net zero emissions. Drawing from successful implementations in other countries, the UK's most effective approach would involve a combination of key strategies:

1. Refining the UK ETS with industry-specific caps and ensuring market liquidity
2. Implementing a progressive carbon tax and
3. Creating an AMC for DAC technologies or working with an existing AMC to drive investment and innovation for a risky, emerging technology
4. Issuance of more green bonds that are targeted for carbon removal and encouraging private investment through sustainable investment funds through government regulation

By implementing this multi-faceted approach, the UK can simultaneously stimulate demand and incentivize supply, creating the necessary conditions to accelerate the adoption and scaling of DAC technologies.

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