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Costing Direct Air Capture Towards Zero and Negative Carbon Emissions

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The question is often asked, "Is Direct Air Capture viable at a large scale?" Prof. Don MacElroy does the maths to find out.

This article endeavours an initial examination of the possible economic costs of Direct Air Capture (DAC) (net of carbon storage) and recent questions on the scalability of DAC to tackle anthropogenic emissions to Earth's atmosphere.

The discussion is provided in two parts:

1. We briefly examine the application of DAC as a tool in our drive towards net-zero CO_2 emissions by 2050.
2. We then focus on the wider issue of legacy CO_2 emissions, namely those resulting from human activities since the beginning of the industrial revolution.

A number of assumptions will be made to arrive at what we believe is a reasonable and appropriate path to the future deployment of DAC.

Mitigation of Hard-to-Abate Annual CO_2 Emissions

Current global CO_2 emissions stand at **41.6 billion tonnes per year** (Global Carbon Budget). These can be broadly divided into two categories:

1. **Manageable emissions**, which can be reduced through renewable energy, transport electrification, building materials development, insulation and retrofitting, building design, sustainability in agriculture etc.
2. **Hard-to-abate emissions**, which come from heavy industry (cement, steel), aviation (especially long-haul), shipping, certain heavy transport systems, and energy-from-waste incineration.

These hard-to-abate emissions represent typically ~20% of total emissions and this proportion will only grow as we succeed in CO_2 emissions reduction within other areas.

The focus of the rest of this section is on using DAC in the latter. To acknowledge the possible role of other approaches in this endeavour (notably BECCS through afforestation, wetland developments etc, ERW etc), I will assume DAC can be ultimately deployed to capture up to 50% of hard-to-abate emissions or **4.16 billion tonnes of CO_2 per annum from the atmosphere until the year 2050** in order to reach effective net-zero emissions by the target date. This further assumes the other, more manageable emissions sources have been dealt with in their own time.

A Simplified DAC Deployment Model

We consider the availability of modular DAC units, with **each module capable of capturing 500 tonnes CO_2/annum**. DAC systems of this kind have been proposed by a number of technology developers, including NEG8 Carbon, at varying levels of TRL.

While these DAC units could be employed individually I will consider deployment as a cluster in the form of a **DAC park with 144 modules per park**. (Based on developments of modular DAC systems, each of these parks would typically occupy less than 10 hectares in land area).

Following the simple linear strategy suggested by Carl E. Rasmussen, atmospheric CO_2 (which would cumulatively add 208 billion tonnes to the atmosphere between now and 2050 if all hard-to-abate emissions were not tackled) will be captured over this period of 25 years by building $\mathbf{N}_{\text{DAC Parks}}$ in year 1, then another $\mathbf{N}_{\text{DAC Parks}}$ in year 2, i.e. two sets of parks running in parallel in year 2, then another $\mathbf{N}_{\text{DAC Parks}}$ in year 3 etc. until 2050. The details of the analysis for this system are provided in the Appendix and the results obtained are summarised in Table 1 below.

Table 1. Estimates for Capture of 50% of Hard-to-Abate CO_2 Emissions

$N_{\text{DAC Parks}}$ (Year 1)	Total Number of DAC Parks in 2050	Global CAPEX Per Year	Global OPEX (Year 1) (Increasing linearly each year)	Power Demand (Year 1)	Projected Power Demand in 2050
4,400	111,000	€800 Billion (0.82% of GDP (2025 basis))	€32 Billion	14.6 GW (0.51% of global ***renewable*** energy consumption)	365 GW (5.7% of global ***renewable*** supply) **

*** It is central to DAC operation that renewable energy is available and therefore DAC would be predicted to require approximately 5.7% of available (electrical) energy resources by mid-century. I believe this merely emphasises the need for accelerated deployment of renewable resources.*

In Ireland the costs will be €0.8 Billion (CAPEX) in Year 1 (0.15% GDP or 0.26% GNI(modified)) and remain as such until 2050 and the OPEX will be €32 Million increasing linearly until 2050. In light of recent National budgetary estimates these numbers are modest.

I strongly believe the above numbers demonstrate the viability of DAC at scale and that they are manageable as indicated by the corresponding fractions of the GDP involved.

It is also clear however that if the target of net-zero is to be achieved with the implementation of DAC, the development and deployment of this technology must occur as quickly as possible otherwise the costs of mitigation will accelerate.

The Management of Legacy CO_2 Emissions

The total mass of the atmosphere is 5.15×10^{15} tonnes. This is primarily air of molecular weight 29 so the number of moles is 1.78×10^{20} moles. While other components (other than oxygen and nitrogen) are present they are generally at very low concentrations.

Given the mole % of CO_2 in air is 0.0430% then in 2025:

$$N_{Atm-CO_2} = 7.64\,x\,10^{16}$$ moles of CO_2

Or the total mass of CO_2 in the atmosphere is

$$m_{Atm-CO_2} = 3.36\,x\,10^{12}$$ tonnes of CO_2

This includes both preindustrial levels as well as contemporary levels of CO_2.

In his recent article **C.E. Rasmussen** considered scalability of DAC as a major barrier to its implementation. In his analysis Rasmussen considered the removal of 1% of the ***total*** CO_2 content of the atmosphere. However, only that portion of the CO_2 in the atmosphere corresponding to anthropogenic ***legacy*** emissions need be considered.

Prior to the industrial revolution, the atmospheric CO_2 level was **280 ppm i.e. 2.19×10^{12} tonnes of CO_2** (largely made up by the natural carbon cycle). So with the current CO_2 level at 430 ppm, anthropogenic emissions would be primarily associated with 1.17×10^{12} tonnes of carbon dioxide or more correctly (due to absorption primarily by land and sea sinks and the dynamic equilibrium that subsequently ensues between the atmosphere and these sinks) this is 45% of the total emissions over the last two centuries or more i.e.

Total man-made cumulative CO_2 emissions = 2.6×10^{12} tonnes CO_2.

This is ideally the mass of CO_2 we need to remove from the atmosphere (today) but realistically we can consider a lower target akin to Rasmussen. In his 1% case this corresponds to a little under 2.5% of legacy emissions. I will take this value so, based on Rasmussen's minimal approach, the target legacy CDR is 0.025×2,600 billion tonnes = 65 billion tonnes.

The second assumption by Rasmussen is that this amount of CO_2 must be removed by 2050. This is incorrect. The temperature target of 1.5 C which has been driving the concept of net-zero by 2050 refers to current emissions, not necessarily legacy emissions. We could in fact take a more relaxed approach to legacy CDR and consider, for example applying it over a period of 75 years (by 2100) instead of 25 years.

In this case I will consider that DAC alone will be employed and that each DAC park has an operational lifetime of 25 years before full replacement is required. With each of the DAC parks operating in a ***continuous*** manner during their individual 25 year lifetimes and each of the

$N_{DAC\ Parks}$ capturing X_{CO2} tonnes of CO_2 per year then the total amount of CO_2 extracted (2.5% of today's legacy emissions) from the atmosphere by year 2100 is:

$65\times10^9 = X_{CO2}$x25x(5×25+1)/2

i.e.

$X_{CO2} = 41.3\times10^6$ tonnes CO_2/year/ $N_{DAC\ Parks}$

The computation of the system final estimates for 2.5% of legacy emissions is provided in the Appendix and the results are listed in Table 2 below.

Table 2. Estimates for Removal of 2.5% of Legacy Emissions

$N_{DAC\ Parks}$ (Year 1)	Total Number of DAC Parks in 2100	Global CAPEX per Year	Global OPEX (Year 1) (Increasing linearly each year)	Power Demand (Year 1)	Projected Power Demand in 2100
574	14,350	€103 Billion (0.107% of GDP (2025 basis))	€4.13 Billion	1.88 GW (<0.01% of global ***renewable*** energy consumption)	4.71 GW (0.23% of global supply) **

*** In this it is assumed that renewable, non-fossil power resources dominate global demand.*

The relatively modest costs and energy requirements indicated by the results tabulated above is the primary reason why I disagree with Rasmussen.

A significantly larger CDR could be applied to legacy emissions than indicated above which may also be counterbalanced by considering only those legacy emissions which have arisen since 1990 when the level of CO_2 was 354 ppm (Kyoto Protocol baseline year). If this 'extreme' case was tackled, then the total CDR would be

Total man-made cumulative CO_2 emissions (1990-2025) = 1.32×10^{12} tonnes CO_2.

This gives

$1.32\times10^{12} = X_{CO2}$x25x(5×25+1)/2

Or

$X_{CO2} = 0.84 \times 10^9$ tonnes CO_2/year/ $N_{DAC\ Parks}$

Based on the numbers reported in Table 3 it is clear that DAC faces significant challenges, but as in the case of the automotive and aviation industries and other large scale engineering systems developed over the last 100 years, I see no major barriers to the large-scale development of a DAC industry during the 21st century.

A number of elements not taken into consideration in the above are: the impact of learning analysis over the period of 75 years on the magnitude of the costs and energy requirements for carbon capture and nature's rehabilitation and resilience to gradual moderation of the levels of CO_2 in the atmosphere. Both of these will gradually lower the above estimates.

In this regard I believe DAC will play a major role in future climate control lowering the probability of severe climate events which could be of enormous cost during this century both in infrastructure and ecosystem damage as well as in human life and health.

Table 3. Estimates for Removal of 1990-2025 Legacy Emissions

$N_{DAC\ Parks}$ (Year 1)	Total Number of DAC Parks in 2100	Global CAPEX per Year	Global OPEX (Year 1) (Increasing linearly each year)	Power Demand (Year 1)	Projected Power Demand in 2100
11,600	0.29×10^6	€2.1 Trillion (2.2% of GDP (2025 basis))	€84 Billion	38.2 GW (1.3% of global ***renewable*** energy consumption)	0.96 TW (4.6% of global supply) **

*** In this it is assumed that renewable, non-fossil power resources dominate global demand in 2100.*

Appendix

Mitigation of Hard-to-Abate Annual CO_2 Emissions

With each of the DAC systems operating in a ***continuous*** manner and each group of $\mathbf{N_{DAC\ Parks}}$ capturing $\boldsymbol{X_{CO2}}$ tonnes of CO_2 per year then the total amount of CO_2 extracted from the atmosphere at year n is:

$$X_{CO2}\, n.(n+1)/2$$

In 2050 we therefore have

$$0.104\times10^{12} = X_{CO2} 25\times26/2$$

or

$$X_{CO2} = 320 \text{ Million tonnes/year}/N_{DAC\ Parks}$$

i.e. $\mathbf{N_{DAC\ Parks}}$ = 4,440 in the first year, a further $\mathbf{N_{DAC\ Parks}}$ in year 2 etc. By 2050, this strategy ultimately leads to 111,000 DAC Parks distributed globally.

The targeted capital cost of CO_2 capture via DAC is frequently cited as €100/tonne with a similar operating cost so for a single module capable of capturing 500 tonnes/annum, its equivalent CAPEX for 25 years operation is €2,500/tonne, the CAPEX of a module is ~ €1.25M with operating costs of €0.05M/yr then a DAC park will cost €180M with operating costs of €7.2M/yr. The global CAPEX for year 1 would be €800 billion (note that current Global Domestic Product is $114 trillion = €97 trillion, so CAPEX in year 1 is approximately 0.82% of GDP with

€32 billion OPEX). In years 2, 3, 4 etc the same CAPEX will arise but the OPEX will double, triple etc.

With regard to energy demand, based on a survey of modular DAC systems currently under development, both solid (adsorbent) based DAC and electrochemically based DAC, the minimum energy consumption requirement for such systems at this time is considered to be 400 kWh/tonne CO_2.

For the capture rate of 320 million tonnes in year 1 of the strategy outlined above the total energy demand in the first year of operation would be 128 TWh (14.6 GW) which is approximately 0.075% of ***total*** global primary energy consumption in 2025 (statista.com). This will increase to 3.2 PWh (365 GW) or 1.76% of projected global primary energy consumption (181 PWh) in 2050.

One difficulty which is implied by the source of the magnitudes of the primary energy consumption is that, strictly, only that contribution arising from non-fossil sources (renewables, hydroelectricity) should be considered and in 2025 the contribution from these is only 14.75 % of the total global non-fossil energy available which is 25.3 PWh (2.88 TW). The contribution required by DAC would be 0.51% of this figure. In 2050, non-fossil energy consumption is projected to increase to 56 PWh (31% of the total global energy consumption) and in this case the projected demand by DAC is estimated to be 5.7% of global supply.

The Management of Legacy CO_2 Emissions

With each module capturing 500 tonnes/yr and 144 modules per DAC park then the number of DAC parks distributed around the world per year each year until 2100, based on an assumption aligned with Rasmussen of removing 2.5% of legacy CO_2 emissions from the atmosphere by 2100, would be $\mathbf{N}_{\text{DAC Parks}}$ = 574 parks in each year (adjusted for park lifetime) which would lead to approximately 14,350 DAC Parks distributed globally by 2100.

For the 75 years involved I believe this is manageable and well within the capabilities of the world's governments. The CAPEX would be €103 Billion/year (0.107% of Global GDP, the same in each year until 2100) and the OPEX would be €4.13 Billion/yr. The energy demand at 400 kWh/tonne CO_2 would be 16.53 TWh in year 1 (less than 0.01% of global primary renewable energy consumption), increasing to 413 TWh in 2100 (0.23% of global consumption).

For the extreme case in which the removal of cumulative emissions corresponding to the period 1990-2025 is carried out then, in each year up to 2100, $\mathbf{N}_{\text{DAC Parks}}$ = 11,600 (€2.1 trillion CAPEX in year 1 (2.2% of today's Global GDP) accumulating to 0.29 million DAC parks worldwide by 2100). The energy demand would be 335 TWh in year 1 (1.3% of global primary non-fossil energy consumption), increasing to 8.4 PWh in 2100 (4.6% of global consumption).