



The Value of Direct Air Carbon Capture and Storage (DACCS)

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IEAGHG

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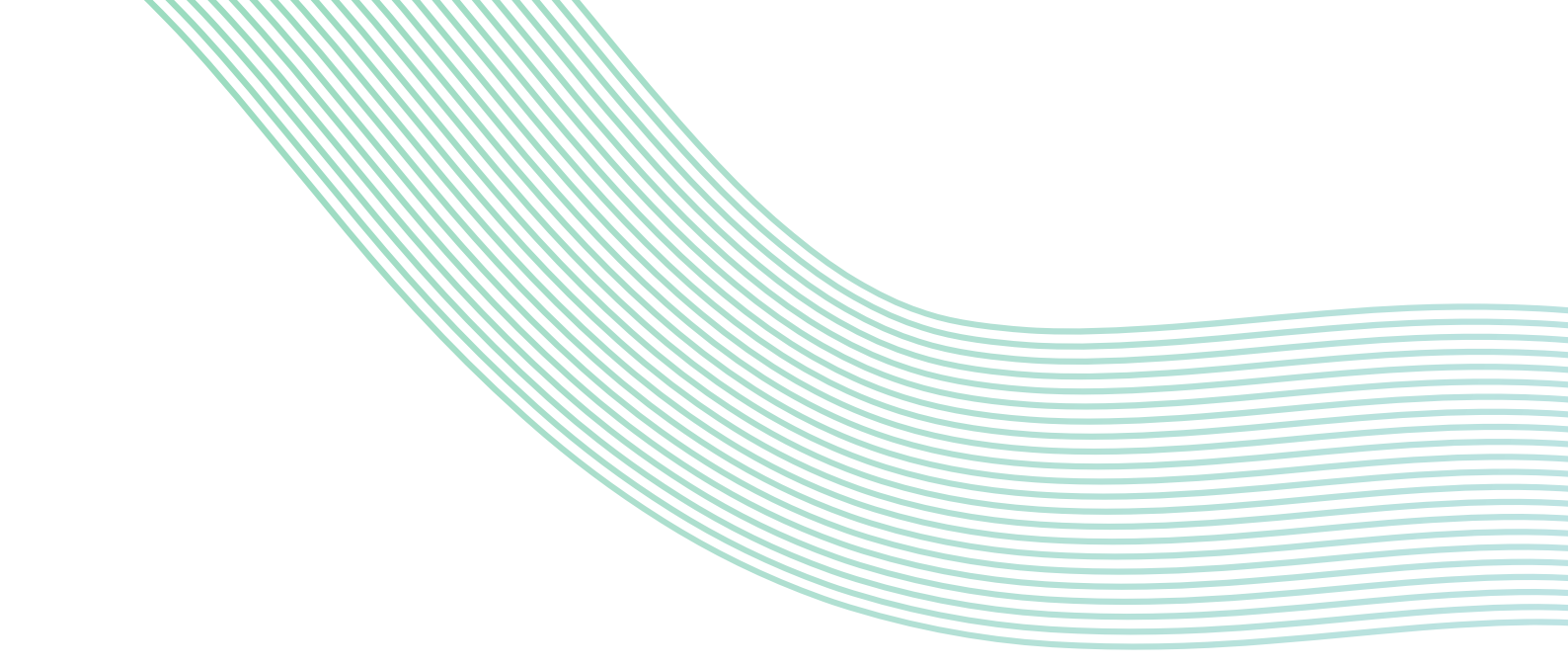
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To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The report is also reviewed by a panel of independent technical experts before its release.

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Report Overview:

The Value of Direct Air Carbon Capture and Storage (DACCS)

Introduction

The aim of this study is to evaluate the value of direct air capture and storage (DACCS) in the energy transition (down to the regional level), accounting for key factors, including carbon removal efficiency, timeliness, durability, land footprint and techno-economic performance. The analysis focused on comparing the performance of liquid sorbent direct air capture (L-DAC) and solid sorbent direct air capture (S-DAC). Comparison of DACCS with other mitigation technologies was outside the scope of this study.

Key Messages

- DACCS should not be viewed as a substitute for emissions reduction. The mitigation/abatement of greenhouse gas (GHG) emissions should be the priority, but carbon removal and permanent CO₂ storage (e.g. geologically, in cement or concrete but not in synthetic fuels as it would be re-emitted when the fuel is combusted) will still be an essential technology required to address residual emissions.

- Current cost and performance estimates for DACCS vary widely across literature due to inconsistent assumptions about energy supply, plant scale, sorbent degradation, and economic parameters.
- Given that energy supply carbon intensity (CI) is a strong contributing factor in overall value chain emissions, it is critical to incorporate energy supply scenarios based on realistic assumptions and to recognise the related uncertainty.
- Achieving net-negative emissions with DACCS depends primarily on the CI of supplied energy. Both L-DAC and S-DAC with permanent storage can deliver negative emissions today in regions where clean energy is available, or when co-located with renewable energy (RE). Thus, dedicated low-carbon energy supply systems (e.g., stand-alone renewables, geothermal, or CCS-abated fossil) should be actively explored as enablers of early DACCS deployment.
- DAC is relatively expensive but delaying all DACCS deployment until after 2030 may miss critical opportunities to build supply chains, test regulatory frameworks, and reduce costs via learning.
- Scaling DACCS to the gigatonne (Gt) scale requires major investment in manufacturing, workforce, and logistics, especially for modular components like contactors and heat exchangers. Deployment could face bottlenecks in power supply, CO₂ transport and storage (T&S) infrastructure, which may delay or limit DACCS's contribution. Projects also require significant upfront capital investment which can be challenging to acquire, which can contribute further to delays.
- Reducing energy consumption is one of the most effective ways to improve DAC performance across multiple dimensions, including carbon removal efficiency, land footprint, and operating costs (OPEX).
- The report makes several recommendations for further work, such as improving energy supply assumptions, better recognising uncertainty, considering biodiversity impacts, expanding scenarios to include other DACCS technologies and compare them with other carbon dioxide removal (CDR) pathways, and exploring dedicated low CI energy supply systems.

Scope

IEAGHG commissioned Foresight Transitions, UK, to assess the wider value of DACCS. This includes the following tasks:

1. Define the value of DACCS, taking into account the three key criteria efficiency, timeliness and durability of the carbon removal (for this task, liaison with current IEAGHG report 2022-09 'Defining the Value of CCUS for a Low-carbon Future'). The scope includes both DAC with CO₂ utilisation and with geological storage, in whose contexts the definition of value can be different. Regarding the capture technology,

the study should focus on the more mature examples of solid and liquid DAC, i.e. technology readiness level (TRL) 4 at least. Promising lower TRL approaches can be discussed with the necessary care, highlighting the related uncertainties. The focus of this study is not a comparison with other mitigation technologies, such as point source CCS, but it should be ensured that this study can be used as a building block for such a comparative assessment in a future study.

2. Detailed assessment of the land footprint related to DACCS (including the indirect land footprint for a set of different energy sources).
3. Evaluate and discuss other criteria, such as e.g.:
 - a. costs ('value-for-money'),
 - b. scalability,
 - c. water use,
 - d. energy demand/sources,
 - e. required CO₂ transport and storage capacity/infrastructure,
 - f. life cycle emissions
 - g. geographical differences etc.
4. Identify and discuss the value, key constraints and impacts of DACCS systems in the short-, medium- and long-term (2023-25, 2030, 2050). This should include discussing scenarios where the value could change drastically (e.g. changes in waste heat availability, public acceptance, climate change mitigation targets etc.). Where adequate, make recommendations how constraints and negative impacts can be overcome or alternatively identify gaps in the research.

Conclusions

Current cost and performance estimates for DACCS vary widely across literature due to inconsistent assumptions about energy supply, plant scale, sorbent degradation, and economic parameters. There is a critical need for standardised techno-economic and life cycle assessment (LCA) frameworks tailored to DACCS. These should account for regional energy systems, siting conditions, and infrastructure availability.

Future studies on the LCA of DACCS must move away from abstracted and arbitrary energy supply assumptions. Given that energy supply carbon intensity is a strong contributor to overall value chain emissions, it is critical to incorporate energy supply scenarios based on realistic assumptions when assessing the value chain emissions of DACCS. It is important to recognise the uncertainty associated with these scenarios.

The reduction of energy usage of DAC technologies can be used as a strong engineering factor for improving the overall performance of a DACCS system. The use of energy with lower carbon intensity can enable lower value chain emissions and leads to improved

environmental effectiveness. Low energy usage is the strongest available factor for reducing the land footprint requirements of DAC systems.

Achieving net-negative emissions (i.e., net carbon removal from the atmosphere) with DACCS depends primarily on the carbon intensity of supplied energy. As demonstrated in this work, both L-DAC and S-DAC coupled with permanent storage can deliver negative emissions today in regions where clean energy is available, or when co-located with renewables. Thus, dedicated low-carbon energy supply systems (e.g., stand-alone renewables, geothermal, or CCS-abated fossil) should be actively explored as enablers of early DACCS deployment.

DAC processes deployed today perform poorly in terms of average CO₂ removal efficiency, and the duration of process operations required to offset emissions associated with process construction. Given its relatively high abatement cost, delaying DACCS deployment until 2030 could leverage potential advancements in energy system decarbonisation which could, in turn, result in more efficient cumulative CO₂ removal operations. However, the actual effectiveness of such a strategy is highly dependent on the specific DAC technology used and the rate at which the energy system decarbonises.

Moreover, delaying all DACCS deployment until after 2030 may miss critical opportunities to build supply chains, test regulatory frameworks, and reduce costs via learning. Early deployment in favourable regions can provide real near-term removals while laying the groundwork for future scale-up.

Scaling DACCS to the gigatonne (Gt) scale of CO₂ removal requires major investment in manufacturing, workforce, and logistics, especially for modular components like contactors and heat exchangers. Modelling in this study assumed idealised infrastructure readiness. However, in reality, deployment of technologies like DACCS could face bottlenecks in power supply, CO₂ transport, and storage infrastructure, which may delay or limit DACCS's contribution. Projects also require significant upfront capital investment which can be challenging to acquire and can contribute further to delays. Further research on constraints and factors that can impact DACCS deployment and establishment of regional supply chains should be prioritised to provide insights on realistic project timelines and build rates.

The analysis also highlights that low energy usage directly reduces indirect land and infrastructure requirements, providing additional co-benefits in siting-constrained regions. Reducing energy consumption is one of the most effective ways to improve DACCS performance across multiple dimensions, including carbon removal efficiency, land footprint, and operating costs.

DACCS should not be viewed as a substitute for emissions reduction. The mitigation/abatement of GHG emissions should be the priority, but carbon removal and permanent storage will still be an essential technology required to address residual

emissions. Whole-system planning is needed to ensure DACCS is sited where low-carbon intensity energy, low-cost energy, CO₂ storage, and infrastructure align.

Expert Review

Expert reviewers from six different organisations provided comments on the draft report. In general, reviewers thought that the report contains important considerations for DACCS, is informative for the wider DACCS community and that the authors have systematically investigated the relevant aspects of DAC technology development.

The reviewers also had several suggestions for improvement, e.g. including direct RE acquisition and power purchase agreements (PPAs) into the discussion of DAC energy supply, the issue of dynamic grid factors, more clearly defining the terminology around DACCS lifecycle and plant-level efficiency, adding more detailed legends to the figures, emphasising the importance of identifying early DACCS locations, better contextualisation of the CO₂ utilisation options, and rewriting the sections with CAPEX and OPEX discussions. All of these have been addressed/clarified in the final report.

Some raised issues (like detailed water footprint modelling, impact of optimised DAC performance on efficiency, ambient variability) were out of scope of this study.

Recommendations

- Future studies on the LCA of DACCS must move away from abstracted and arbitrary energy supply assumptions and recognise the uncertainty associated with these scenarios.
- Further research on constraints and factors that can impact DACCS deployment and establishment of regional supply chains should be prioritised to provide insights on realistic project timelines and build rates.
- Further research on biodiversity impacts of DACCS technologies.
- Explore a variety of other DAC technologies than S-DAC and L-DAC and compare them.
- Undertake a comparative analysis of DACCS vs other CDR pathways.
- There is a critical need for standardised techno-economic and LCA frameworks tailored to DACCS.
- Dedicated low-carbon energy supply systems (e.g. stand-alone renewables, geothermal, or CCS-abated fossil) should be actively explored as enablers of early DACCS deployment.
- Other topics for future studies include: digital enablement (e.g. AI, digital twins), alternative/tailored business models, water footprint, ambient variability, public acceptance.

The Value of Direct Air Carbon Capture and Storage

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Abbreviations

ADB	Asian Development Bank
BAU	Business As Usual
BECCS	Bioenergy with Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CCS	Carbon Capture & Storage
CHP	Combined Heat and Power
DAC	Direct Air Capture
DACCS	Direct Air with Carbon Capture and Storage
ESA	Electrical Swing Adsorption
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
LCI	Lifecycle inventory
MRV	Monitoring, Reporting and Verification
MSA	Moisture swing adsorption
NZE	Net Zero Emissions
OPEC	Organisation of the Petroleum Exporting Countries
POLES	Prospective Outlook on Long-term Energy Systems
PV	Photo Voltaic
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption

Executive Summary

Background and scope of study

Greenhouse gas removal (GGR) is the removal of greenhouse gases from the atmosphere, with the majority of approaches focused on removing carbon dioxide (CO₂). Carbon dioxide removal (CDR) from the atmosphere will be an essential technology required to meet the Paris Agreement target of temperature rise well below 2 °C. There is a portfolio of CDR approaches, including afforestation and reforestation, bioenergy with carbon capture and storage (BECCS), biochar, direct air carbon capture and storage (DACCS), enhanced weathering, soil carbon sequestration and ocean-based CDR. These options for CDR differ in terms of key performance characteristics, e.g., technology readiness levels (TRL), cost, scalability, permanence, efficiency, timing, co-benefits, and public perception and ease of monitoring, reporting and verification (MRV).

Most land-based CDR approaches tend to have great land requirements, e.g., such as afforestation and reforestation, BECCS, biochar, soil carbon sequestration and enhanced weathering. A key requirement of DACCS will be the need to install large-scale infrastructure to provide access to sustainable and low carbon energy as well as geological CO₂ storage capacity. However, DACCS does have some key advantages compared to other land-based CDR approaches such as ease of MRV and the ability to provide immediate and permanent CO₂ removal as facilities become operational. It is critical to gain a comprehensive understanding of how different characteristics of DACCS technology will impact the value of DACCS in the context of capital and operating cost, efficiency, energy requirements, timeliness, durability, and scalability – to ensure that such technology can practicably be deployed at large scale.

This report presents a techno-environmental evaluation of direct air carbon capture (DAC) to understand its performance under region-specific deployment scenarios. Rather than attempting to provide a definitive cost or lifecycle estimate, this study explores how the effectiveness and value of DAC varies across different world regions, energy contexts, and deployment timelines. To do this, we assess five key dimensions of DAC performance: carbon removal efficiency, timeliness, durability of DAC utilisation pathways, land footprint, and techno-economic performance.

A key feature of the analysis is the dual-scale framing, we distinguish between:

1. Process-scale performance, i.e., the emissions, costs, and land footprint of an individual DAC plant;
2. System-scale performance, i.e., global deployment trajectories, cumulative removals, and costs over time.

This allows us to identify where early trade-offs (in terms of scale) may be necessary to unlock later benefits.

The analysis focuses on the two most commercially mature DAC technologies to date: liquid solvent DAC (L-DAC) and solid sorbent DAC (S-DAC). Both are evaluated across six world regions under a common set of assumptions for energy supply, infrastructure, and deployment timelines. Importantly, we model DAC as grid-connected in each region to reflect realistic **integration** scenarios, while also highlighting the potential of stand-alone, low-carbon DAC configurations in selected cases. The work includes a logistic growth model for system-scale deployment, as well as a bottom-up estimate of operating costs based on energy use and thermodynamic work. The modelling results are used to inform broader system design considerations and deployment strategy questions, including the role of energy system decarbonisation, the importance of early investment, and the limitations of comparing DAC in isolation from enabling infrastructure or policy.

Transition of regional energy systems

The projected carbon intensity of energy supply over time across six regions of the world is illustrated in Fig. A. The carbon intensity is expected to decrease over time as regions transition towards cleaner energy sources, with trajectories varying due to the differences in energy mix and policies in each of these regions. The results show that L-DAC processes are currently unable to provide significant net carbon removal (i.e., positive carbon removal efficiency) in Europe, North America, and Asia – according to the current carbon intensity of electricity supply in these geographical regions. In contrast, S-DAC processes can currently operate with net-negative emissions along their entire value chain in several world regions, including Europe and North America. In practice, DAC developers might secure low-carbon energy through power purchase agreements (PPAs) or direct connections to renewable energy, which could mitigate these effects.

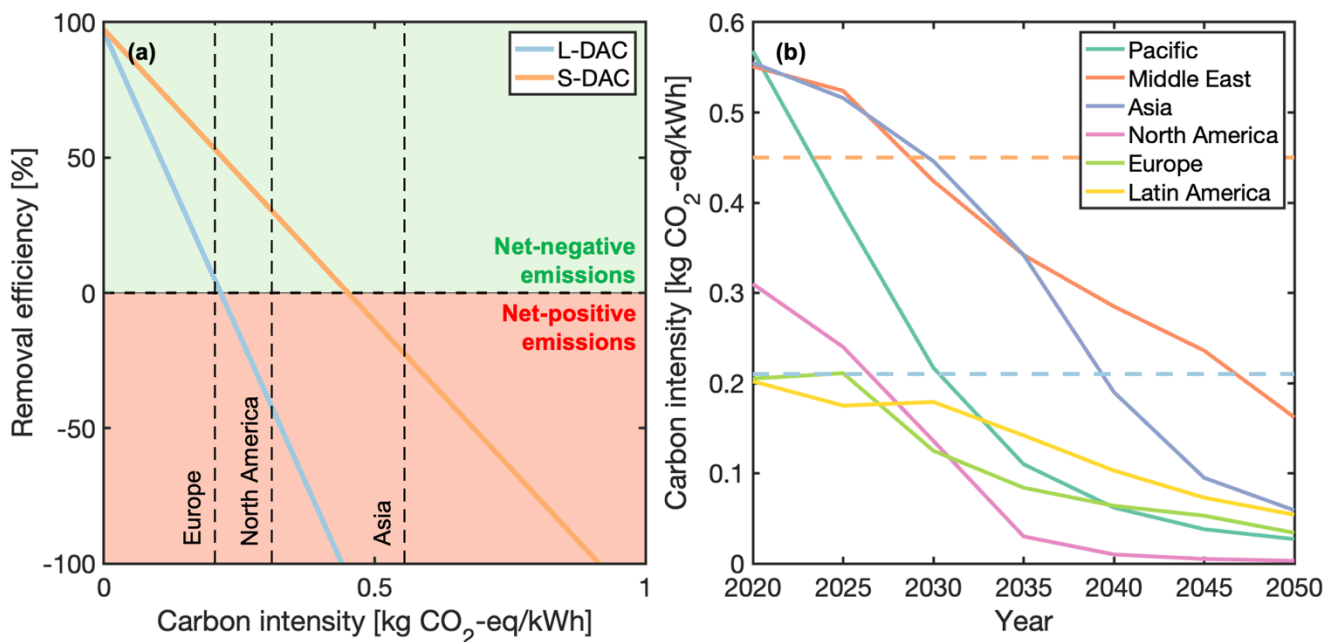


Fig. A: (a) Carbon dioxide removal efficiency as a function of carbon intensity of energy supply for L-DAC (blue) and S-DAC (orange) processes. Shaded regions indicate operation with net-negative emissions (green) and net-positive emissions (red) along the cradle-to-grave value chain. Dashed lines correspond to current-day carbon intensity of energy supply in Europe, North America, and Asia. (b) projected carbon intensity of energy supply as a function of time in six world regions (Pacific, Middle East, Asia, North America, Europe, Latin America). Data obtained from the EnerOutlook energy & emissions to 2050 pathway; this data is available in tabular form in Appendix 2.

The performance of L-DAC and S-DAC processes over time in different geographical contexts is evaluated by integrating these scenarios of the regional energy decarbonisation pathways as a function of time. Figure A (b) shows the projected carbon intensity of electricity generation for six world regions as specified in the EnerOutlook energy & emissions 2050 projections published by Enerdata.¹ The dataset covers the Pacific, Middle East, Asia, North America, Europe, and Latin America regions over the period 2020–2050.

¹ Enerdata (2023): “Energy & emissions projections 2050 - EnerOutlook”.

Carbon removal efficiency

In this report, carbon removal efficiency is defined as the net quantity of CO₂ removed from the atmosphere and permanently stored, divided by the gross amount of CO₂ captured by the DAC processes. This reflects a lifecycle-based assessment of the DAC value chain, accounting for emissions associated with energy supply, materials and infrastructure. This is distinct from process-scale capture efficiency, which refers to the percentage of CO₂ captured from the air stream itself within the DAC equipment (also referred to as the CO₂ capture rate).

As shown in Fig. B, carbon dioxide removal efficiency of direct air capture processes is predominantly determined by the carbon intensity of supplied energy. Sufficiently low-carbon energy supply is a necessary pre-condition to enabling highly efficient direct air capture value chains. For the current performance of the L-DAC system assessed in this report, achieving net-negative emissions requires the electricity supply to have a carbon intensity below 0.21 kgCO₂eq/kWh. For the S-DAC process assessed in this report, this threshold of electricity carbon intensity is 0.45 kgCO₂eq/kWh. These thresholds are derived for processes delivering 1 tCO₂ of net carbon removal and are based on typical DAC energy requirements reported in the literature.

When considering the carbon intensity of current-day energy system, the carbon dioxide removal efficiency of direct air capture processes is poor in all world regions. Projected energy system decarbonisation in the period 2020–2050 will enable an environment which is appropriate for direct air capture deployment by 2050 in all world regions to achieve negative emission value chains.

Direct air capture should not be seen as a substitute for deep and timely energy system decarbonisation. Rather, it is a complementary technology designed to address residual emissions and to compensate for sectors where emissions abatement is not technically or economically feasible. While decarbonising the wider energy system is needed to support the effective integration of DAC, it is not strictly a pre-condition for net-negative emissions in regions that already have energy systems with low carbon intensity. DAC systems powered by dedicated low-carbon energy sources (e.g., stand-alone renewables or fossil energy with CCS) can achieve net-negative outcomes within the system boundary of DAC + energy supply. However, the opportunity cost of diverting low-carbon energy to DAC must be considered in broader energy system planning.

Synergistic whole-systems planning remains essential to ensure that DAC deployment complements, rather than competes with, other decarbonisation priorities. For instance, planning may need to consider the development of green hydrogen, industrial decarbonisation and electrification infrastructure – these efforts potentially will require similar resources to DAC. Therefore, DAC must be co-developed with energy, any decarbonisation infrastructure, and policy systems to deliver meaningful, timely, and durable negative emissions.

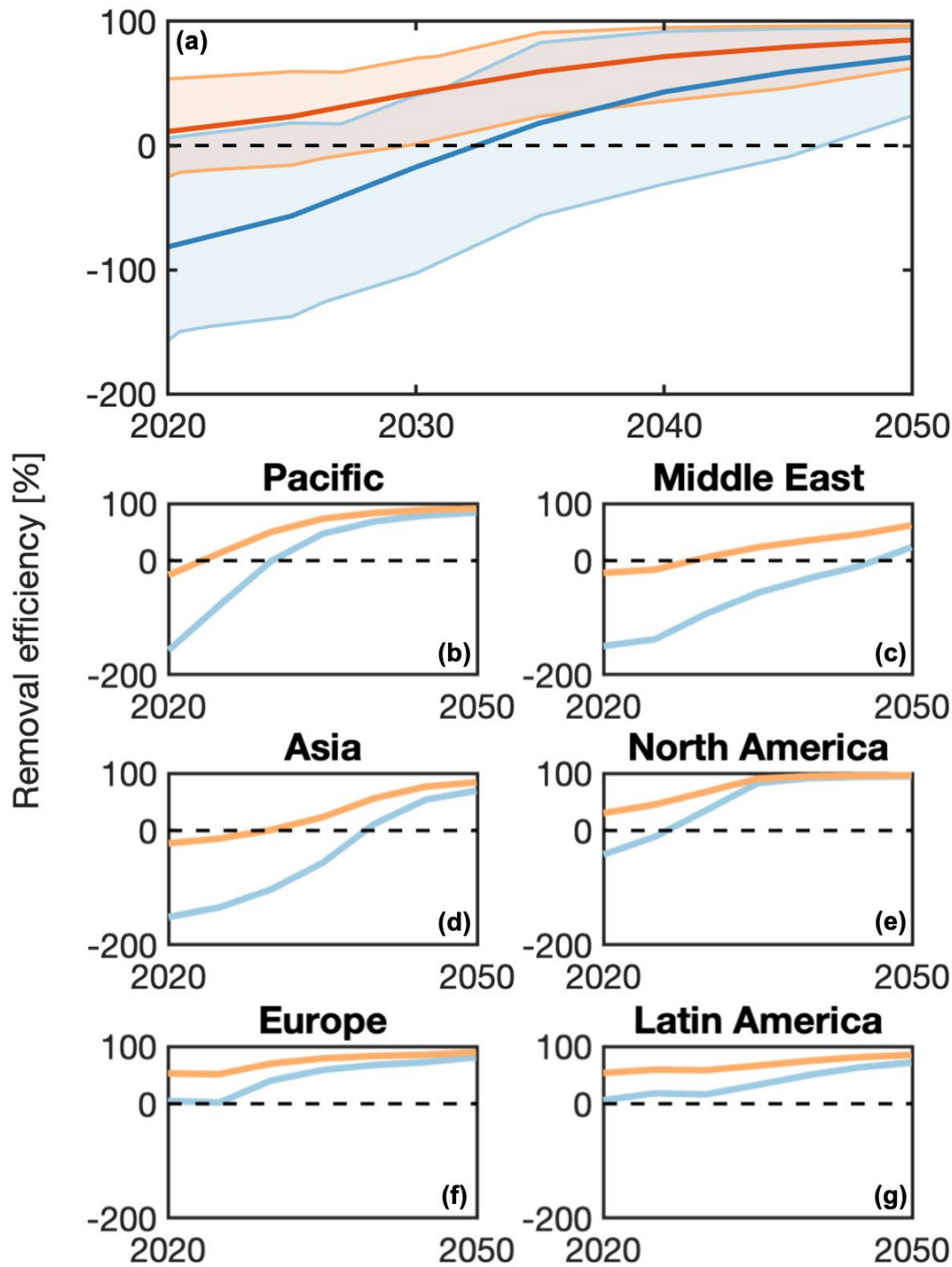


Fig. B: projected carbon dioxide removal efficiency for L-DAC and S-DAC processes in the period 2020–2050 in six world regions. **(a)** global-average carbon dioxide removal efficiency of L-DAC (blue) and S-DAC (orange). Shaded regions correspond to variability observed in individual regional scenarios. **(b)–(g)** Regional carbon dioxide removal efficiency scenarios for L-DAC (blue) and S-DAC (orange). Regions included are: (b) Pacific, (c) Middle East, (d) Asia, (e) North America, (f) Europe, (g) Latin America. In each panel, the dashed line at $\eta_{\text{CDR}} = 0$ indicates the transition from net-positive value chain emissions ($\eta_{\text{CDR}} < 0$) to net-negative value chain emissions ($\eta_{\text{CDR}} > 0$). Note: Lines in panel (a) represent global average, while the shaded areas reflect the spread across regional outcomes, which are shown individually in panels b-g.

Timeliness

The carbon removal performance of DAC systems deployed is strongly influenced by the emissions associated with construction and operation. When connected to carbon-intensive energy systems, this results in lower average carbon removal efficiency and requires longer operational periods (i.e., long plant lifetimes) to compensate for embedded emissions.

Fig. C illustrates the process-scale cumulative emissions of a 1 MtCO₂/yr DAC plant deployed in 2020 and operated for 30 years, across different global regions. This analysis shows that regional differences in energy system decarbonisation can lead to vastly different outcomes. While solid sorbent DAC (S-DAC) already achieves net-negative emissions in all regions by mid-century, liquid solvent DAC (L-DAC) does not, especially in the Middle East and Asia, where energy systems remain highly carbon-intensive.

However, delaying all DAC deployment until after 2030 is not necessarily optimal. Early deployment in favourable contexts – such as energy systems with access to low-carbon energy sources (e.g., geothermal, hydro, or co-located renewables), supportive policy environments, or strategic siting – can already deliver net-negative removals. Moreover, early DAC projects can provide valuable learning, de-risk future investments, support supply chain development, and build institutional capacity, which are critical to scaling up in later decades. Thus, the timing of DAC deployment must be considered on a regional and project-specific basis, accounting for local carbon intensity, technology performance, energy supply options, and regulatory structures. Rather than proposing a universal delay, this work highlights the importance of assessing the cumulative impacts of deployment strategies, and ensuring alignment between energy system decarbonisation, DAC project design, and enabling policies.

To assess global-scale deployment, we apply a logistic growth model assuming DAC capacity expands from near-zero today to 1 GtCO₂/yr by mid-century. Under this scenario, DAC could cumulatively remove 35 – 50 GtCO₂ by 2100, depending on technology choice (i.e., L-DAC or S-DAC) and energy system decarbonisation rates. Rapid early deployment is particularly important, as slow ramp-up rates drastically reduce cumulative removals by mid-century. Additionally, a delay in removals is observed even under fast scale-up, due to positive emissions associated with construction and early operation – highlighting the importance of initiating deployment in the right locations and reducing embedded emissions.

Current trends in energy system decarbonisation suggest that regions like North America, Europe, the Pacific, and Latin America are well-placed to host early DAC deployment. Meanwhile, regions such as Asia and the Middle East may require accelerated energy transitions to enable grid-connected DAC or may instead pursue stand-alone DAC using dedicated low-carbon energy with nearby CO₂ storage. Rather than implying uniform DAC deployment rates across all geographies, this analysis supports targeted DAC development where conditions enable early and effective climate benefits.

The carbon removal performance of a global-scale direct air capture deployment is strongly influenced by the growth rate achieved during the scale-up phase. Scenarios with low peak deployment rates result in minimal cumulative removals by mid-century, whereas rapid early scale-up enables significantly higher cumulative removals. This highlights the importance of not only accelerating deployment but also strategically identifying suitable locations for early DAC projects, particularly where low-carbon energy, infrastructure, and storage access are available. Such early deployments can serve as anchors for future scale-up while delivering real near-term removals.

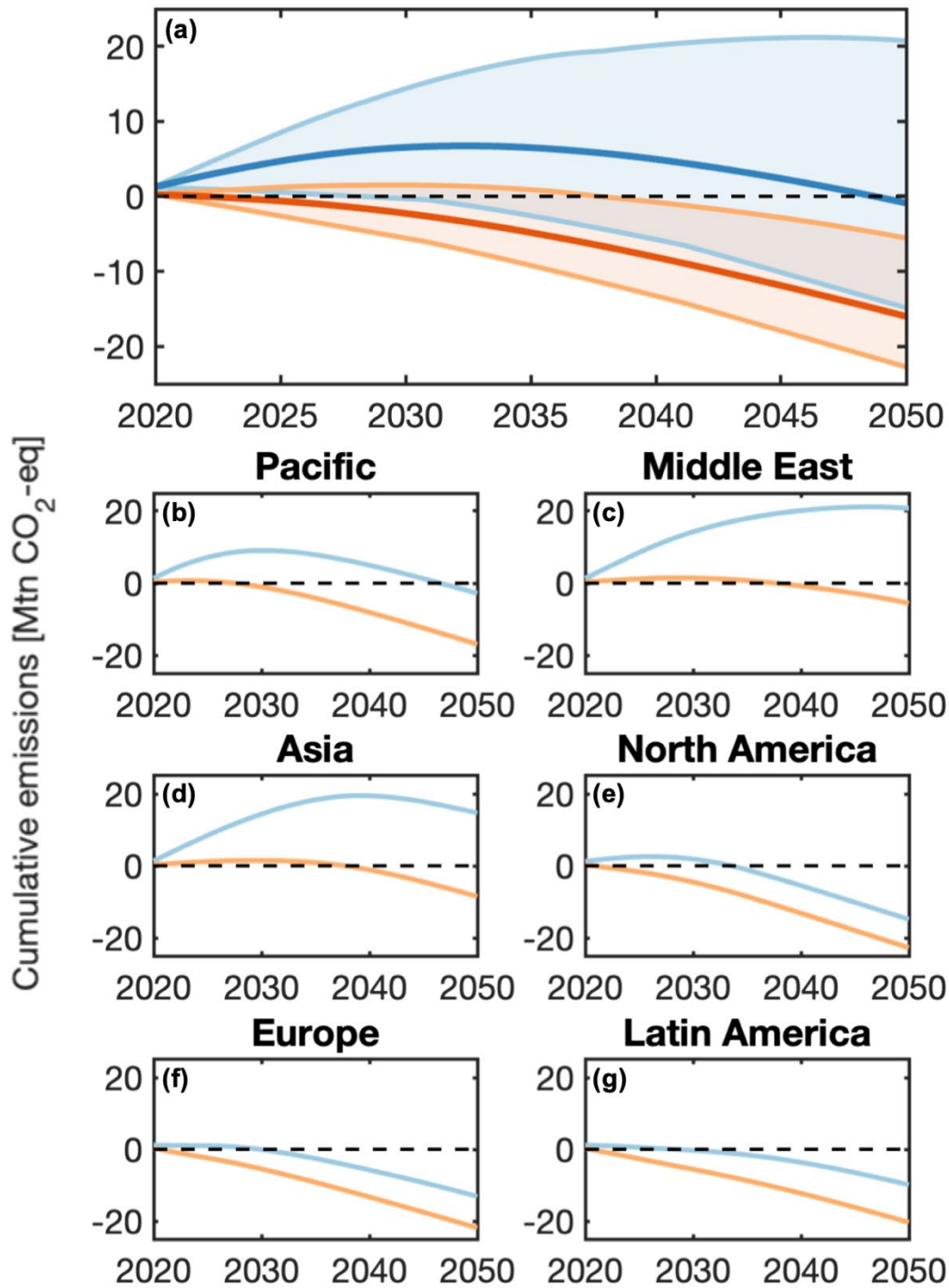


Fig. C: Cumulative emissions (CO₂eq) of a 1 MtCO₂ removal/yr direct air capture plant with a lifetime of 30 years constructed in the year 2020 in six world regions. (a) global-average cumulative emissions of an L-DAC process (blue) and an S-DAC process (orange). Shaded regions correspond to variability observed in individual regional scenarios. (b)-(g) regional cumulative emissions scenarios for L-DAC (blue) and S-DAC (orange).

Energy system decarbonisation efforts in the Pacific, North America, Europe, and Latin America regions are currently on track to deliver a platform that can enable environmentally effective wide-scale direct air capture deployment. In contrast, regions such as Asia and Middle East may need to accelerate energy system decarbonisation efforts to enable grid-connected DAC at scale. However, the Middle East region also holds considerable potential for dedicated renewable energy systems (i.e., solar energy potential)

with proximate access to CO₂ storage, which could support stand-alone DAC projects. Rather than suggesting that all regions must deploy DAC uniformly, this analysis assumes that DAC will be strategically located where low-carbon energy and geological storage are accessible.

Durability

Durability (or permanence) refers to the length of time that the carbon captured from the atmosphere remains stored. In this analysis, the primary focus is on geological storage, which is currently the most mature and widely accepted option for achieving long-term or permanent CO₂ sequestration. However, it is important to acknowledge that there are other high durability storage approaches that can store the carbon for thousands of years. The other options which can permanently store CO₂ include ex-situ mineralisation into carbonate materials, and storage in long-lived products such as aggregates used in concrete. These approaches may be less mature than geological storage, there are some industrial scale facilities in operation (e.g., Neustark in Europe and O.C.O Technology in the UK), and thus they could provide alternative forms of durable carbon sequestration in the future.

Captured CO₂ can also be used as a feedstock to produce a wide range of carbon-based products, including fuels, chemicals, plastics, and construction materials. Most of these carbon utilisation pathways do not offer permanent storage and CO₂ is re-released to atmosphere at the end of the product lifetime. For example, short-lived fuels typically release CO₂ within weeks to months, whereas concrete or aggregates may retain carbon for decades, centuries or longer. Short-lived utilisation options do not deliver carbon dioxide removal from the atmosphere, but they can play a role in near-term climate strategies by displacing fossil-derived products and support decarbonisation efforts in hard-to-abate sectors such as aviation. Such pathways are better described as contributing to emissions displacement or reduction and are not durable carbon removal.

Mixed-sink DAC systems, which direct a portion of captured CO₂ to permanent storage and another portion to utilisation. These mixed-sink DAC systems can be particularly relevant during the transition phase of an energy system, when there is a need for alternative low-carbon fuels or materials, alongside the requirement for durable removal to meet net-zero goals. The proportion of CO₂ allocated to each sink will influence the overall carbon balance of the system and needs to be carefully considered in deployment strategies.

Fig. D illustrates the performance of mixed-sink DAC systems where CO₂ is stored permanently (e.g., geological storage) and a proportion is utilised (θ_U) within air-to-fuel value chains. Three air-to-fuel utilisation scenarios are assessed: methane unabated, methane abated and aviation fuel. For any direct air capture system to achieve net-negative emissions today, some portion of the captured CO₂ must be directed to a durable storage sink. This is necessary to offset the construction and operational emissions associated with the DAC system. As deployment of a mixed-sink system scales, understanding the climate impact of different sinks with varying durability becomes critical to ensuring the environmental integrity.

Air-to-fuel value chains (e.g., for sustainable aviation fuels or synthetic methane) are a prominent example of mixed-sink applications for DAC. These offer the potential to enable carbon-neutral or near-carbon-neutral fuels by recycling atmospheric CO₂ into energy carriers. While such pathways can offer circularity, there are energy and cost trade-offs to consider. Producing synthetic fuels from DAC-derived CO₂ and green hydrogen is technically feasible, but generally more energy-intensive and expensive than fossil fuels. This raises questions about cost-effectiveness of DAC utilisation pathways relative to direct DACCS to offset fossil fuel emissions. Nevertheless, these systems may have a role to play in decarbonising sectors with limited alternatives. More comprehensive comparative analysis, including energy return on investment (EROI), lifecycle emissions, and cost benchmarking, is needed to guide optimal deployment of DAC utilisation pathways.

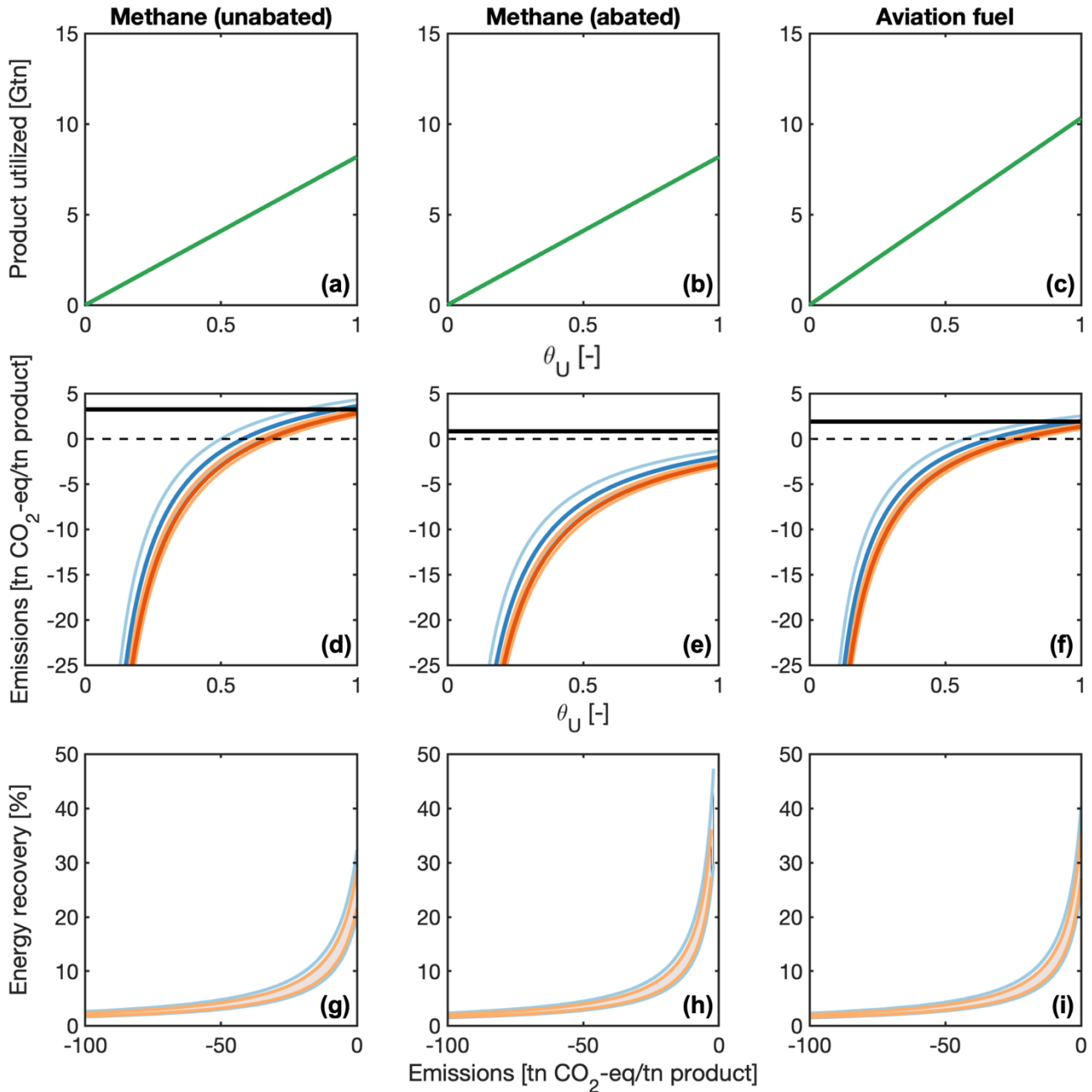


Fig. D: Performance of mixed-sink systems with embedded air-to-fuel value chains for: (i) methane production used in unabated NGCC, (ii) methane production used in abated NGCC, and (iii) jet fuel production. (a) – (c): cumulative amount of product utilisation by 2100 as a function of the utilised fraction (θ_U). (d) – (f): average emissions factor in the period 2020–2100 as a function of the utilised fraction (θ_U). (g) – (i): average energy recovery factor in the period 2020–2100 as a function of the emissions factor. Blue lines correspond to L-DAC processes. Orange lines correspond to S-DAC processes. Shaded regions represent uncertainty arising from regional energy decarbonisation scenarios. Black lines correspond to the emissions factor of conventional production pathways.

For the unabated methane production and combustion pathway in Fig. D, 50–71% (L-DAC: 50–65%, S-DAC: 63–71%) of captured CO₂ can be directed towards methane production with net-zero system emissions overall. This pathway cumulatively generates 4.1–5.8 Gt of methane by 2100. For the abated methane production and combustion pathway, all of the captured CO₂ from DAC can be directed towards methane production while achieving net-negative system emissions overall. The abated methane system cumulatively produces 8.2 Gt of methane by 2100. The abated methane system has a lower relative power output per amount of methane utilised compared to the unabated methane case because of the parasitic energy consumption of the post-combustion capture process on the natural gas combined cycle (NGCC)

power plants.² However, the co-benefit of the abated methane system is that it achieves net-removal of CO₂ from the atmosphere, cumulatively achieving 11–26 GtCO₂ removal by 2100. For the aviation fuel pathway, 57–81% of captured CO₂ can be directed towards fuel production with net-zero system emissions overall. This pathway cumulatively generates 5.9–8.4 Gt of jet fuel by 2100.

While this study focuses on DACCS and not DAC utilisation pathways, it is important to recognise that DAC systems have the potential to be integrated with a range of downstream options – permanent storage or CO₂ utilisation pathways. Further research is necessary to understand the role and value of DAC utilisation, considering the combination of different CO₂ utilisation/storage pathways and their contribution to broader decarbonisation objectives.

Land footprint

The land footprint requirements of direct air capture systems are affected by the direct land footprint of the direct air capture plant itself, and the indirect land footprint required to site supporting infrastructure for the provision of electricity, heat, and water.

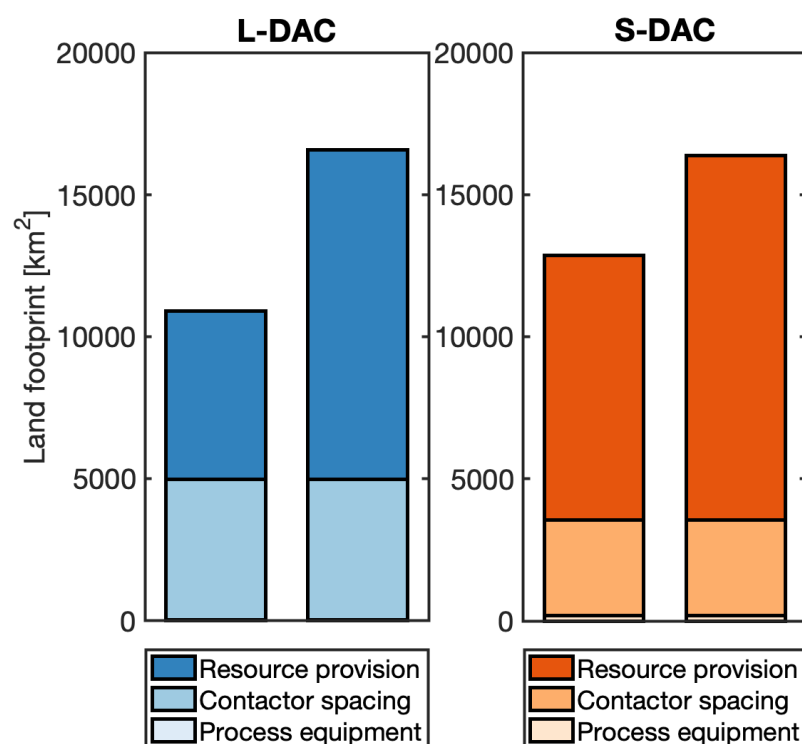


Fig. E: Breakdown of land footprint requirements for a global-scale direct air capture system, with capture capacity of 1 GtCO₂/yr, in terms of (i) the direct land footprint of process equipment, (ii) the direct land footprint of air contactor spacing, and (iii) the indirect land footprint associated with the provision of resources (electricity, heat, and water). Left bars correspond to the best-case scenario in terms of resource provision uncertainty. Right bars correspond to the worst-case scenario in terms of resource provision uncertainty.

Among available pathways for achieving greenhouse gas removal, direct air capture has a low total land footprint. As shown in Fig. E, large-scale direct air capture systems have a total land footprint requirement of 10.9–16.6 km²/(MtCO₂/yr). The land footprint requirement is highly sensitive to the direct air capture technology selection performance, and to the energy requirements for the operation of direct air capture.

² Zhang et al. (2014): “Post-combustion carbon capture technologies: Energetic analysis and life cycle assessment”. International Journal of Greenhouse Gas Control (27).

Shared use of land for air contactor spacing with infrastructure for resource provision can reduce the land footprint requirements of direct air capture by 21–45%. Further practical research efforts are required to establish if this approach is feasible.

Techno-economic performance

Understanding the techno-economic performance of DAC requires evaluating both process-scale and system-scale costs. At the process level, current state-of-the-art DAC technologies remain capital-intensive, with capital expenditures (CAPEX) generally dominating total costs over operational expenditures (OPEX). However, the balance between CAPEX and OPEX will shift over time as deployment scales up, technology learning accelerates, and marginal costs fall in established systems.

Fig. F summarises reported capital and operating costs from the academic literature for both liquid solvent (L-DAC) and solid sorbent (S-DAC) technologies. Notably, CAPEX estimates range widely (\$100 – 400/tCO₂), and significant uncertainty exists due to variations in underlying assumptions such as plant throughput, sorbent lifetimes, and heat recovery efficiency. The wide range in cost estimates highlights the need for standardized techno-economic methodologies, as assumptions differ across studies and often reflect optimistic or inconsistent baselines.

Reported operating costs are particularly uncertain, with some studies presenting implausibly low estimates. For example, OPEX values below \$10/tCO₂ do not reflect thermodynamic realities or real-world energy prices. A bottom-up analysis in this study, which considers energy demand and equivalent work based on typical thermodynamic efficiencies, suggests that the minimum feasible OPEX for current DAC technologies is in the range of 43–97 \$/tCO₂. These estimates do not account for additional operational costs such as water usage, sorbent degradation, or maintenance, and therefore should be considered a lower bound.

Technology learning is expected to drive significant CAPEX reductions over time. These cost reductions will also depend on supply chain development, policy support, and DAC integration with carbon capture and storage (CCS) infrastructure. L-DAC may benefit from economies of scale, while S-DAC may benefit more from modularisation and mass manufacturing, making it premature to conclude which technology will ultimately be more cost-effective.

System-scale modelling in this analysis estimates a total cumulative cost of \$3.3 - 9.9 trillion for deploying 1 GtCO₂/yr of DAC capacity globally by 2050, rising to 2100. The choice of 1 GtCO₂/yr as a benchmark reflects a policy-relevant milestone (e.g., IEA NZE scenario) rather than a full assessment of least-cost decarbonisation portfolios. Comparisons to other CDR options remain essential when evaluating DAC's strategic role in net zero targets.

Ultimately, the high variability in current cost estimates, along with the dependence on assumptions around future energy systems, underscores the importance of creating clear, transparent, and consistent techno-economic frameworks. This will be essential for guiding early deployment decisions, prioritising R&D investments, and aligning DAC's development with broader climate and energy transition goals.

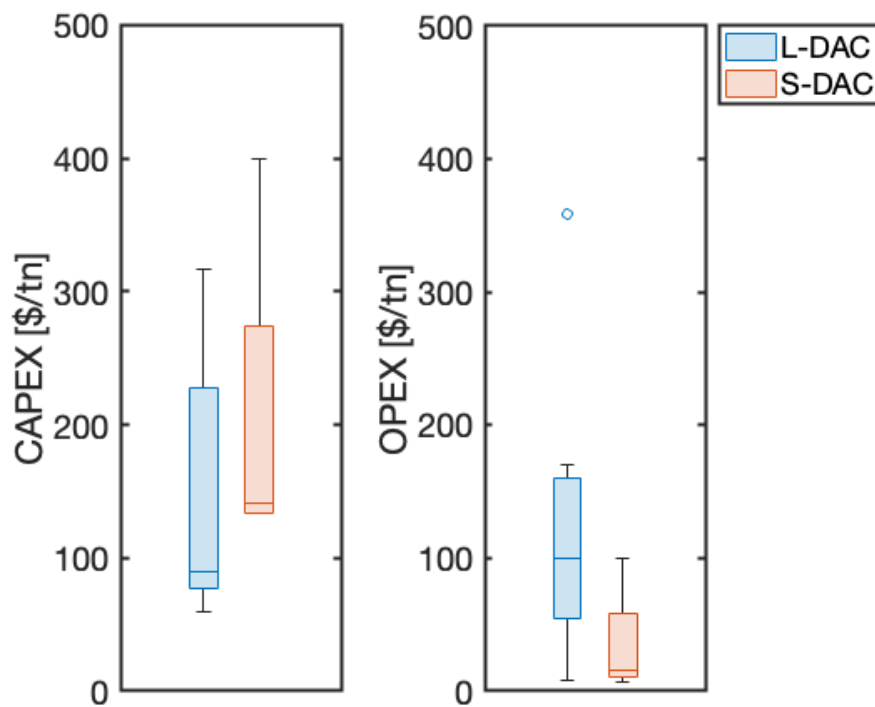


Fig. F: Capital costs (CAPEX) and operating costs (OPEX) in units of \$/t CO₂ capture for L-DAC and S-DAC processes based on techno-economic analysis studies presented in the academic literature.

Key conclusions and recommendations

- ▶ Current cost and performance estimates for DAC vary widely across literature due to inconsistent assumptions about energy supply, plant scale, sorbent degradation, and economic parameters. There is a critical need for standardised techno-economic and life cycle assessment (LCA) frameworks tailored to DAC. These should account for regional energy systems, siting conditions, and infrastructure availability.
- ▶ Future studies on the life cycle assessment of direct air capture must move away from abstracted and arbitrary energy supply assumptions. Given that energy supply carbon intensity is a strong factor towards overall value chain emissions, it is critical to incorporate energy supply scenarios based on realistic assumptions when assessing the value chain emissions of direct air capture. It is important to recognise the uncertainty associated with these scenarios.
- ▶ The reduction of energy usage of direct air capture technologies can be used as a strong engineering factor for improving the overall performance of a direct air capture system. The use of energy with lower carbon intensity can enable lower value chain emissions and leads to improved environmental effectiveness. Low energy usage is the strongest available factor for reducing the land footprint requirements of direct air capture systems.
- ▶ Achieving net-negative emissions (i.e., net carbon removal from the atmosphere) with DAC depends primarily on the carbon intensity of supplied energy. As demonstrated in this work, both L-DAC and S-DAC can deliver negative emissions today in regions where clean energy is available, or when co-located with renewables. Thus, dedicated low-carbon energy supply systems (e.g., stand-alone renewables, geothermal, or CCS-abated fossil) should be actively explored as enablers of early DAC deployment.

- ▶ Delaying all DAC deployment until after 2030 may miss critical opportunities to build supply chains, test regulatory frameworks, and reduce costs via learning. Early deployment in favourable regions can provide real near-term removals while laying the groundwork for future scale-up.
- ▶ Scaling DAC to the gigatonne (Gt) scale of CO₂ removal requires major investment in manufacturing, workforce, and logistics, especially for modular components like contactors and heat exchangers. Modelling in this study assumed idealised infrastructure readiness. However, in reality, deployment of technologies like DAC could face bottlenecks in power supply, CO₂ transport, and storage infrastructure, which may delay or limit DAC's contribution. Projects also require significant upfront capital investment which can be challenging to acquire, which can contribute further to delays. Further research on constraints and factors that can impact DAC deployment and establishment of regional supply chains should be prioritised to provide insights on realistic DAC project timelines and build rates.
- ▶ Our analysis also highlights that low energy usage directly reduces indirect land and infrastructure requirements, providing additional co-benefits in siting-constrained regions. Reducing energy consumption is one of the most effective ways to improve DACCS performance across multiple dimensions, including carbon removal efficiency, land footprint, and operating costs.
- ▶ DAC should not be viewed as a substitute for emissions reduction. The mitigation/abatement of GHG emissions should be the priority, but carbon removal will still be an essential technology required to address residual emissions. Whole-system planning is needed to ensure DAC is sited where low-carbon intensity energy, low-cost energy, CO₂ storage, and infrastructure align.

1 Introduction

1.1 Carbon Dioxide Removal

Greenhouse gas removal (GGR) is the removal of greenhouse gases directly from the atmosphere. Some GGR approaches specifically provide carbon dioxide removal (CDR). The removed carbon dioxide (CO₂) is stored in a “sink”, either in geological formations, soil, ocean or biomass, to prevent them from re-entering the atmosphere (shown in Figure 1.1). Provided that the greenhouse gas (GHG) emissions over the value chain of the GGR technology are smaller than the emissions removed from the atmosphere, the net result is a reduction of the amount of greenhouse gases in the atmosphere.

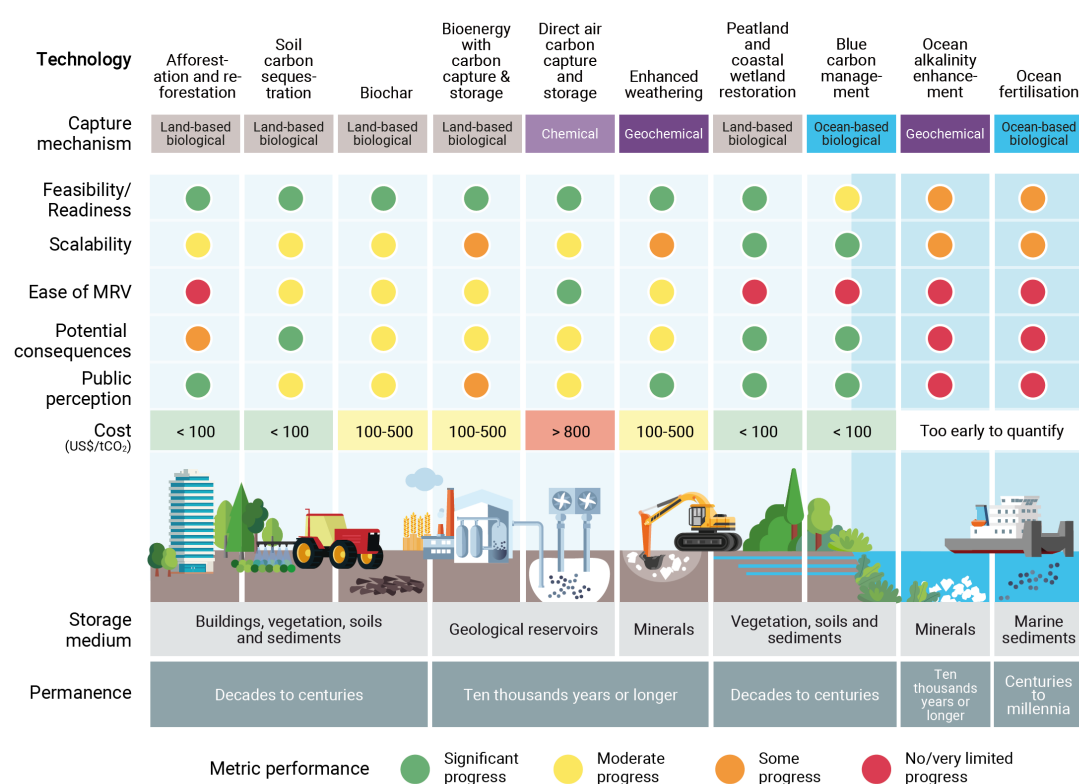


Figure 1.1: Overview of current status of CDR technologies. These CDR methods differ in terms of stage of development and performance. The coloured circles indicate the current progress towards target levels required for wider adoption of the technology.³

³ Geden, O, Gidden, M., Bui, M, Bustamante, M., (2023). Chapter 7 Emissions Gap Report. United Nations Environment Programme (UNEP), <https://www.unep.org/resources/emissions-gap-report-2023>

According to the IPCC⁴, to meet climate change mitigation goals that align with the Paris Agreement, all cost-effective pathways starting 2020 require a significant increase of CDR over time. CDR methods can be classified as conventional or novel. Conventional land-based methods include afforestation, reforestation and management of existing forests. Novel CDR methods include bioenergy with carbon capture and storage (BECCS), biochar, direct air carbon capture and storage (DACCS) and enhanced weathering. The majority of direct removals are done through conventional land-based methods estimated at 2 (± 0.9) GtCO₂ annually, whereas novel methods account for 0.0013 GtCO₂ annually⁵. The cost-effective pathways for limiting global warming to 1.5°C and 2°C assume significant increases in both conventional and novel CDR, with estimates suggesting that conventional and novel CDR could grow to 6 and 4 GtCO₂ annually by 2050, respectively (Figure 1.2)⁶.

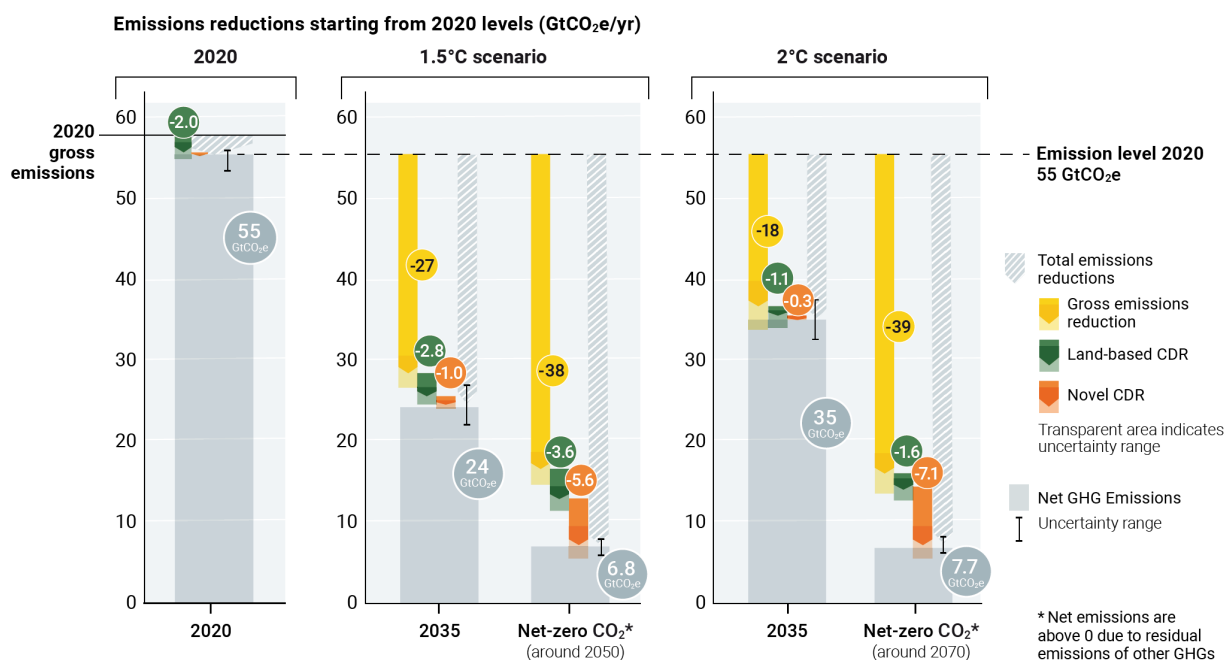


Figure 1.2: the contribution of gross emission reduction and carbon dioxide removal (CDR) in least-cost pathways consistent with the Paris Agreement.⁷

CDR provides a unique set of services within the context of climate mitigation, allowing for the handling of:

⁴ **IPCC (2023)**. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. doi: 10.59327/IPCC/AR6-9789291691647.001

⁵ **Smith, S. M. et al. (2024)**. The State of Carbon Dioxide Removal - 2nd Edition. <https://osf.io/f85qj/>

⁶ **United Nations Environment Programme (2023)**. Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again). <https://doi.org/10.59117/20.500.11822/43922>

⁷ **Geden, O, Gidden, M., Bui, M, Bustamante, M., (2023)**. Chapter 7 Emissions Gap Report. United Nations Environment Programme (UNEP), <https://www.unep.org/resources/emissions-gap-report-2023>

1. **Residual emissions:** a large proportion of overall CO₂ emissions reduction will be facilitated through conventional mitigation approaches. This can include switching technologies or fuel to options with lower carbon emissions compared to the current status-quo technologies (*e.g.* renewable or nuclear energy technologies, switching to low carbon hydrogen), improving energy efficiency, or integrating technologies which directly reduce carbon emissions. For example, the application of post-combustion carbon capture to fossil fuel-based power generation can capture up to 90–99% of CO₂ but there will be a remaining 1–10% of residual emissions.⁸ In these cases, some residual GHG emissions remain, which must be addressed to allow for an overall net-zero emissions system.
2. **Hard-to-abate emissions:** in some sectors, notably aviation, maritime and agriculture applications, conventional mitigation technologies are not a viable option due to the decentralised nature of emissions and the lack of cost-effective low carbon alternatives. These hard-to-abate emissions⁹ persist when: (i) alternative technologies with reduced carbon emissions are not available at an acceptably low cost, and (ii) the emissions are decentralised in nature and are not compatible with emissions reduction technologies. In the context of an overall system with net-zero emissions, these emissions would need to either be offset with CDR or innovations in technology required (*e.g.*, zero emission aircraft).
3. **Historical emissions:** during the previous century, large amounts of carbon emissions to the atmosphere have occurred. The IPCC 1.5°C scenarios indicate that it will become necessary during the current century to not only stop releasing more emissions to the atmosphere – but for emissions to become net negative¹⁰, which will involve reversing some of the historical emissions and reducing the CO₂ concentration of the atmosphere. Greenhouse gas removal is the only tool we have for directly removing past emissions, however, the ability to remove historical emissions will depend on whether net zero of the system is achieved at a global scale. Once net negative emissions have been achieved, while some may attribute this to be the reversal of specific historical emissions, others consider this to be a contribution toward the broader goal of global 1.5°C climate targets.

⁸ Feron, P., Cousins, A., Jiang, K., Zhai, R., Shwe Hla, S., Thiruvengkatachari, R., Burnard, K. (2019). Towards zero emissions from fossil fuel power stations. <https://doi.org/10.1016/j.ijggc.2019.05.018>

Danaci, D., Bui, M., Petit, C., Mac Dowell, N. (2021). En route to zero emissions for power and industry with amine-based post-combustion capture. <https://doi.org/10.1021/acs.est.0c07261>

⁹ IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. doi: 10.59327/IPCC/AR6-9789291691647.001

¹⁰ In this report, **net negative** is used interchangeably with **net carbon removal** and refers to the net 'neutralisation' of CO₂ emissions (*e.g.*, residual or historical CO₂ emissions). **Net CO₂ removal** (*i.e.*, net negative emissions) is calculated by considering the amount of **CO₂ captured** from the atmosphere (*e.g.*, via the direct air capture unit) and deducting the lifecycle emissions across all stages of deployment and operation.

Carbon dioxide removal technologies are currently an expensive option relative to the emissions reduction/mitigation. It is therefore not appropriate from an economic perspective to apply greenhouse gas removal in situations where alternative, more affordable, mitigation options exist. However, in the absence of a globally coordinated effort, some jurisdictions may still justify the use of CDR despite its higher cost, depending on local policy priorities, technological readiness and available mitigation opportunities.

However, once we consider net zero GHG emission targets, CDR represents the only option that we have for addressing the aforementioned emission types, and under these conditions, cost becomes a less relevant decision criteria by which optimal deployment is considered.¹¹ However, cost may still influence the selection of specific removal technologies.

1.2 Direct air capture

Direct Air Carbon Capture (DAC) is a promising technological solution for achieving CDR. In general, direct air capture is a chemical separation process which processes ambient air to remove carbon dioxide (Figure 1.3). The process produces an air stream with a reduced CO₂ concentration, which is then released back to the atmosphere. The removed carbon dioxide is output from the direct air capture process at high purity and can be sent to either: (i) permanent storage in underground geological formations (carbon storage i.e., DACCS), or (ii) chemical conversion processes which turn the removed carbon dioxide into useful carbon-based products such as plastics, building materials, or fuels and chemicals (Direct Air Carbon Capture and Utilisation (DACCU)). Several engineering approaches have been proposed for achieving direct air capture in practice, with each approach being at a different stage of development and presenting unique advantages and drawbacks.

¹¹ **Environmental Defense Fund (2021)** Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems. <https://www.edf.org/revamped-cost-curve-reaching-net-zero-emissions#>

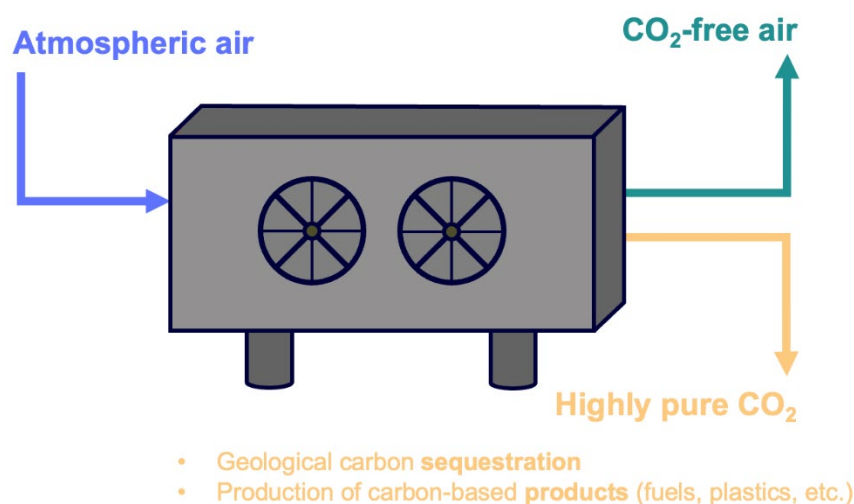


Figure 1.3: schematic representation of a direct air capture process. Atmospheric air is fed to the process and CO₂ is removed before returning the air to the atmosphere. The captured CO₂ is sent downstream for either storage or utilisation.

DAC offers the opportunity to remove CO₂ directly from the atmosphere and hence providing a flexible and scalable solution for addressing residual and legacy emissions. However, it faces thermodynamic challenges due to the low concentration of CO₂ in ambient air, typically around 0.04%. This low concentration requires substantial energy input to capture CO₂ effectively. Furthermore, the cost of DAC is relatively high compared to other carbon removal methods, primarily due to the aforementioned energy demands and the need for advanced materials and infrastructure. Despite these challenges, DAC presents significant opportunities for innovation and cost reduction. Advances in materials science, process optimisation and the integration of DAC with renewable energy sources and other industrial processes could lower costs and/or improve the efficiency of DAC systems. Moreover, DAC's ability to be deployed in various locations without directly competing with land for agriculture or forestry makes it a versatile tool in the portfolio of carbon removal solutions.¹² However, its deployment will still require access to low carbon energy (e.g., renewables, nuclear), which in some regions could compete with other energy demands or land use priorities.¹³

According to the International Energy Agency (IEA) there are currently 27 commissioned DAC plants worldwide, with various companies and research institutions leading the efforts in scaling up this technology¹². The Technology Readiness Level (TRL) of DAC varies across different systems and approaches, reflecting the diverse stages of development within the field. Most DAC technologies

¹² IEA (2022) Direct Air Capture. <https://www.iea.org/reports/direct-air-capture-2022>

¹³ Sendi, M., Bui, M., Mac Dowell, N., Fennell, P. (2024). Geospatial techno-economic and environmental assessment of different energy options for solid sorbent direct air capture. Cell Reports Sustainability 1(8): 100151. <https://doi.org/10.1016/j.crsus.2024.100151>

are currently in the early to mid-TRL stages, typically ranging from TRL 4 to TRL 7.¹⁴ Key processes are demonstrated in a controlled environment at TRL 4. As these technologies advance to TRL 6 or 7, they move into prototype or pilot-scale testing, where the DAC systems are demonstrated in relevant operational environments, though not yet at full commercial scale. Only a few DAC systems have reached TRL 8, where they are fully operational and deployed.

The IEA's 2022 report on DAC technology introduced an extended TRL scale to better capture the industrial maturity of these technologies, adding two additional layers to the conventional TRL ladder. This extended scale includes TRL 10 and TRL 11, where TRL 10 indicates a solution is commercially available and competitive but needs evolutionary improvements to stay competitive. At the highest level, TRL 11 indicates that the technology achieved full stability and is sustainable without the need for government aids or incentives. The extended TRL levels are crucial for assessing the market readiness of DAC technologies.¹⁵

1.3 Carbon removal efficiency of direct air capture

A key concept in the use of direct air capture technologies is carbon removal efficiency. It is unavoidable that the construction and operation of a DAC process will be itself associated with some amount of carbon emissions. This means that the net amount of emissions which are ultimately CO₂ removal from the atmosphere will be smaller than the amount of emissions which is CO₂ captured by the direct air capture process.

$$\begin{aligned} \text{Net CO}_2 \text{ removal from atmosphere} \\ &= \text{Amount of CO}_2 \text{ stored geologically} \\ &\quad - \text{Amount of CO}_2 \text{ emitted over the DAC value chain} \end{aligned}$$

This relationship is characterised by the carbon dioxide removal efficiency, which compares the amount of emissions CO₂ removed from the atmosphere with the amount of emissions which are captured by a direct air capture process and stored geologically. Even a highly efficient direct air capture process will have some amount of emissions associated with construction and operation, so the net emissions of CO₂ removed from the atmosphere are always smaller than the amount of CO₂ emissions captured. Accurately characterising the carbon removal efficiency of direct air capture processes is critical to understanding the value that they offer for achieving greenhouse gas removal and depends on a wide variety of factors.

As highlighted in recent research¹⁶, CDR pathways, including DAC, can vary in terms of net CO₂ removal efficiency, depending on the deployment context and time scale. For DAC deployed in 2020, the CDR efficiency can range between -5 and 90%, with

¹⁴ Bisotti, F., Hoff, K. A., Mathisen, A., Hovland, J. (2024) Direct Air Capture (DAC) deployment: A review of the industrial deployment. <https://doi.org/10.1016/j.ces.2023.119416>

¹⁵ IEA (2022) Direct Air Capture. <https://www.iea.org/reports/direct-air-capture-2022>

¹⁶ Chiquier, S., Patrizio, P., Bui, M., Sunny, N., Mac Dowell, N. (2022). A comparative analysis of the efficiency, timing and permanence of CO₂ removal pathways. DOI: 10.1039/d2ee01021f

the lower end of negative percentages corresponding to scenarios using carbon-intensive energy systems and the upper bound being scenarios using low carbon intensity energy. However, if DAC is deployed later in the century within decarbonised energy systems, the efficiency can reach more than 92%. These findings highlight the importance of the carbon intensity of the energy and timescale of energy system decarbonisation when evaluating the effectiveness of DAC and other CDR technologies in terms of carbon removal efficiency and timeliness.

1.4 Timeliness of direct air capture

The timing of CO₂ removal technologies has been discussed by Chiquier et al.¹⁷ A key advantage of DAC processes is the ability to immediately remove CO₂ from atmosphere. In contrast, enhanced weathering and afforestation can take years to decades to achieve net CO₂ removal owing to the slower reactions or biophysical limits. The timeliness of delivering CO₂ removal via DAC will be a function of constraints in build rate and supply chains.

Currently, deployed DAC capacity globally is approximately 0.01 MtCO₂/yr. Global decarbonisation pathways predict that this should significantly expand over the coming decades. For example, in the IEA Net Zero Emissions by 2050 scenario, DAC is responsible for capturing 0.7 GtCO₂/yr – representing a 100,000-fold increase in deployed capacity over the next three decades.¹⁸

There are currently major barriers to the wide-scale expansion of global DAC capacity. Costs of the technology remain prohibitively high (estimated to be 200 – 1000 USD/tCO₂ depending on the DAC technology),¹⁹ preventing viable business cases from existing outside of voluntary carbon markets or heavily subsidised technology demonstration projects. Additionally, the lack of well-structured and continuous financial and policy support for early-stage development further limits widespread deployment. Supply chains necessary for wide-scale expansion of deployment are in the early phases of development. This includes challenges in accessible CO₂ transport and storage infrastructure, availability of commercialised liquid and solid sorbent manufacturing capabilities, renewable energy supply and supporting utilities. As a result, even if viable business cases existed at the necessary scale – deployment at that scale is not currently feasible.

Both key barriers need to be overcome to enable larger deployments of DAC. Although immediate large-scale deployment is not required, starting now will help ensure that DAC technology can be deployed at the scale needed in the long-term. It is necessary to understand what the deployment trajectory of the technology will look like at the global scale to understand the value that direct air capture can offer for achieving timely greenhouse gas removal compatible with global ambitions for

¹⁷ Chiquier, S., Patrizio, P., Bui, M., Sunny, N., Mac Dowell, N. (2022). A comparative analysis of the efficiency, timing and permanence of CO₂ removal pathways. DOI: 10.1039/d2ee01021f

¹⁸ IEA (2023): Net Zero Roadmap. A Global Pathway to Keep the 1.5 °C Goal in Reach.

¹⁹ Fuss, S. (2022): Chapter 11 Comparison of Technologies and Practices for Removing Carbon Dioxide from the Atmosphere in Greenhouse Gas Removal Technologies. Royal Society of Chemistry, UK.

carbon removal as a pillar of wider decarbonisation strategies. This study considers timeliness of direct air capture at both the process level and systems level.

1.5 Durability of direct air capture

Capturing carbon dioxide from the atmosphere does not itself achieve a removal of those emissions from the atmosphere. Direct air capture processes must be coupled in a value-chain to downstream processes which stores the captured carbon, keeping the carbon out of the atmosphere. The duration of storage for the net carbon removed from atmosphere is defined as the durability or permanence. As shown in Figure 1.1, the permanence of the stored carbon varies across different CO₂ removal approaches and depends on the storage mechanism (e.g., geological, mineralisation, soil, ocean, biomass or long-lived materials). In the case of DAC, there are two main options which exist for achieving longer durability/permanence.

First, captured carbon dioxide can be stored in underground geological formations (carbon storage). The IPCC identifies this option as permanent storage of the captured carbon dioxide.²⁰

Second, captured carbon dioxide can be sent to chemical conversion processes which embody it within carbon-based products, such as plastics, building materials, chemicals, or fuels (carbon utilisation). The durability of carbon storage varies significantly depending on the type of product produced. The captured carbon is temporarily removed from the atmosphere for a period until the products useful lifetime is expired and CO₂ is re-released back into atmosphere. For instance, fuels and many chemicals release CO₂ back into the atmosphere within a relatively short timeframe of weeks to months, whereas building materials and mineralised CO₂-based products can store carbon for decades or even centuries. Different types of products have widely different lifetimes, so the choice of product has a strong effect on the durability of the carbon removal which is achieved by the whole system²¹, as shown in Figure 5.1 and discussed in Section 5.3.

The consequences of choosing different portfolios of carbon storage and/or utilisation pathways for downstream handling of the captured carbon dioxide is still unclear. However, understanding the impact of this choice is central to the long-term value of direct air capture systems in our wider efforts towards decarbonisation. If a deployed direct air capture pathway has a low durability (e.g., DAC with CO₂ utilisation), this pathway will only act to delay decarbonisation efforts some amount of time into the future – rather than playing a role in the final decarbonised economy. Most short-lived CO₂-based products does not provide long-term carbon removal. The total global scale of carbon-based products is estimated to utilise 200–300

²⁰ **IPCC (2005):** “IPCC Special Report on Carbon Dioxide Capture and Storage”. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport.pdf

²¹ **Energy Transitions Commission (2022)** Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited. <https://www.energy-transitions.org/wp-content/uploads/2022/08/ETC-CCUS-Report-V1.9.pdf>

millions of tonnes of CO₂.²² Although CO₂ utilisation products that displace fossil-derived emissions, such as sustainable aviation fuel (SAF), may still contribute to near-term decarbonisation efforts, climate targets will require the mitigation of gigatonnes of CO₂ emissions. For direct air capture systems to play a credible role in long-term climate targets, DAC will mainly need to be used for high durability (i.e., high permanence) carbon removal. It will be important to consider the impact of carbon durability for different DAC pathways on the overall cumulative CO₂ emissions when evaluating the value of DAC.

1.6 Costs of direct air capture

As with any industrial process, there are economic costs associated with the deployment of direct air capture. However, there are also several indirect costs which interact with other sectors of the economy which need to be considered to ensure that a wide-scale deployment of direct air capture is feasible. The construction and operation of direct air capture systems requires large amounts of available land, construction materials (e.g., cement, steel), and operational resources (e.g., electricity, heat, and water). The deployment of direct air capture systems will interact with planned carbon capture, transport and storage infrastructure, which may be primarily designed for the decarbonisation of power and industry. While this could create additional demand, DAC may also provide a long-term use case for CCS infrastructure as fossil-based industrial emissions decline, ensuring continued viability for CO₂ transport and storage networks. Ensuring the availability of these key resources in the correct time and location is central to enabling any wide-scale deployment of direct air capture. Further to enabling the deployment, it will be important to weigh the required resources against the anticipated benefit of a deployment of direct air capture. This is an inherently multi-dimensional challenge which will depend on a variety of interconnected factors and interactions at local, national, and international levels.

1.7 Objectives: Value of direct air capture

The net carbon removal efficiency of DAC processes is strongly influenced by the life cycle emissions associated with the construction and operation of the DAC units themselves (e.g., carbon intensity of energy required, supply chain emissions, carbon footprint of construction materials), as well as any dedicated accompanying infrastructure.

Timeliness considers how much we can rely on the CO₂ removals provided by DAC in the energy transition, taking into account realistic expectations for its global deployment rate. Furthermore, DAC provides more immediate CO₂ removals

²² Mac Dowell, N., Fennell, P. S., Shah, N., Maitland, G. C. (2017). Nature Climate Change 7(4): 243–249. <https://doi.org/10.1038/nclimate3231>

compared to some other CDR options. For instance, enhanced weathering can take months, years to decades to remove CO₂.

Durability (also referred to as permanence) refers to the length of time for which carbon is stored. It will be important to consider the suitability of the carbon sinks (permanent geological sequestration, or short-term utilisation), and how this affects our ability to rely on DACCS to achieve permanent CDR across relevant timescales.

From the perspective of physical constraints, there has been little work conducted to collate and assess information relating to the land footprint of DAC systems which achieve the significant CO₂ removal rates set out in global energy transition pathways. Additionally, we can anticipate that supporting infrastructure, including low-carbon electricity production, the provision of heat and water, and CO₂ transport and storage infrastructure, will play a significant role in the total land requirement for DAC as well as impact cost and scalability.

Geographical factors, such as availability of these resources and variable climatic conditions, are also expected to play a major role in determining the scope to utilise DAC to achieve CDR. Understanding these factors at relevant scales is important to facilitate informed planning and decision making for selecting CDR technologies.

This study aims to evaluate the value of direct air capture and storage in the energy transition, accounting for key factors, including carbon removal efficiency, timeliness, durability, land footprint, techno-economic performance and geopolitical factors. The impact of these key factors on the overall value of DAC must be analysed in the context of regional energy transitions to enable cost-effective, large-scale deployment of DAC at wide-scale.

As outlined above, assessing the value of direct air capture in the context of wider decarbonisation efforts is an inherently multi-dimensional task. The assessment needs to encompass several key elements, including carbon removal efficiency in Chapter 3, timeliness of CO₂ removal in Chapter 4, durability of carbon stored and utilised in Chapter 5, land footprint in Chapter 6, as well as techno-economic performance and costs in Chapter 7. In this report, we aim to analyse the performance of state-of-the-art direct air capture technologies against these criteria to provide a comprehensive understanding of the value of direct air capture to the wider energy system. Chapter 8 summarise key findings which can be taken forward as recommendations for future research in both the technical engineering and systems analysis of direct air capture value chains. Where necessary, we also highlight key areas where there are knowledge gaps in existing research which act as barriers to accurately assessing the value of direct air capture.

1.8 Framing, Scope, and Limitations of This Study

This is a systems-level analysis of the value of direct air carbon capture (DAC) within the context of global and regional decarbonisation efforts. The assessment is based on a set of scenario-driven assumptions, synthesised from literature, to evaluate and compare the performance of different DAC technologies (specifically L-DAC and S-DAC). Rather than offering a forecast or project-level evaluation, this work is

intended to support strategic thinking by highlighting the key factors, constraints, and trade-offs that influence DAC deployment at wide scale.

The analysis draws on techno-economic values reported in academic literature, which vary in scope, assumptions, and level of detail. Many of these studies were published before 2020 and do not incorporate cost learnings or performance data from contemporary commercial DAC projects. Additionally, there is limited availability of standardised, process-level techno-economic assessments. As such, this report presents a scenario-based comparison using available literature as a foundation, recognising that this limits the precision of the results but still provides valuable insight into the broader system-level implications.

The scope of the assessment is deliberately focused on techno-economic and energy-related factors influencing DAC performance. The analysis does not incorporate dynamic power system modelling (e.g. marginal emissions,²³ hourly grid dispatch), site-specific factors, or commercially bespoke configurations such as DAC systems powered by dedicated renewable generation. Instead, the approach in this study models DAC as grid-connected infrastructure, which allows for consistent comparison across energy mixes and timeframes. Stand-alone systems powered by co-located and dedicated renewables or fossil sources with CCS are outside the scope of this work.

This report also does not account for GHG emissions avoided from the displacement of conventional materials or fuels through using an equivalent CO₂ utilisation product. The carbon removal efficiency estimates are based on reported operational and embodied emissions from the literature and may not comprehensively cover supply chain impacts such as chemical production or sorbent longevity, particularly where data is limited.

In focusing on carbon removal efficiency, timeliness, durability, land footprint, and cost, this study provides an integrated view of the systemic impacts and requirements associated with large-scale DAC deployment. The scenarios presented illustrate how different assumptions regarding technology performance, energy supply, and system design influence DAC value and feasibility. These results are intended to inform future planning, modelling, and policy development. This is especially important in identifying the most influential parameters and the conditions under which DAC can deliver net-negative emissions at meaningful scale. While recognising its limitations, this report contributes to the growing body of work on carbon removal by offering a structured comparison between DAC technologies within a systems context. It helps clarify where further research, real-world data, and cross-sector coordination are most urgently needed.

²³ Marginal emissions are the greenhouse gases emitted per unit of energy generated caused by the power plant ramping up or down.

2 Technologies for Direct Air Capture

2.1 Proposed direct air capture technologies

There are a wide variety of engineering approaches which have been proposed for achieving the separation of CO₂ from ambient air in a direct air capture process. There are various ways to classify DAC technologies, including the physical state of the sorbent material, the method used for sorbent regeneration, the operating process temperature, among other factors. Each DAC system couples a specific capture medium (e.g., liquid solvents, solid sorbents, membranes) with a regeneration technique (e.g., thermal, vacuum, moisture-swing, electrochemical). In this report, DAC technologies are categorised based on their capture media and the regeneration method applied to release the captured CO₂. The following sections outline key DAC technology groups, though variations exist within each category.

- 1) **Liquid sorbent DAC (L-DAC):** air is contacted with an aqueous alkaline solution which reacts with the CO₂ in the air, producing a CO₂-rich solution. The CO₂-rich solution goes to the pellet reactor where small pellets of carbonate form and are removed from the solution. The solid pellets are heated in a high temperature calciner (300–900°C) to regenerate and release high purity CO₂. The regenerated pellets are hydrated in the slaker before recycled back to the pellet reactor and used in the air contactor to allow capture of more CO₂. The process is continuous, and individual plants can have a large capture production rate (> 1 Mt/yr)²⁴. There are other liquid-based DAC processes, including those using liquid amines or amino acid salts, which can be regenerated at lower temperatures or through electrochemical processes.
- 2) **Solid sorbent DAC (S-DAC):** air passes over a solid sorbent filter that absorbs CO₂. The CO₂ is then released at high purity when the sorbent is heated (80 – 100 °C) or placed under mild to deep vacuum (0.05 – 0.5 bar). Since the process is semi-batch, many individual contactors need to be arranged in parallel to achieve continuous capture of CO₂. Individual units have a small capture rate (e.g., 50 tCO₂/year)²⁵. Moisture swing adsorption (MSA), a variation of S-DAC, uses sorbents that bind CO₂ under dry conditions and

²⁴ IEA (2022) Direct Air Capture. A key technology for net zero. https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf

²⁵ Beuttler, C., Charles, L. & Wurzbacher, J. (2019). The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. *Frontiers in Climate* 1. DOI: 10.3389/fclim.2019.00010
 Tollefson, J (2018) Sucking carbon dioxide from air is cheaper than scientists thought. *Nature* 558, 173
 McQueen, N. et al. (2021) A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. *Progress in Energy* 3, 032001. DOI:10.1088/2516-1083/abf1ce

release it in humid conditions. While MSA differs in its regeneration mechanism, it still falls within the broader category of solid sorbent DAC.

- 3) **Electrical-swing adsorption (ESA):** the process is based on the operation of an electrochemical cell²⁶. CO₂ is selectively adsorbed from the air while a negative charge is applied to the electrode and is released from the surface at high purity when a positive charge is applied to the electrode. The process is semi-batch, so many individual cells need to be arranged in parallel to achieve continuous capture of CO₂. The process has the potential to have a very low primary land footprint, as the electrochemical cells can be stacked together very efficiently. The process does not require any heat for the regeneration of CO₂, so it is inherently electrified and is therefore highly compatible with renewable energy sources for achieving strong environmental effectiveness. However, it is currently an emerging DAC technology (TRL 4) where it has been tested at a lab scale and not yet commercially deployed.
- 4) **Membrane DAC (m-DAC):** air is introduced to a selectively permeable membrane designed to allow CO₂ to pass through while retaining other gases. High purity CO₂ is produced on the permeate side of the membrane. Advantages of membranes for gas separation include compactness, lower capital costs and low energy requirements. However, membranes often are unable to achieve high degrees of separation and consequently require multiple stages and a stream recycle. This can result in increased process complexity, as well as higher energy consumption and cost. Membrane-based direct air capture is still in the proof-of-concept stage of development. A recent modelling analysis by Fujikawa, et al.²⁷ proposes a target membrane performance that would be required to make membrane-based direct air capture economically competitive. The authors indicate that these target membrane properties will be challenging to achieve.

2.2 Technology readiness level (TRL)

Technology readiness level (TRL) is a scale which is used to assess the maturity of technologies for a given application in a systematic manner. The TRL scale is typically divided into 9 levels, where TRL 1 corresponds to a technology where only the basic principles have been defined, and TRL 9 corresponds to a technology where there is an established and competitive market (Figure 2.1). Current direct air capture technologies fall in the range of TRL 1-6.

Throughout this report, we will only be considering in significant detail direct air capture technologies which have already achieved a TRL of at least 6. The motivation for this threshold is two-fold:

²⁶ Voskian, S., and Hatton, T. A. (2019) Faradaic electro-swing reactive adsorption for CO₂ capture. <https://doi.org/10.1039/C9EE02412C>

²⁷ Fujikawa, S., Ariyoshi, M., Selyanchyn, R., Kunitake T. (2019) Ultra-fast, selective CO₂ permeation by free-standing siloxane nanomembranes. doi: 10.1246/cl.190558

- ▶ **Technology proven in deployment conditions:** operation of a direct air capture process requires operating with ambient air as the feed stream, which presents unique technological challenges. First, the composition of CO₂ in the air is ultra-dilute ($\approx 400\text{ppm}$). This presents significant engineering challenges in achieving high CO₂ capacity and CO₂ capture rates at these conditions. Additionally, while CO₂ selectivity is primarily dependent on material properties, designing sorbents or membranes that maintain high selectivity at ultra-dilute concentrations remain a challenge. Second, ambient air presents significant variability across a large range of time scales in terms of temperature and humidity content. This challenges the design of direct air capture units which can operate under variable and uncertain feed conditions.
- ▶ **Technology proven at suitable scale:** to provide a meaningful assessment of the value of direct air capture processes in terms of life cycle assessment (LCA) and techno-economic analysis (TEA), a technology must already be proven at a sufficiently large scale. Moreover, to enable meaningful deployment in the near-term, a technology must already be proven to be scalable.

For these reasons, we contend that DAC technologies below TRL 6 are unlikely to be feasible for wide-scale deployment in the near-term. While it is possible for certain technologies – particularly modular approaches – to progress rapidly, most low-TRL DAC pathways still face significant technical and scaling challenges that require further deployment at scale. While such technologies may become relevant in future decades, they are not suited for first-generation deployment commencing within the next decade. Given the urgency in the global agenda to rapidly scale carbon dioxide removal technologies, our analysis focuses on technologies that have already been demonstrated in deployment conditions and can begin immediate scaling.

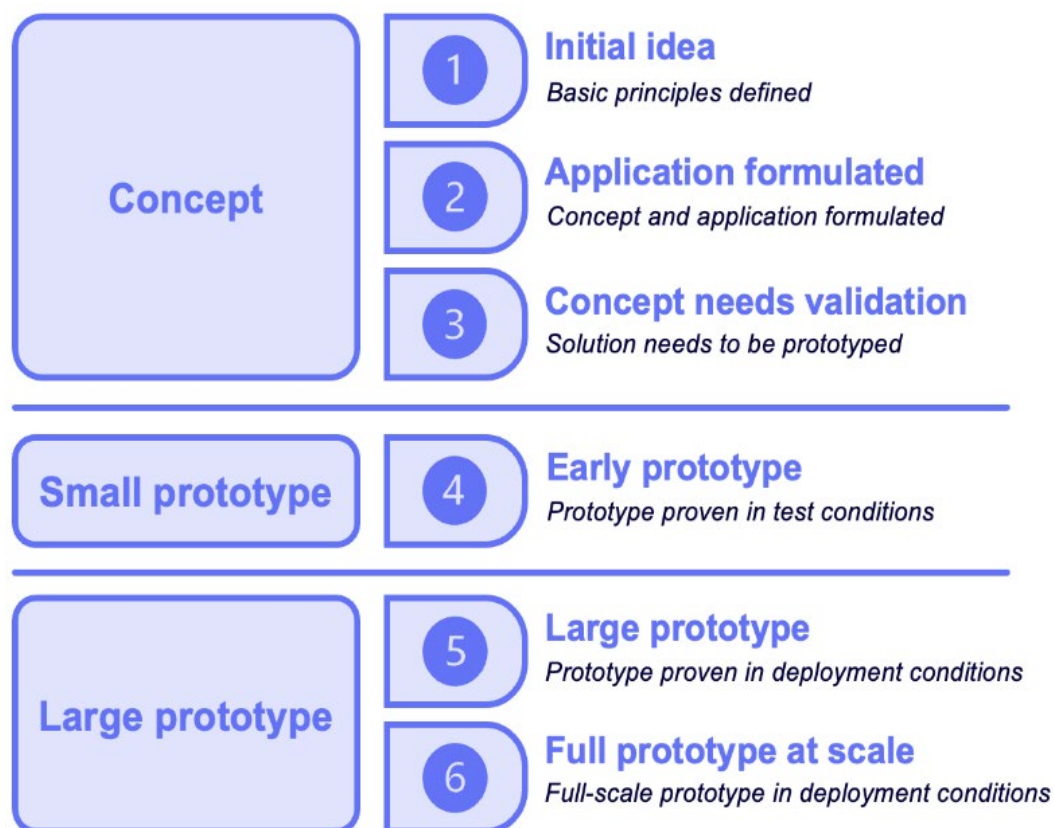


Figure 2.1: Technology readiness level (TRL) scale for levels 1–6.

Currently, the most mature technologies for direct air capture are liquid sorbent direct air capture (L-DAC) and solid sorbent direct air capture (S-DAC) (Figure 2.2). Both technologies have been proven in deployment conditions and at significant scale, forming the basis for early commercial projects. L-DAC, as exemplified by Carbon Engineering's process, uses aqueous alkaline solutions to capture CO₂ followed by high-temperature regeneration. S-DAC has been demonstrated in commercial operations by companies like Climeworks. Climeworks relies on solid sorbents regenerated via temperature or vacuum-swing cycles. Both pathways are currently being scaled toward multi- and megaton-deployment.²⁸

²⁸ IEA (2024) Direct Air Capture. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture#overview>

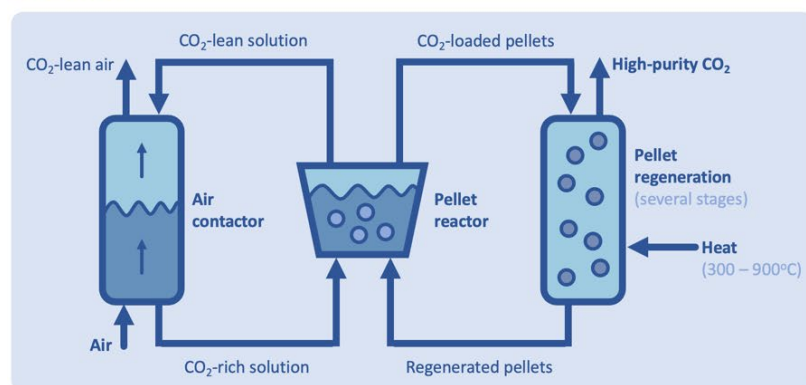
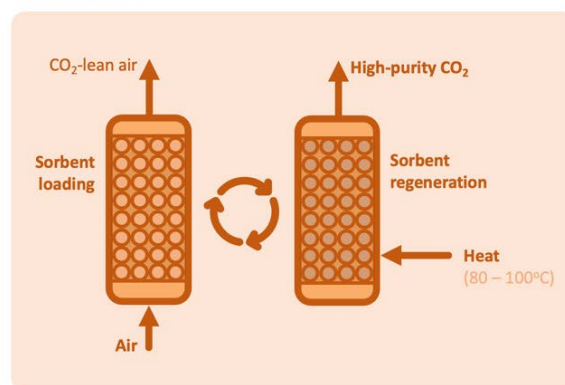
L-DAC:**S-DAC:**

Figure 2.2: schematics of the working principles of liquid sorbent DAC (L-DAC) and solid sorbent DAC (S-DAC) processes.

A wide range of technologies are under development, including electrical-swing adsorption (ESA)²⁹, membrane-based DAC (m-DAC), and MSA. While there is significant interest in advancing these approaches, they remain at lower TRLs and currently face challenges related to scalability process efficiency and operation under realistic ambient conditions.^{30,31}

Given the urgency of scaling CDR technologies, this report focuses on L-DAC and S-DAC as the two most mature and well-characterised approaches, using them as archetypes to evaluate the role of DAC in large-scale deployment.

²⁹ Verdox (2024) <https://verdox.com/>

³⁰ Sanz-Perez, E. S., Murdock, C. R., Didas, S. A., Jones, C. W. (2016) Direct Capture of CO₂ from Ambient Air. <https://doi.org/10.1021/acs.chemrev.6b00173>

³¹ Sodiq, A., Abdullatif, Y., Aissa, B., Ostovar, A., Nassar, N., El-Naas, M., Amhamed, A. (2023) A review on progress made in direct air capture of CO₂. <https://doi.org/10.1016/j.eti.2022.102991>

3 Carbon removal efficiency of direct air capture

3.1 Carbon captured vs. carbon removed

The unit operation of a direct air capture process receives a feed of ambient air from the atmosphere and aims to capture CO₂ from that feed, before returning the resulting CO₂-lean air stream to the atmosphere. Both technologies identified in Chapter 2 (L-DAC and S-DAC) have been shown to be capable of achieving this unit operation at the conditions and scale required to enable wide-scale deployment. However, the ultimate objective of deploying direct air capture is to ensure that there is a net-removal of CO₂ from the air, once the emissions associated with deploying and operating the direct air capture process are accounted for. The use of direct air capture will inevitably always incur some level of emissions along the value chain (e.g., associated with the energy consumed or construction). Therefore, the net amount of CO₂ removal which is achieved is always smaller than the amount of CO₂ which is captured by the direct air capture unit itself.

The translation of captured and stored CO₂ into removed CO₂, once accounting for the equivalent CO₂ emissions of the entire direct air capture value chain, is characterised by the carbon dioxide removal efficiency, which is defined as:

$$\eta_{\text{CDR}}(\%) = \frac{m_{\text{CO}_2}^{\text{captured}} - m_{\text{CO}_2}^{\text{emitted}}}{m_{\text{CO}_2}^{\text{captured}}} \times 100\%$$

where η_{CDR} is the carbon dioxide removal efficiency, $m_{\text{CO}_2}^{\text{captured}}$ is the mass of CO₂ captured and stored the direct air capture process, and $m_{\text{CO}_2}^{\text{emitted}}$ is the total mass of CO₂ equivalent emissions associated with achieving the capture of that CO₂.

In the best case, if the emissions along the value chain are small compared to the CO₂ captured and stored, DAC can achieve a high net carbon removal. However, if these emissions are too large, the ability of the DAC facility to deliver net negative emissions is reduced. It is therefore critically important to accurately assess the emissions associated with the entire direct air capture value chain to enable an understanding of the actual environmental effectiveness being achieved by a given level of DAC deployment.

3.2 Cradle-to-grave value chain emissions

To assess the emissions along the entire value chain of a direct air capture process, we need to conduct a full cradle-to-grave life cycle assessment which accounts for all significant sources of emissions associated with the deployment and operation of the process (Figure 3.1). There are several categories of emissions which need to be accounted for in such an assessment to ensure that the carbon dioxide removal efficiency is accurately characterised, these include:³²

- ▶ Emissions associated with the construction of the direct air capture process air contactors and regeneration equipment.
- ▶ Emissions associated with the construction of supporting infrastructure for the provision of electricity, heat, and water.
- ▶ Emissions associated with the operational provision of electricity, heat and water.
- ▶ Emissions associated with capture chemicals or material (e.g., sorbent or solvents) production to enable operational sorbent replenishment at regular intervals.
- ▶ Emissions associated with CO₂ conditioning, and subsequent geological storage or chemical conversion and end-use.

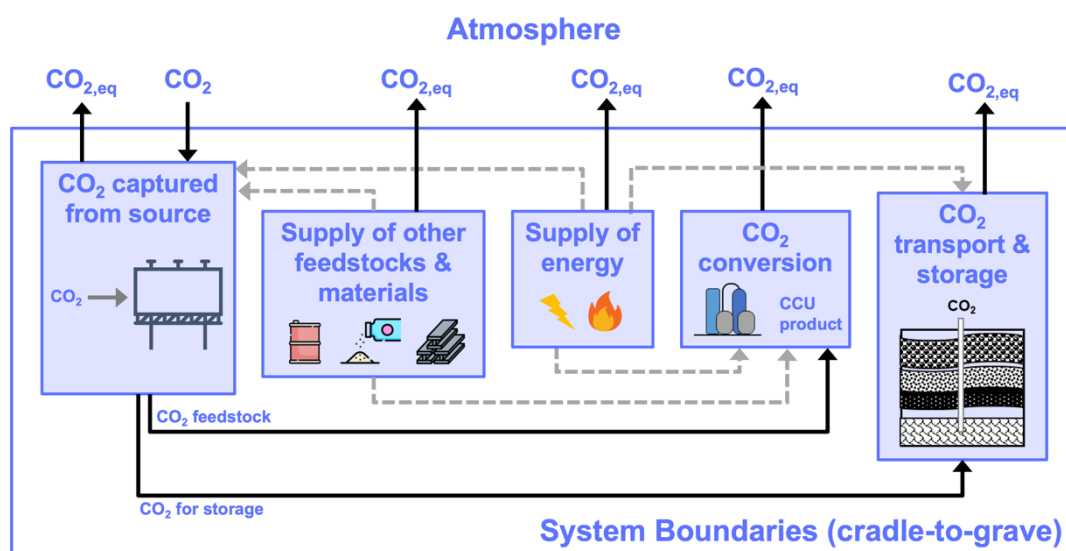


Figure 3.1: cradle-to-grave value chain for assessing the life cycle emissions of a direct air capture process coupled to either (i) geological carbon sequestration, or (ii) carbon utilisation. Reproduced from Müller et al. (2020).³²

³² Müller et al. (2020): "A guideline for life cycle assessment of carbon capture and utilization". Frontiers in Energy Research (8).

3.3 Carbon dioxide removal efficiency

A literature review of life cycle assessments (LCA) of direct air capture identified 5 studies which perform LCA for L-DAC processes,³³ and 6 studies which perform LCA for S-DAC processes.³⁴ The carbon dioxide removal (CDR) efficiencies reported in these studies vary widely. For L-DAC processes, the removal efficiency is reported to fall within the range 41.3–80.3%. For S-DAC processes, the removal efficiency is reported to fall within the range 36.2–97.6%.

This variation in CDR efficiency can be considered relatively broad and is influenced by several key factors. One major factor contributing to this wide range is the energy supply, particularly the carbon intensity of the electricity used in the DAC processes. For instance, the studies have shown that switching to renewable energy sources can significantly improve CDR efficiency. As noted in the study by de Jonge et al. (2019), using solar power instead of grid electricity can increase carbon efficiency from 62% to 84% in an L-DAC system. Additionally, the study by Terlouw et al., (2021) and highlighted that the GHG intensity of the grid electricity mix is a crucial factor driving the variation in CDR efficiency, with country-specific grid mixes leading to significant differences. Moreover, GHG emissions related to the construction, sorbent consumption, and CO₂ storage infrastructure also play substantial roles in influencing the overall carbon removal efficiency of DAC systems.

Another critical aspect influencing CDR efficiency is the technology archetype and operational configuration of the DAC system. Madhu et al. (2021) compared temperature swing adsorption (TSA) S-DAC and high-temperature L-DAC, demonstrating the impact of system layouts and configuration. They showed that TSA S-DAC outperforms L-DAC across various environmental impact categories, mainly due to differences in energy and material consumption.

Overall, the wide variation in reported CDR efficiencies reflects the complex interplay of energy supply, system design, and operational parameters in DAC processes.

³³ **Chiquier et al. (2022)**: “A comparative analysis of the efficiency, timing, and permanence of CO₂ removal pathways”. *Energy & Environmental Science* (15); **Madhu et al. (2021)**: “Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment”. *Nature Energy* (6); **NETL (2021)**: “Life cycle greenhouse gas analysis of direct air capture systems”; **Qiu et al. (2022)**: “Environmental trade-offs of direct air capture technologies in climate mitigation towards 2100”; *Nature Communications* (13); **de Jonge et al. (2019)**: “Life cycle carbon efficiency of direct air capture systems with strong hydroxide sorbents”. *International Journal of Greenhouse Gas Control* (80).

³⁴ **Chiquier et al. (2022)**: “A comparative analysis of the efficiency, timing, and permanence of CO₂ removal pathways”. *Energy & Environmental Science* (15); **Madhu et al. (2021)**: “Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment”. *Nature Energy* (6); **NETL (2021)**: “Life cycle greenhouse gas analysis of direct air capture systems”; **Qiu et al. (2022)**: “Environmental trade-offs of direct air capture technologies in climate mitigation towards 2100”; **Terlouw et al. (2021)**: “Life cycle assessment of direct air carbon capture and storage with low-carbon energy sources”. *Environmental Science & Technology* (55); **Deutz & Bardow (2021)**: “Life-cycle assessment of an industrial direct air capture process based on temperature-vacuum swing adsorption”. *Nature Energy* (6).

3.4 Embodied emissions

The embodied emissions are the GHG emissions associated with the upstream stages of a product's lifecycle. For a DAC process, embodied emissions include the supply chain of the materials (e.g., extraction, processing, production, manufacturing, transportation) used for the construction of the DAC process and any supporting infrastructure. For both L-DAC and S-DAC processes, three of the reported studies explicitly report the embodied emissions of the direct air capture process. Embodied emissions are reported in units of tonnes of CO₂ (equivalent) emissions per tonne of CO₂ captured over the process lifetime (tCO₂eq/tCO₂cap).

The embodied emissions³⁵ reported in the literature studies vary widely. For L-DAC processes, the embodied emissions are reported to fall in the range 0.002–0.11 tCO₂eq/tCO₂cap. For S-DAC processes, the embodied emissions are reported to fall in the range 0.0015–0.019 tCO₂eq/tCO₂cap. While we can see that there is significant variation in the reported estimates of the embodied emissions,^{33,34} these emissions typically represent a relatively small proportion of the total value chain emissions. This is particularly true for S-DAC systems, where embodied emissions account for just 2.0 – 6.3% of lifecycle emissions across studies. However, for L-DAC, this proportion can range from 0.5% to as high as 18.7%, with the upper end arising from the most conservative modelling assumptions, which include broader system boundaries and less efficient energy supply configurations. Overall, these findings reinforce that while operational emissions dominate value chain impacts, embodied emissions may become more significant under certain configurations and should not be overlooked. It is therefore central to the accurate assessment of the environmental effectiveness of a direct air capture process to accurately characterise the operational emissions.

³⁵ **Embodied emissions** refer to the GHG emissions associated with the extraction, production, transportation of materials, the construction process, maintenance and repair during the use phase and end-of-life activities such as decommissioning, demolition and waste processing or recycling. **Operational emissions**, on the other hand, are the GHG emissions generated during the ongoing operation of the DAC facility, including the energy required to run the capture processes, maintain the facility, and transport and store the captured CO₂. Together, these two categories encompass the total carbon footprint of a DAC facility. For a visual representation of what is included in embodied emissions, refer to the diagram provided by the World Green Building Council in their report "Bringing Embodied Carbon Upfront". https://worldgbc.s3.eu-west-2.amazonaws.com/wp-content/uploads/2022/09/22123951/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf

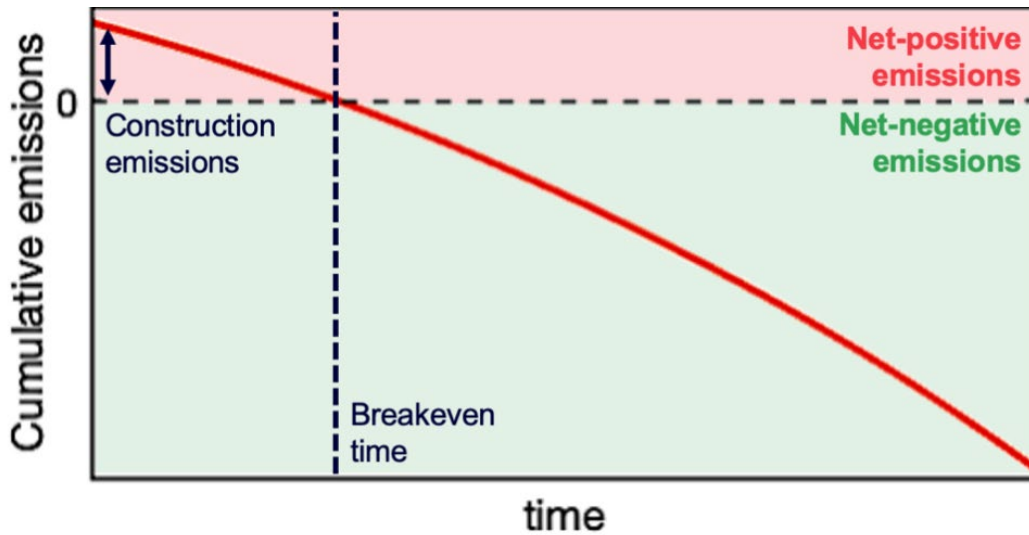


Figure 3.2: Visualisation of the concept of breakeven time for a direct air capture process. Cumulative emissions of the cradle-to-grave value chain are initially positive because of emissions associated with construction of the value chain. As time progresses, the cumulative emissions decrease as the direct air capture process operates and removes emissions from the atmosphere. Eventually, the cumulative emissions of the system become zero. The time at which this occurs is defined as the breakeven time.

3.5 Breakeven time

When a direct air capture process and its associated value chain are established, some amount of carbon emissions are released to the atmosphere. Therefore, the direct air capture process must operate for a period of time to recover an equivalent amount of emissions from the atmosphere to those released during construction (Figure 3.2). The breakeven time (t_{BE}) for a direct air capture process can be calculated as:

$$t_{BE} = \frac{(\text{construction emissions})}{(\text{removal efficiency}) \times (\text{capture rate})}$$

where the emissions associated with construction can be calculated using the embodied emissions:

$$\begin{aligned} &(\text{construction emissions}) \\ &= (\text{embodied emissions}) \times (\text{capture rate}) \times (\text{plant lifetime}) \end{aligned}$$

By assuming a plant lifetime of 30 years for the direct air capture process, the data acquired from the literature sources indicates that the breakeven time is approximately 1.2–95.9 months (0.1–8 years) for L-DAC processes, and approximately 0.6–9.8 months for S-DAC processes. Again, we can see that there is significant variation in the estimation of the breakeven time (Figure 3.3), which is caused by significant variability in both the embodied emissions and the removal efficiency, which are used as inputs for the calculation. The range of estimated breakeven times for L-DAC processes indicates that it is possible to achieve CO₂ removals within 1.2 months of L-DAC operation. However, under high carbon intensity process configurations and conditions (e.g., high carbon intensity energy), L-DAC may have poor process-scale timeliness, taking up to 8 years before the carbon

removed from the atmosphere by operation of the DAC process counter-balances the embodied emissions. For S-DAC processes, we observe improved process-scale timeliness between the various studies compared to L-DAC, with S-DAC processes beginning to achieve net carbon removal from the atmosphere in under 1 year.

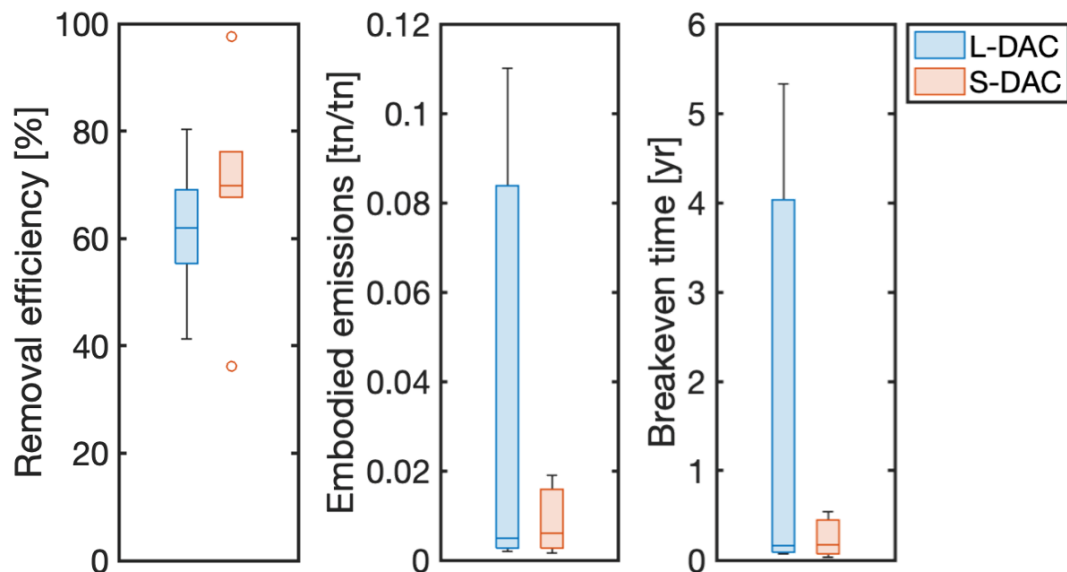


Figure 3.3: carbon dioxide removal efficiency, embodied emissions, and breakeven time for L-DAC and S-DAC processes, as reported in literature with life cycle assessments of direct air capture processes. Data is available in tabular form in Appendix 1. Each box represents the interquartile range (IQR) between the 25th and 75th percentile of reported values, with the central line indicating the median. The whiskers extend to the minimum and maximum values from the quartiles. Circles denote outlier values beyond this range. The variation observed reflects differences in assumed energy inputs, system boundaries, and process configurations across studies.

This upper bound breakeven time of approximately 8 years for L-DAC originates from the scenario reported in Madhu et al. (2021), which combines relatively high embodied emissions (0.11 tCO₂eq per tCO₂ captured) with a low removal efficiency of 41.3%. These pessimistic assumptions result in extended breakeven times and are likely reflective of early-stage system configurations and CO₂eq intensity of energy and construction materials are high. While important to include as part of the literature range, such scenarios are not necessarily representative of the performance expected from commercial-scale deployments. In contrast, most other studies report significantly shorter breakeven times for L-DAC, for example as low as 1.2 months in the case of NETL (2021), which indicates substantial sensitivity to input assumptions. Furthermore, the distribution of values suggests that the median breakeven time for L-DAC lies much closer to that of S-DAC. This reinforces the need to interpret the breakeven time range in the context of assumptions used, especially regarding energy system carbon intensity, construction data sources, and process design maturity. Future studies should strive for greater transparency and harmonisation in assumptions to improve comparability and better inform policy and investment decisions.

It is important to recognise that the life cycle assessments conducted across the studies in literature use different input data and assumptions. The sources of variation across different LCAs are discussed in the next section.

3.6 Variation across life cycle assessments

As outlined above, we observe significant variation in the estimates of all key performance indicators for the life cycle assessment of L-DAC and S-DAC processes, including carbon dioxide removal efficiency, embodied emissions, and breakeven time. As the operation of DAC processes is highly energy intensive, the carbon intensity of the energy consumed has a major influence on the CO₂ removal efficiency and breakeven time. A key aspect of the life cycle assessment studies, which is inconsistent between the available literature, is the methodology and assumptions used to determine the scenarios for the provision of electricity and heat. We observe that there is no systematic approach between the studies for selecting the sources of energy. Importantly, performance of DAC will likely vary significantly due regional factors, energy infrastructure and process design configurations, including the intermittency of renewable energy sources.

The variation observed in the aforementioned literature studies is due to differences and inconsistencies in assumptions and methodologies. Thus, the performance across different studies or scenarios should be reported as a range to account for such variations. This range is not only an expression of uncertainty but rather reflects the variability arising from different DAC value chain decisions (e.g., DAC technology archetype, energy carbon intensity), including effects of regional techno-economic factors and the supporting infrastructure (e.g., type of energy source).

Since operational emissions are attributed to the largest fraction (*ca.* 81-98%) of the overall DAC value chain emissions, arbitrary selection of the energy supply scenarios for conducting life cycle assessment significantly impacts the carbon dioxide removal efficiency. Further, arbitrary decisions of the energy supply scenarios also cause significant variability in the embodied emissions, which includes stages of the value chain impacted by the carbon intensity of energy supply (e.g., raw material extraction, manufacturing, construction of supporting infrastructure). As outlined above, variability in both of the operational emissions and embodied emissions results in a large range for the estimation of the breakeven time for each process. The observed variation across literature values is large enough that it is challenging to make comparisons between the two proposed technologies based on the available data. The remaining chapters 4 to 7 provide an analysis of DAC value and performance using a more consistent approach.

We note that guidelines exist which have been published by the United States Department of Energy (US DoE) for conducting life cycle assessments of direct air capture processes.³⁶ In addition to emerging start-up-led initiatives, several

³⁶ US DoE (2022) Best practices for life cycle assessment (LCA) of direct air capture with storage (DACs).

established standards organisations³⁷ and regulatory frameworks³⁸ are also developing DAC-specific methodologies. These efforts are part of a broader movement towards standardising life cycle assessments for direct air capture processes.³⁹ We recommend that such guidelines need to be more widely and consistently adhered to in academic studies providing life cycle assessments for direct air capture. Ideally, we would like to see a stronger level of agreement between independent bodies of work. Thus, widely adopting standards for life cycle assessments of DAC processes would contribute significantly towards improving comparability.

Life cycle assessments of novel technologies may be speculative because these processes have not yet been deployed at a sufficiently large scale. However, LCA studies at early stages of deployment can help quantify the potential upper and lower bounds of LCA performance to demonstrate the impact of different DAC value chain decisions. We also note that this speculative nature of current life cycle assessment studies necessitates particular care with respect to the use of lifecycle inventory (LCI) databases used to provide input data. LCI databases contain representative emissions data for various world regions and sets of assumptions, some of which may be out-of-date. It is therefore important to review LCI data as a first step, to ensure that relevant data is up to date for the specific case studies being analysed. Furthermore, if more data from actual DAC projects becomes available for use in LCI databases, this would build confidence in the outcomes of these studies.

Global-scale deployment of direct air capture technology will likely require interactions with national infrastructure for electricity and heat provision. Arbitrary energy supply scenarios that neglect to account for such interactions are not useful for understanding the environmental effectiveness of direct air capture at the real-world conditions and the relevant scale. We therefore suggest that future work should seek to integrate case studies utilising realistic energy supply carbon intensities from real-world data in a variety of geographical contexts and time horizons. This will allow for relevant and realistic interpretation of life cycle assessment outcomes, as well as providing a better basis for policy development and energy system planning in different national contexts where direct air capture may represent a significant pillar of wider decarbonisation strategy.

We note that standardised case studies have been published for the benchmarking of technologies for post-combustion carbon capture, e.g., by the UK Department of Energy Security and Net Zero (DESNZ).⁴⁰ An analogous set of benchmarking cases for direct air capture has been developed by the US National Energy Technology

³⁷ Verra (2024) CO₂ Capture from Air (Direct Air Capture), v1.0

³⁸ European Commission (2024) EU Carbon Removals and Carbon Farming Certification (CRCF) Regulation

³⁹ Puro.earth (2024): "[Geologically stored carbon – methodology for CO₂ removal](#)"; Isometric (2023): "[Direct air capture protocol](#)"; Carbon(plan) (2022): "[CDR verification framework: direct air capture](#)"; Climeworks (2022): "[Carbon Dioxide Removal by Direct Air Capture](#)".

⁴⁰ BEIS (2018): Assessing the cost reduction potential and competitiveness of novel (next generation) UK carbon capture technology – benchmarking state-of-the-art and next generation technologies.

Laboratory (NETL)⁴¹, which has been very valuable to understanding DAC performance at commercial-scale. Such case studies should aim to represent a wide variety of energy system decarbonisation pathways and climatic conditions in different geographical contexts. Such an approach will; (i) allow for standardised comparisons between competing direct air capture technologies under relevant conditions, and (ii) allow for identification of world regions which are most suitable to accommodate wide-scale deployment of direct air capture processes with high environmental effectiveness.

The recommendation outlined in this section is central to building confidence in the feasibility of DAC technology. The work towards developing LCA and benchmarking standards are currently being used to develop methodologies for monitoring, reporting and verification (MRV) of commercial DAC projects. Reliable and robust MRV of CDR projects is essential to the evolution and scale-up of the voluntary and compliance-based CDR markets.

3.7 Regional efficiency of direct air capture

We have identified that a significant source of variation in literature on LCA is the energy supply scenarios in terms of electricity and heat supply considered in each study. Efforts have been made in academic literature towards rationalising this uncertainty. Particularly, Chauvy & Dubois (2021) collated data from life cycle assessment studies for L-DAC and S-DAC processes for the reported carbon dioxide removal efficiency and the assumed carbon intensity of energy supply.⁴² The study found that carbon dioxide removal efficiency can be strongly correlated as a sole function of the carbon intensity of energy supply among the considered life cycle assessments. While other factors, such as ambient conditions, may also influence CDR efficiency, this study specifically examined the relationship between carbon intensity and removal performance. The resulting correlation for the carbon dioxide removal efficiency is reported with the following linear form:

$$\eta_{\text{CDR}}(t) = \delta_{\text{DAC}} I_{\text{grid}}(t) + \epsilon_{\text{DAC}}$$

where $I_{\text{grid}}(t)$ is the carbon intensity of energy supplied by the energy grid (kgCO₂-eq/kWh) at time t , and δ_{DAC} and ϵ_{DAC} are coefficients of the correlation – which take specific values for each direct air capture technology. The coefficients of the correlation are available in tabular form in Appendix 3.

The power consumption values used in this analysis are taken from Chauvy & Dubois (2021), which collated data from multiple sources in the literature. While alternative estimates exist, they depend on the inclusion of thermal energy sources (e.g., waste heat use or heat pumps for S-DAC). The correlation presented here follows the

⁴¹ NETL, (2022): Direct air capture case studies: Solvent system.

https://netl.doe.gov/projects/files/DirectAirCaptureCaseStudiesSolventSystem_083122.pdf;

⁴² Chauvy & Dubois (2022): Life cycle and techno-economic assessments of direct air capture processes: An integrated review. International Journal of Energy Research (46).

assumptions in the cited study, which are consistent with peer-reviewed LCA methodologies.

The reported correlation is shown graphically in Figure 3.4(a). We can see that when the carbon intensity of energy supply is low, the performance of L-DAC and S-DAC processes in terms of carbon dioxide removal efficiency is very similar. However, we see that S-DAC processes are significantly more effective than L-DAC processes as the carbon intensity of energy supply increases. This difference arises because L-DAC can be more energy intensive and has a higher reliance on high-temperature heat, which often comes from fossil fuels. The carbon intensity of an electricity grid is influenced by the energy mix used in each country or region. Countries with a high reliance on fossil fuels for power generation would have energy grids with higher carbon intensities, while those with greater shares of nuclear and renewable energy sources would have energy grids with lower carbon intensities.

Figure 3.4 (b) shows the projected carbon intensity of energy supply over time across six regions of the world. The data highlights how carbon intensity is expected to decrease over time as regions transition towards cleaner energy sources. The trajectories vary significantly due to the different energy mixes and policies in these regions. The results show that L-DAC processes are currently unable to provide significant net carbon removal (i.e., positive carbon removal efficiency) in several world regions, including Europe, North America, and Asia – according to the current carbon intensity of energy supply in these geographical regions. In contrast, S-DAC processes can currently operate with net-negative emissions along their entire value chain in several world regions, including Europe and North America. In practice, DAC developers usually aim to secure low-carbon energy through power purchase agreements (PPAs) or direct connections to renewable energy, which could mitigate these effects.

To understand how the carbon dioxide removal efficiency of L-DAC and S-DAC processes will develop over time in different geographical contexts, we can integrate scenarios of the regional energy decarbonisation pathways in different world regions as functions of time into the correlation for carbon dioxide removal efficiency provided above. In Figure 3.5, we provide the predicted carbon intensity of electricity generation in six world regions as specified in the EnerOutlook energy & emissions projections to 2050 scenario published by Enerdata.⁴³ Enerdata's EnerOutlook projections predict the carbon intensity of energy supply in the Pacific, Middle East, Asia, North America, Europe, and Latin America regions in the period 2020–2050. For a more detailed description of the EnerOutlook methodology and the specifics of the model used, refer to Box 1.

By using these pathways as an input, we have projected the carbon dioxide removal efficiency in each world region as a function of time until 2050 for both L-DAC and S-DAC processes. The outcome of this exercise is shown in Figure 3.5. As anticipated above, S-DAC processes are always more efficient in terms of carbon dioxide removal efficiency than L-DAC processes in all global regions. S-DAC processes can provide marginal carbon removal using the current energy system (i.e., with today's

⁴³ Enerdata (2023): "Energy & emissions projections 2050 - EnerOutlook".

electricity grid carbon intensity) in the North America, Europe, and Latin America regions, and evolves to provide significant net carbon removal in all global regions by 2050. L-DAC processes produce essentially net-zero, or net-positive emissions, in all global regions using the current energy system. However, L-DAC processes become environmentally effective in all global regions by 2050. In some global regions, particularly the Middle East and Asia, there is a significant time delay between now and the point at which L-DAC processes is operational and generating net-negative emissions. In Figure 3.6, we show the carbon dioxide removal efficiency of L-DAC and S-DAC processes in 2020 and 2050 in each of the global regions. We can see that both L-DAC and S-DAC processes are similarly effective by 2050 in most regions, with the notable exception of the Middle East – where sluggish energy decarbonisation can hinder the effectiveness of L-DAC. This highlights the importance of geographical context. This difference is not due to the technology itself, but rather to the carbon intensity of the energy supply in each region. As a result, the siting of large DAC facilities will need to carefully consider long-term energy system transition trajectories to ensure high carbon removal efficiency.

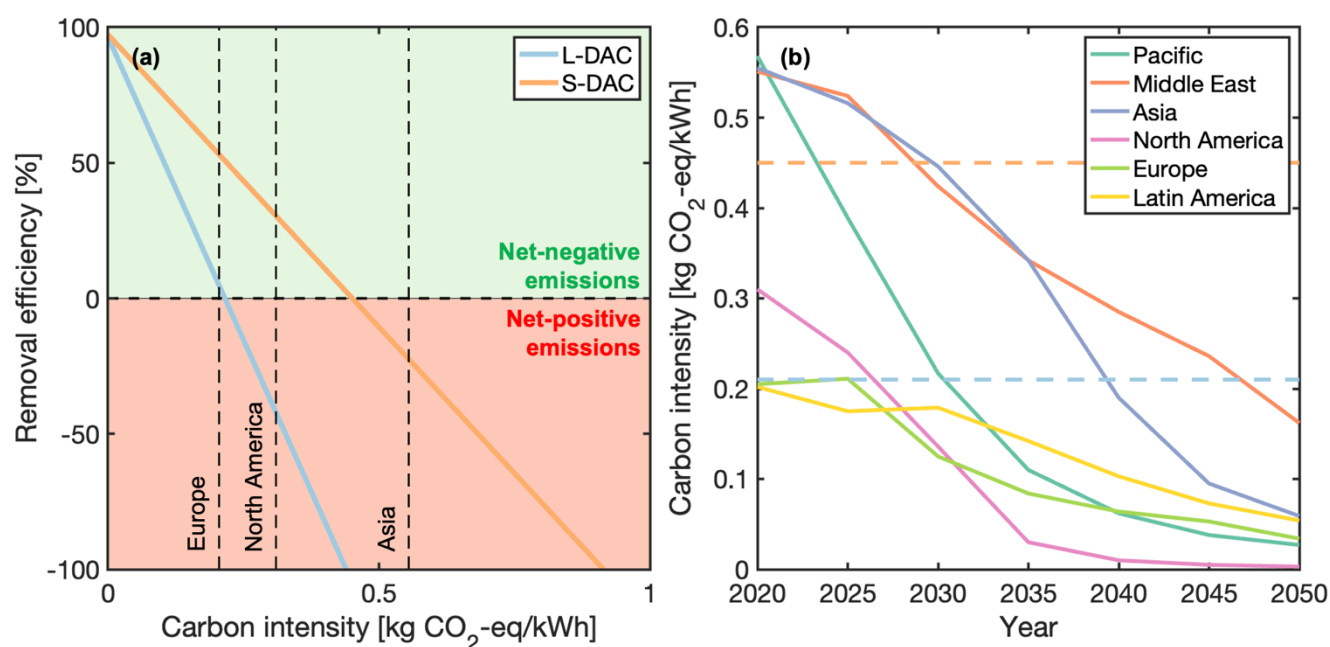


Figure 3.4: (a) carbon dioxide removal efficiency as a function of carbon intensity of energy supply for L-DAC (blue) and S-DAC (orange) processes. Shaded regions indicate operation with net-negative emissions (green) and net-positive emissions (red) along the cradle-to-grave value chain. Dashed lines correspond to current-day carbon intensity of energy supply in Europe, North America, and Asia. (b) projected carbon intensity of energy supply as a function of time in six world regions (Pacific, Middle East, Asia, North America, Europe, Latin America). Data obtained from the EnerOutlook energy & emissions to 2050 pathway. Data is available in tabular form in Appendix 2.

Box 1: Enerdata's EnerOutlook Projections

Enerdata's EnerOutlook projections serve as the foundation for our calculations of carbon intensity (CI) forecasts, a critical component in assessing the life cycle performance of DAC technologies. Given the importance of these forecasts, it is essential to establish the reliability of the source, and the methodologies employed.

Data Sources and Quality: Primary historical energy data is sourced predominantly from the IEA. This data is further supplemented by statistics from regional organisations such as Eurostat, ADB, and OPEC, as well as specialised institutions like CEDIGAZ and EurObserv'ER. Additionally, Enerdata leverages an extensive international network of over 100 partners in more than 60 countries, enabling it to refine and update data comprehensively. The methodologies and definitions used by Enerdata are consistent with those of the IEA and Eurostat⁴⁴.

Modelling Methodology: The EnerOutlook projections are generated using Enerdata's POLES (Prospective Outlook on Long-term Energy Systems) model⁴⁵, a well-established global energy model that has been used extensively in energy and climate policy analysis⁴⁶. The POLES model offers a comprehensive framework for forecasting global energy trends up to 2050. The model provides dynamic, year-by-year simulations of energy supply and demand, incorporating endogenous international energy prices and adjusting for changes in fuel supply and energy demand. POLES covers a broad spectrum of factors, including energy production, consumption, technology diffusion, greenhouse gas emissions, and policy impacts. It includes detailed projections of energy prices, technology developments, and CO₂ abatement costs.

Scenarios Used: Enerdata offers three global energy scenarios within the EnerOutlook framework: EnerBase, EnerBlue, and EnerGreen⁴⁷.

- **EnerBase** is a BAU scenario where existing policies are continued without further climate ambition, leading to a temperature rise above 3 °C.
- **EnerBlue** is based on the achievement of Nationally Determined Contributions (NDCs) and ongoing climate efforts. This scenario leads to a global temperature rise between 2.0 °C and 2.5 °C.
- **EnerGreen** explores a more ambitious pathway where countries overachieve their NDCs, leading to improvements in energy efficiency and a strong deployment of renewables, limiting global temperature increase to below 2 °C.

For this work, the **EnerBlue** scenario was used. This choice is justified by its alignment with current global climate commitments and its realistic yet moderately ambitious outlook.

⁴⁴ **Enerdata (2024)**. Global Energy & CO₂ Data. <https://www.enerdata.net/research/energy-market-data-co2-emissions-database.html>

⁴⁵ **Enerdata (2024)** Poles: Prospective Outlook on Long-term Energy Systems.

<https://www.enerdata.net/solutions/poles-model.html>

⁴⁶ EU science hub: Poles. https://joint-research-centre.ec.europa.eu/scientific-tools-and-databases/poles_en

⁴⁷ **Enerdata (2024)**. Scenario description. <https://eneroutlook.enerdata.net/energy-scenarios-description.html>

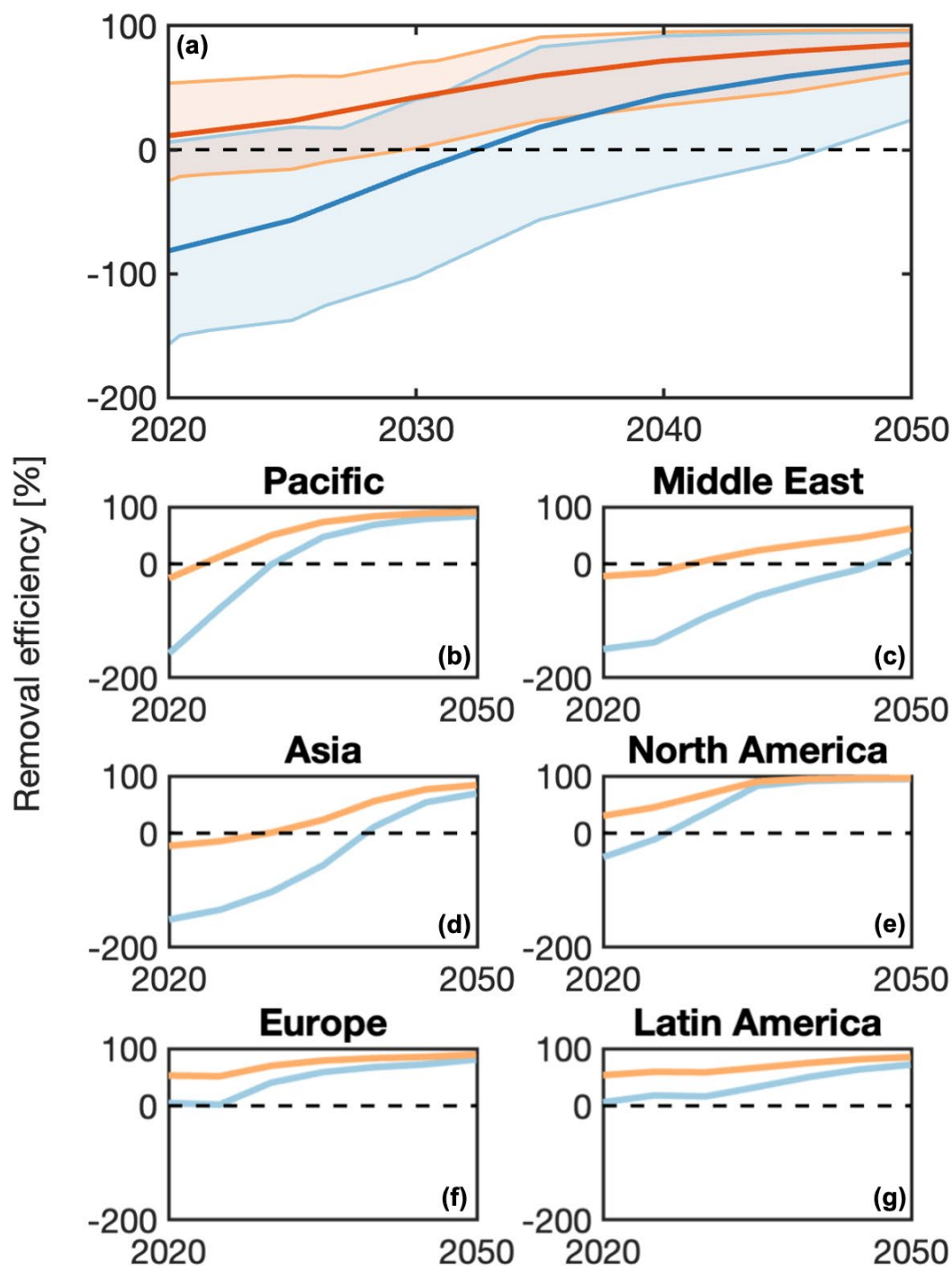


Figure 3.5: projected carbon dioxide removal efficiency for L-DAC and S-DAC processes in the period 2020–2050 in six world regions. (a) global-average carbon dioxide removal efficiency of L-DAC (blue) and S-DAC (orange). Shaded regions correspond to variability observed in individual regional scenarios. (b)–(g) regional carbon dioxide removal efficiency scenarios for L-DAC (blue) and S-DAC (orange). In each panel, the dashed line at $\eta_{\text{CDR}} = 0$ indicates the transition from net-positive value chain emissions ($\eta_{\text{CDR}} < 0$) to net-negative value chain emissions ($\eta_{\text{CDR}} > 0$).

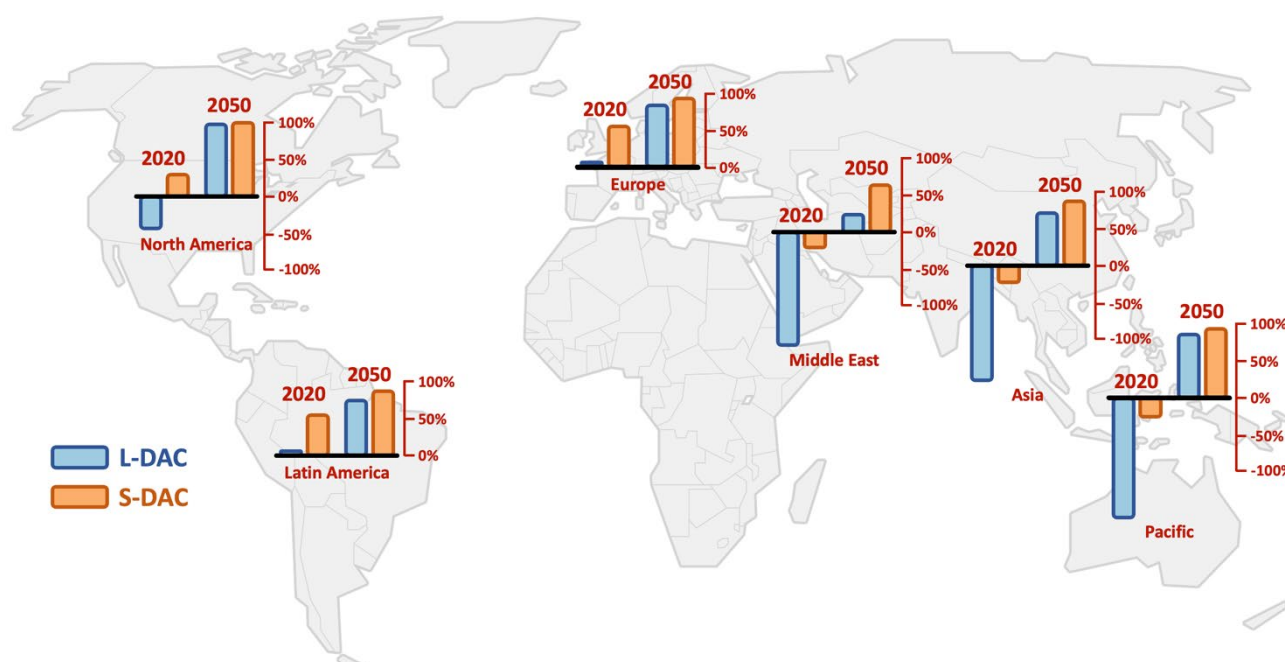


Figure 3.6: A map of projected carbon dioxide removal efficiency in 2020 and 2050 for six world regions for L-DAC (blue) and S-DAC (orange) processes.

3.8 Conclusions and key recommendations

- Carbon dioxide removal efficiency of direct air capture processes is predominantly determined by the carbon intensity of supplied energy under current understanding. Sufficiently low-carbon energy supply is a necessary pre-condition to enabling highly efficient direct air capture value chains. Our results show that for L-DAC processes, carbon intensity of electricity supply should be less than 0.21 kgCO₂eq/kWh. For S-DAC processes, carbon intensity of electricity supply should be less than 0.45 kgCO₂eq/kWh. While these values provide useful benchmarks, actual feasibility may depend on specific process configurations and additional system factors. Moreover, to put these thresholds into context, energy sources such as solar and wind have average carbon intensities of 0.048 and 0.011 kgCO₂eq/kWh, while nuclear is approximately 0.012 kgCO₂eq/kWh. Natural gas power with CCS falls in the range of 0.092 – 0.221 kgCO₂eq/kWh, whereas conventional gas power without CCS has a carbon intensity of around 0.403 – 0.513 kgCO₂eq/kWh. Coal-based electricity is significantly higher at approximately, 0.912 – 1.01 kgCO₂eq/kWh⁴⁸. These comparisons highlight the importance of ensuring that DAC facilities are powered by sufficiently low-carbon energy sources to achieve high carbon removal efficiency.

⁴⁸ UNECE (2022). Life Cycle Assessment of Electricity Generation Options. <https://unece.org/sed/documents/2021/10/reports/life-cycle-assessment-electricity-generation-options>

- ▶ When considering the carbon intensity of current-day energy system, the carbon dioxide removal efficiency of direct air capture processes remains highly dependent on regional energy mixes. In many world regions, current grid emissions present a challenge for achieving net-negative emissions. However, projected energy system decarbonisation in the period 2020–2050 will enable an environment which is appropriate for direct air capture deployment by 2050 in all world regions to achieve negative emission value chains.
- ▶ Direct air capture is not a substitute technology to be used to compensate for poor energy system decarbonisation. Energy system decarbonisation is a pre-condition towards enabling direct air capture value chains with negative emissions. However, early deployment of DAC in suboptimal conditions, where energy systems are still transitioning, can help establish and de-risk the technology before optimal conditions for large-scale deployment are reached. Synergistic whole-systems planning is **essential**. Direct air capture will need to be co-developed with the wider energy system to ensure negative emissions is actually achieved.
- ▶ Standardised approaches to life cycle assessment of direct air capture will help make progress towards improving reliability between independent bodies of work and act to reduce uncertainty in estimating the environmental effectiveness of DAC value chains. Thus, established LCA guidelines, *e.g.* those published by the United States Department of Energy, need to be adopted more widely.
- ▶ Future studies on the life cycle assessment of direct air capture must move away from abstracted and arbitrary energy supply assumptions. Given that energy supply carbon intensity is a strong factor towards overall value chain emissions, it is critical to incorporate energy supply scenarios based on realistic assumptions when assessing the value chain emissions of direct air capture. It is important to recognise the uncertainty associated with these scenarios.

4 Timeliness of direct air capture

4.1 Scales of timeliness

A key concept towards assessing the climate mitigation value of direct air capture for providing greenhouse gas removal is the timeliness with which an amount of carbon removal can be provided. The advantage of direct air capture is that it can provide immediate uptake of CO₂. Conversely, some carbon dioxide removal approaches have slower uptake of CO₂, e.g., carbonation process of enhanced weathering or forest growth with afforestation. This rate of CO₂ uptake will have an impact on the timeliness of the CO₂ removal technology. Moreover, the timeliness of greenhouse gas removal systems is a key consideration when modelling their deployment and determining the scale of carbon removal efforts. The timeliness of a direct air capture system is challenged at two different scales:

- ▶ **Process scale:** at the scale of an individual direct air capture process, carbon removal is not achieved immediately upon the commencement of process operations. When the direct air capture process is deployed, there will be positive carbon emissions to the atmosphere associated with the construction of the process, and its supporting infrastructure. The process must operate for a period to offset these initial emissions before achieving a net removal of carbon from the atmosphere overall. Therefore, there is some delay between the time at which the process is deployed, and the time at which any CO₂ removal is provided.
- ▶ **System scale:** at the system scale deployment of direct air capture, we must account for a complex set of factors which determine how quickly we are able to scale from essentially zero capture capacity today, to the final desired global-scale direct air capture capacity. The deployment is challenged by the availability of required resources, as well as the time needed to establish supply chains and markets which can enable the deployment in a logistically feasible and economically viable manner. Therefore, there is a delay between the time at which wide-scale deployment of direct air capture commences, and the time at which we have a fully operational global-scale system. As we have seen previously, there are also dynamic interactions between direct air capture processes and changes in the energy system, which must be accounted for over long timescales⁴⁹.

⁴⁹ Prado, A., Chiquier, S., Fajardy, M., Mac Dowell, N. (2023) Assessing the impact of carbon dioxide removal on the power system. <https://doi.org/10.1016/j.isci.2023.106303> & Terlouw et al. (2021) Life cycle assessment of direct air carbon capture and storage with low-carbon energy sources. Environmental Science & Technology (55)

Understanding the timeliness of direct air capture at both scales is important towards assessing the value that direct air capture can provide as a global-scale solution for greenhouse gas removal. Particularly, it is important to assess these concepts in the context of realistic geographical scenarios to comprehensively understand opportunities (e.g., most suitable regions for deployment) and barriers (e.g., supply chain constraints) for the effective and timely deployment of these processes.

4.2 Cumulative emissions model of a direct air capture process

We have assessed the process scale timeliness of direct air capture by both L-DAC and S-DAC processes using a discrete time series modelling approach. The cumulative emissions associated with an individual direct air capture plant at a given time are given by the following equation:

$$\begin{aligned} & (\text{Cumulative emissions})_{t_n} \\ &= (\text{Construction emissions}) - \Delta t \cdot \sum_{i=1}^n \eta_{\text{CDR}}(t_i) \times (\text{Capture rate}) \end{aligned}$$

where, $(\text{Cumulative emissions})_{t_n}$ is cumulative emissions in tCO₂eq at time t_n . Construction emissions are emissions associated with construction in tCO₂eq. Δt is time step in years. $\eta_{\text{CDR}}(t_i)$ carbon dioxide removal efficiency at time t_i (dimensionless). Capture rate is the amount of CO₂ captured per unit time in tCO₂/year.

In this model, emissions associated with the construction of the direct air capture process are released into the atmosphere at time $t = 0$. As the process operates and captures carbon dioxide, emissions are removed from the atmosphere at a rate equal to the capture rate of the process (Capture rate, tCO₂eq/year) multiplied with its carbon dioxide removal efficiency (η_{CDR}). The use of the carbon dioxide removal efficiency in this context implicitly accounts for the positive emissions associated with the operation of the process. This analysis focuses on construction emissions and operational CO₂ removal. While ongoing emissions related to maintenance and equipment replacement are partially accounted for through the carbon dioxide removal efficiency which is derived from life cycle assessments. They are not, however, explicitly included in this assessment and could be incorporated in future studies. The carbon dioxide removal efficiency is allowed to vary over time (t_i), according to the carbon intensity of energy supplied to the direct air capture process. The trajectory of the carbon intensity of energy supplied tends to be a function of both the geographical location and the time horizon of the analysis. This trajectory is based on region-specific results from energy system modelling, with the results being subject to scenario assumptions. The model proceeds in a series of short discrete time steps, Δt , each approximately 29.2 days long. This interval allows us to capture the effect of the change in the carbon dioxide removal efficiency over time on the performance of the process. Input data relating to the construction emissions is tabulated in Appendix 4.

4.3 Performance of a direct air capture process removing 1 MtCO₂/yr constructed in 2020

As an initial case-study, we have assessed the timeliness of a 1 MtCO₂ removal/yr direct air capture process constructed in the year 2020. The plant lifetime is assumed to be 30 years. We analyse the performance of both L-DAC and S-DAC processes, in the context of energy system decarbonisation in six global regions, including: the Pacific, Middle East, Asia, North America, Europe, and Latin America regions.

Figure 4.1 shows the results of the calculation of cumulative GHG emissions in MtCO₂eq over the 30 years of plant lifetime. For details on the calculation methodology, refer to Appendix 4. For deployment in the year 2020, we can see that an S-DAC process is able to achieve net carbon removal in all global regions, i.e., the cumulative emissions are negative. Although L-DAC processes constructed today can provide net cumulative carbon removal in most regional contexts, L-DAC can result in net positive emissions if deployed in the Middle East or Asia regions.

In several global regions, the carbon dioxide removal efficiency of direct air capture is negative (i.e., emits CO₂ to atmosphere) when coupled to the current-day energy system, owing to the higher energy carbon intensity of their energy systems in those regions. Consequently, as shown in Figure 3.5, deployment of L-DAC processes in the Pacific, Middle East, Asia, and North America regions can result in significantly negative carbon dioxide removal efficiencies using current-day energy supply. In the Europe and Latin America regions, coupling current energy systems with L-DAC processes results in carbon dioxide removal efficiency of essentially zero (i.e., does not achieve any CO₂ removal). In the Pacific, Middle East, and Asia regions, S-DAC processes coupled to the current day energy system also have a negative carbon dioxide removal efficiency, which suggests net emissions of CO₂ but to a smaller extent compared to L-DAC processes. The consequence of this is that the cumulative emissions of a direct air capture process deployed in these regions is not a decreasing function of time. As shown in Figure 4.1, cumulative emissions will increase until the point when the regional energy supply is sufficiently decarbonised.

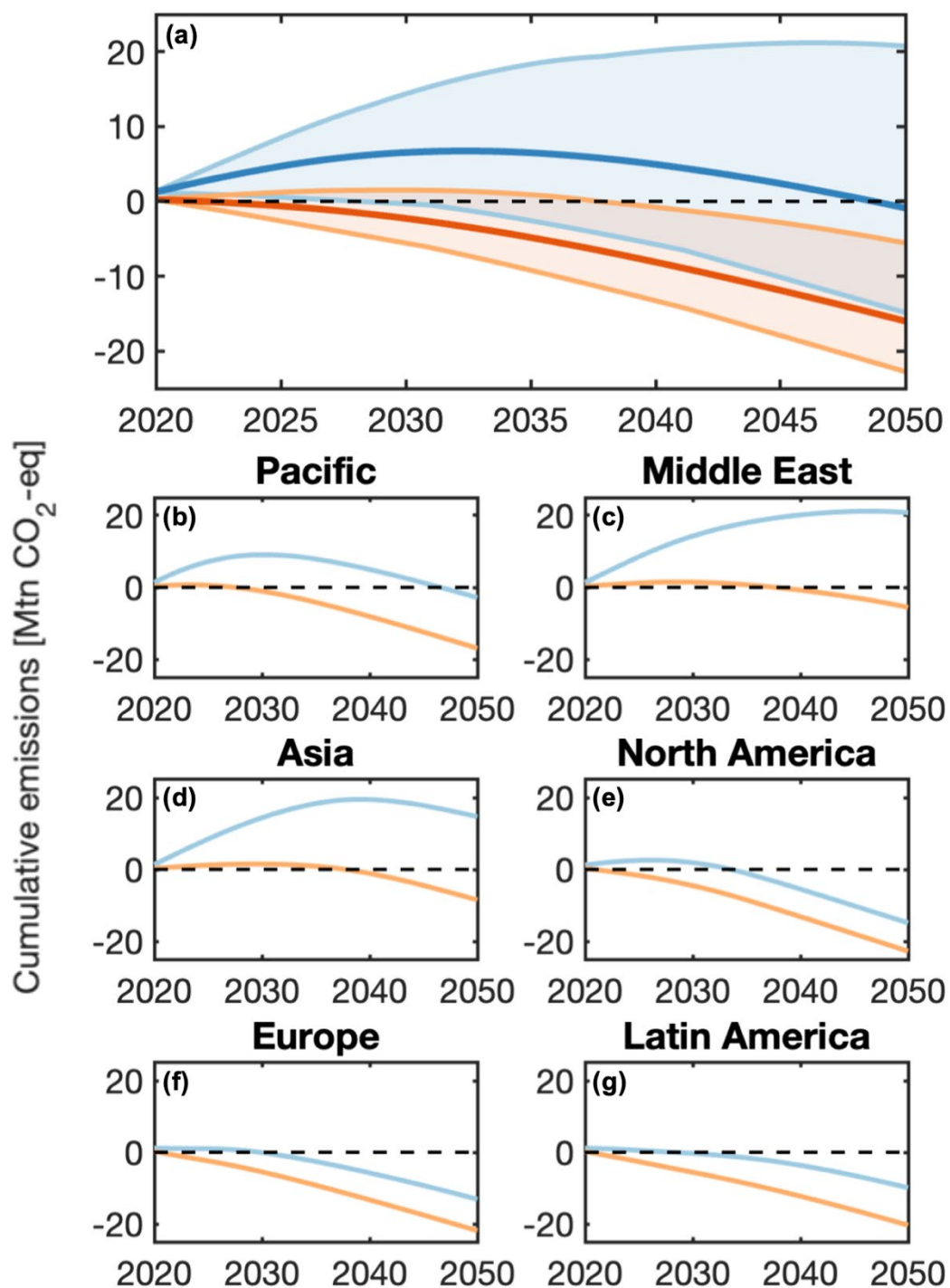


Figure 4.1: Cumulative emissions (CO₂eq) of a 1 MtCO₂ removal/yr direct air capture plant with a lifetime of 30 years constructed in the year 2020 in six world regions. **(a)** global-average cumulative emissions of an L-DAC process (blue) and an S-DAC process (orange). Shaded regions correspond to variability observed in individual regional scenarios. **(b)-(g)** regional cumulative emissions scenarios for L-DAC (blue) and S-DAC (orange).

The climate value of deploying direct air capture in regions with highly carbon-intensive energy is limited unless projects are specifically designed to source low-emissions energy or the energy system is decarbonised (e.g., with CCS). While early deployments in such regions may still offer value for demonstrating and scaling DAC technologies, it is critical that these efforts prioritise low-carbon energy procurement and ensure transparency regarding the overall emissions balance of the project. Moreover, the outlook for decarbonisation of the regional energy system should also be considered when assessing the long-term climate effectiveness of DAC deployment in a given location.

Once the energy system is decarbonised and the direct air capture plant is capturing CO₂, the initial period of operation will be needed to compensate for the CO₂ emissions associated with construction. There is a potentially significant delay between the time at which the process is constructed and the time at which a net removal of carbon from the atmosphere is achieved, which is referred to as the breakeven time (Section 3.5). In the Pacific region, the S-DAC process takes approximately 18 years to breakeven and achieve a net carbon removal, whereas the L-DAC process takes approximately 27 years to breakeven. Secondly, we can see that the environmental effectiveness of these processes is poor in terms of cumulative CO₂ emissions removed by the end of the plant lifetime. The North America region represents the best-case scenario, where the L-DAC process achieves cumulative net CO₂ removal of approximately 15 MtCO₂ over the 30-year plant lifetime and the S-DAC process approximately 23 MtCO₂. This corresponds to an average carbon dioxide removal efficiency of 49.6 and 75.9%, respectively, under the assumptions that the process has a capture capacity of 1 MtCO₂/yr and the operational lifetime of 30 years.

The results clearly indicate that interactions with the supply of energy in different regional contexts strongly controls the performance of the process over its lifetime. In this context, both the level of decarbonisation achieved, and the rate at which it is achieved, are both relevant factors which contribute towards overall CO₂ removal performance and timeliness of DAC processes.

4.4 Effect of delaying direct air capture deployment

The analysis outlined above highlights that immediate deployment of direct air capture processes in the current-day energy system is not favourable. In several world regions, energy systems are currently too carbon-intensive to enable DAC to deliver meaningful net carbon removal, and in some cases, operations may even result in net positive emissions when the grid electricity is predominantly unabated fossil fuel energy.

The timing at which DAC systems begin delivering net CO₂ removal will therefore depend on the pace of energy system decarbonisation. While early-stage DAC deployment is essential to advance the technology, improve efficiencies, and scale supply chains, its environmental effectiveness will increase over time as cleaner energy sources become more widely available. Rather than delaying deployment, this

highlights the need for coordinated planning to align DAC development with broader energy system transitions, and for early DAC projects to prioritise low-carbon energy sourcing wherever possible.

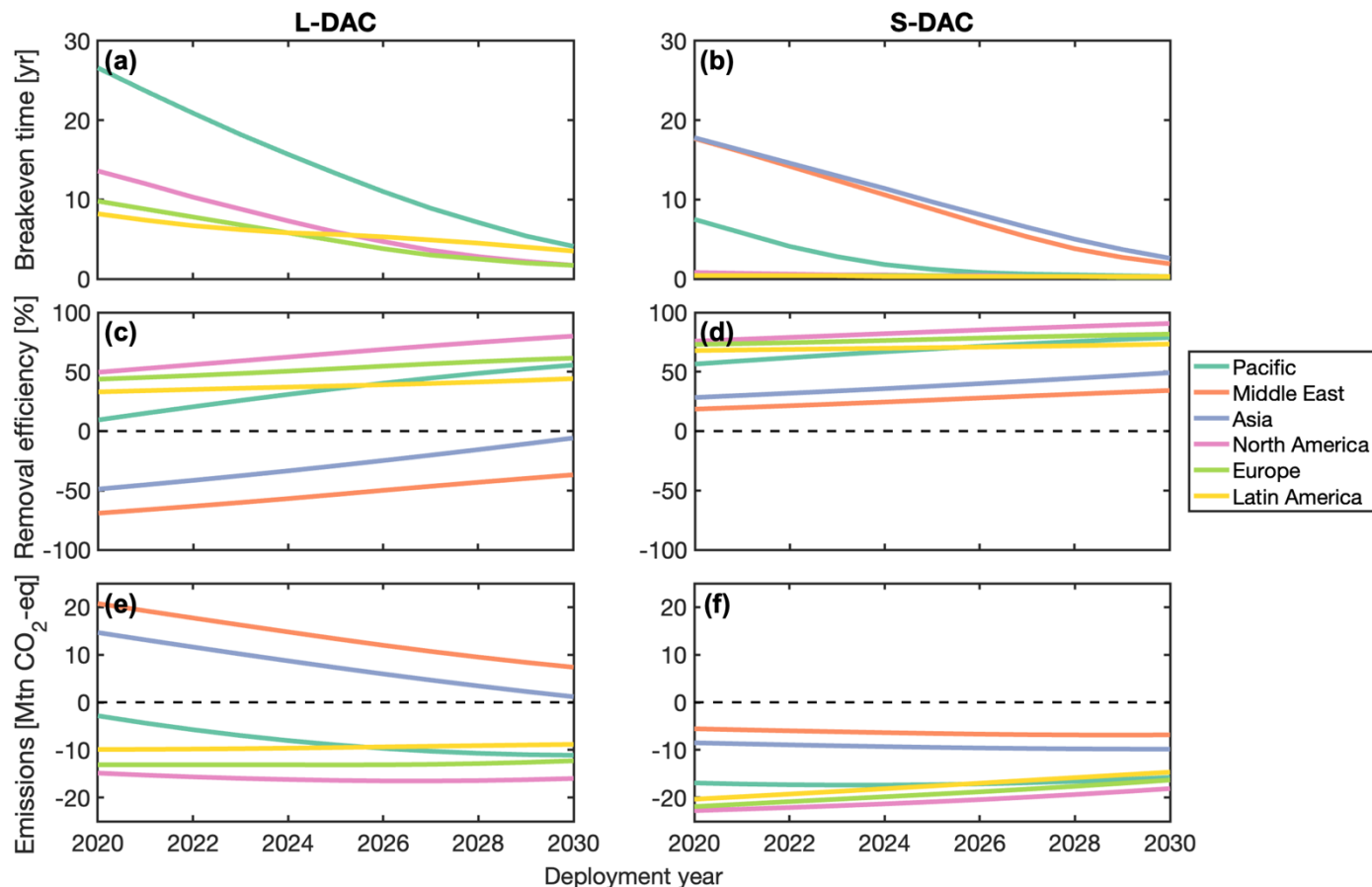


Figure 4.2: Performance of a 1 MtCO₂/yr direct air capture process in six world regions for different start year of deployment, illustrating the effect of delaying DAC deployment. (a)-(b) breakeven time of L-DAC and S-DAC processes deployed between 2020–2030. (c)-(d) average carbon dioxide removal efficiency throughout plant lifetime of L-DAC and S-DAC processes deployed between 2020–2030. (e)-(f) cumulative emissions in the year 2050 for L-DAC and S-DAC processes deployed between 2020–2030.

In Figure 4.2, we show the performance of 1 MtCO₂ removal/yr L-DAC and S-DAC processes deployed in the period 2020–2030 in terms of the breakeven time, the average removal efficiency over the plant lifetime, and the cumulative emissions of the plant in the year 2050. We can see that delaying the deployment date significantly reduces the breakeven time for both technologies in almost all global regions, with the exception being in the Middle East and Asia regions, where L-DAC does not breakeven within the plant lifetime. For example, for a deployment in 2020, L-DAC processes breakeven within 8.2–27 years. By delaying deployment to 2030 when the carbon intensity of the energy system reduces, L-DAC process achieves a shorter breakeven of 1.7–4.1 years. For S-DAC processes deployed in 2020, breakeven is achieved within 0.5–18 years, whereas delaying deployment to 2030 decreases the breakeven to 0.3–2.6 years.

This analysis is not intended to suggest delaying all DAC deployment but to illustrate how energy system decarbonisation can significantly improve removal efficiency. In practice, most commercial-scale DAC projects recently initiated would only come online later in the decade, i.e., 2030 or beyond. Early deployment remains essential for advancing the technology, reducing costs through learning-by-doing, and building supply chains – particularly in regions with access to low-carbon energy. At the same time, this analysis supports prioritising alignment with low-carbon energy sources and siting decisions that enable faster breakeven and greater net carbon removal benefits.

The timing of DAC deployment has significant implications on the effectiveness of the system, which is predominantly influenced by the energy system's decarbonisation rate. For L-DAC, delaying deployment generally improves the cumulative CO₂ removal achieved by 2050 as the delay helps avoid the high emissions intensity phase of the energy system transition. Conversely, S-DAC processes use lower temperature heat and benefit from immediate deployment due to their high carbon removal efficiency (as discussed in Section 3). However, this may not apply to emerging S-DAC variants that rely on high-temperature heat, which would face similar limitations to L-DAC. Delaying their deployment tends to diminish their cumulative removal by 2050, as they are already effective assuming the higher carbon intensity of today's energy systems. As shown in Figure 4.2, regional variations also affect these outcomes, with the Middle East and Asia showing poorer performance due to slower energy system decarbonisation.

Table 4-1 summarises the impact of deployment timing on effectiveness of the DAC system across different regions. The average carbon dioxide removal efficiency over the plant lifetime increases to high levels for both technologies in most global regions by delaying deployment of the direct air capture process until 2030. Again, a notable exception is the Middle East and Asia regions, which show significantly worse performance than the other global regions owing to poor energy system decarbonisation. Across the remaining world regions, average carbon dioxide removal efficiency increases to 44–80% for L-DAC processes, and 73–91% for S-DAC processes, for deployment in 2030.

For countries with high carbon intensity energy systems (Middle East and Asia), the effect of delaying the deployment of L-DAC processes is generally to improve the cumulative removal achieved by the year 2050. By delaying L-DAC deployment, we avoid the early phase where carbon intensity of the grid is high, thereby reducing the operational emissions and decreasing the cumulative emissions of the system over time. However, the effect of delaying deployment of S-DAC processes is to generally diminish the cumulative removal achieved by the year 2050. S-DAC processes are already effective within the current-day energy system and should therefore be deployed as soon as possible to enable us to begin to payback the carbon debt associated with construction sooner. Whereas in the case of L-DAC, we see a different behaviour – where delaying deployment is favourable to enable a higher average carbon dioxide removal efficiency, especially in high carbon intensity regions. Selecting the deployment date to target improved carbon dioxide removal efficiency is clearly the dominant factor when the removal efficiency in the current-day context is not favourable. However, more importantly, this will be highly dependent on is the

energy system also undergoing would need decarbonisation at an effective transition rate in order to align with DAC deployment requirements.

Table 4-1: Summary of impacts of delaying deployment of L-DAC and S-DAC (seen in Figure 4.2).

Consideration	L-DAC	S-DAC
Average efficiency for 2030 deployment	44–80% across most regions	73–91% across most regions
Regional variation	Middle East and Asia show worse performance; delaying deployment improves efficiency	Middle East and Asia show worse performance; early deployment preferred
Reason for variation	Energy system decarbonisation rate affects efficiency	High current S-DAC effectiveness means earlier deployment addresses carbon debt immediately and achieves net CDR faster
Effect of delaying deployment	Improves cumulative removal by 2050, avoids early high emissions	Diminishes cumulative removal by 2050; effective in current energy system
Recommendation for deployment timing	Delay deployment to maximise removal efficiency in high carbon intensity countries	Deploy as soon as possible

4.5 Global-scale deployment of direct air capture

We have seen that both L-DAC and S-DAC processes can achieve environmental effectiveness by mid-century when deployed this decade – provided that timing and geographical siting considerations are correctly accounted for. However, the analysis presented above concerns the deployment of a single direct air capture plant that capture 1 MtCO₂/yr. We require a very large amount of direct air capture capacity as part of global decarbonisation efforts, with the IEA Net Zero Emissions by 2050 scenario recommending 1 GtCO₂/yr of direct air capture capacity by mid-century.⁵⁰ It is therefore important to understand what the global-scale deployment of direct air capture technology could look like, in terms of several key factors:

- How the global scale capture capacity develops over time during the deployment phase.

⁵⁰ IEA (2022): Direct air capture: A key technology for net zero.

- ▶ The required deployment rate as a function of time. Specifically; (i) by what date deployment needs to begin to significantly accelerate to wide-spread levels to meet long-term targets, (ii) at what date the deployment rate should peak, and (iii) how large the deployment rate needs to be at the point of peak deployment.
- ▶ How the performance of the system in terms of cumulative removals responds to different possible deployment scenarios.

Accounting for these factors allows us to assess the timeliness of a global-scale deployment of direct air capture from two important perspectives. First, with respect to high-level targets for carbon removal, we can analyse what capture capacity is required in a global-scale system to enable meeting such a target. Second, for a given deployment scenario which we determine to satisfy our needs for achieving a certain level of carbon removal, we can understand what the requirements are to enable that deployment in terms of how quickly, and when, we need to deploy direct air capture capacity.

4.6 Global-scale deployment model

To analyse the global-scale deployment of direct air capture, we have applied a logistic growth model.⁵¹ The logistic growth model is one of many possible models which can be used to describe patterns of growth. However, the logistic growth model has been applied successfully to predict technology growth in a variety of sectors – including energy domains. Therefore, we choose to adopt the logistic model in this analysis for predicting the global growth of direct air capture capacity.

The growth curve predicted by the logistic model is S-shaped, with the growth pattern proceeding in four main phases:⁵²

- ▶ **Phase 1 – learning:** an initial phase of low growth where DAC costs are high, but continued deployment enables technology learning. This phase of deployment will likely need substantial subsidies and/or support to enable sufficient learning to take place, and potentially reduce DAC technology costs. The decrease of costs throughout this phase could enable further wide-scale deployment in later phases.
- ▶ **Phase 2 – reliable expansion:** there is a take-off point and reliable expansion of the technology which may occur once costs are sufficiently low, supportive policy/market mechanisms are in place, viable business models are established, and supply chains are developed. This is followed by a sustained phase of exponential growth supported by mature technology understanding and policy incentivisation or market mechanisms.

⁵¹ Høök et al. (2011): Descriptive and predictive growth curves in energy systems analysis. *Natural Resources Research* (20).

⁵² Zhang et al. (2023): Carbon dioxide storage resource use trajectories consistent with US climate change mitigation scenarios. *EarthArXiv* preprint.

- **Phase 3 – approaching capacity:** a phase of low growth as the maximum desired capacity of the system is approached. During this time costs are likely to increase again as there will be a lower availability of ideal sites with low-cost deployment.
- **Phase 4 – sustaining capacity:** in this final phase, there is a constant deployment rate of the technology. At long time scales, plants which were deployed at earlier times exceed their lifetime and need to be replaced with new plants. The system reaches equilibrium with a constant rate of deployment which sustains the total capacity of the system over long-time scales. This is determined by both the capture capacity of the fully developed system, and the lifetime of individual DAC plants.

The logistic growth model was chosen for this work because it is particularly suitable for capturing the typical S-shaped growth pattern observed in technology deployment, which includes an initial phase of slow growth, followed by rapid expansion, and eventually a plateau as the maximum capacity is approached. The logistic model's capability to represent these phases aligns well with the expected stages of DAC technology development, from early learning and cost reduction to widespread deployment and stabilisation. While alternative models exist, such as exponential growth models or linear growth models, they may not adequately capture the phases of technology deployment, particularly the deceleration and eventual stabilisation seen in the logistic growth pattern.

In the logistic growth model, the global deployed direct air capture capacity as a function of time is given by the following equation:

$$C(t) = \frac{C_{\max} C_0 e^{rt}}{C_{\max} + C_0 (e^{rt} - 1)}$$

where $C(t)$ is the deployed capacity of direct air capture (MtCO₂/yr) at time t (yr), $C_{\max}$ is the targeted maximum capacity of the global-scale direct air capture (MtCO₂/yr), C_0 is the currently deployed capacity of direct air capture (MtCO₂/yr) at time $t = 0$, and r is the logistic growth rate (1/yr).

The deployment rate, which is required to achieve the deployed capacity trajectory, $\dot{C}(t)$, is given by the following equation:

$$\dot{C}(t) = rC(t) \left(1 - \frac{C(t)}{C_{\max}} \right) + \frac{C(t - t_{\text{life}})}{t_{\text{life}}}$$

where $\dot{C}(t)$ is the deployment rate of direct air capture capacity (MtCO₂/yr²), and t_{life} is the lifetime of a direct air capture plant. The functional form for the deployment rate assumes that once a previously deployed direct air capture plant reaches its lifetime, additional capacity is added to the system at that time to compensate.

However, the logistic growth model has limitations that should be considered. This model focuses solely on the DAC technology itself and does not account for potential bottlenecks in developing the necessary supporting infrastructure. Key aspects such

as the availability of power supply, CO₂ transport, and storage infrastructure⁵³ are critical to the successful deployment and operation of DAC systems. These factors can significantly impact the overall deployment timeline and capacity, and their omission may lead to an overestimation of the feasibility and speed of DAC scaling.

4.7 Global-scale cumulative emissions model

The logistic growth model outlined above can be used to project the cumulative emissions of the global-scale deployment of direct air capture. Analogously to the process-scale cumulative emissions model described previously (Section 4.2), we have applied a discrete time series modelling approach to calculate the global-scale cumulative emissions over time. The cumulative emissions of the global-scale deployment of direct air capture are calculated by the following equation:

$$(\text{Cumulative emissions})_{t_n} = \Delta t \cdot \sum_{i=1}^n [\dot{C}(t_i) E_{\text{DAC}} t_{\text{life}}] - [\eta_{\text{CDR}}(t) C(t)]$$

where $C(t)$ is the deployed capacity of direct air capture, $\dot{C}(t)$ is the deployment rate of direct air capture capacity, $\eta_{\text{CDR}}(t)$ is the carbon dioxide removal efficiency, E_{DAC} is the embodied emissions of constructing a direct air capture plant, t_{life} is the lifetime of a direct air capture plant, and Δt is the time step size. As set out in Chapter 3, the carbon dioxide removal efficiency is assumed to follow a linear relationship with the carbon intensity of energy supplied, given by the following equation:

$$\eta_{\text{CDR}}(t) = \delta_{\text{DAC}} I_{\text{grid}}(t) + \epsilon_{\text{DAC}}$$

where $I_{\text{grid}}(t)$ is the carbon intensity of energy supplied, and δ_{DAC} and ϵ_{DAC} are parameters of the relationship.

The model described here accounts for three contributions to the cumulative emissions:

- The carbon dioxide from the atmosphere that is captured and stored via DACCS.
- Positive emissions associated with the release of GHG (expressed as carbon dioxide equivalent) during construction of a direct air capture process plant. Construction emissions are attributed to the time at which capacity is added to the system.
- Positive emissions associated with the release of GHG (expressed as carbon dioxide equivalent) owing to the operation of existing direct air capture process plants. Operational emissions are distributed across time according to the dynamic trajectory of deployed capacity at any given time.

⁵³ **Zhang et al., (2024)** The feasibility of reaching gigatonne scale CO₂ storage by mid-century. *Nature Communications* (15).

In evaluating the effectiveness of DAC systems, it is important to note the difference between carbon removal operational efficiency and life cycle efficiency. As mentioned, the current model primarily accounts for three contributions to cumulative emissions: the negative emissions from capturing and storing CO₂, the positive emissions associated with the construction of the DAC system and the positive emissions resulting from the operation of the system.

Operational efficiency focuses on the emissions directly associated with running the DAC system. It includes the negative emissions from the captured CO₂, the construction emissions associated with the DAC system and the emissions arising from the operation of the DAC process. This approach shows the efficiency during the operational phase of the system, but it does not account for all the factors influencing its total environmental impact.

In contrast, life cycle efficiency, incorporates the entire lifecycle of the DAC system. It does not only include operational and construction emissions but also additional factors such as the decommissioning and disposal emissions, embodied emissions resulting from the manufacturing of the materials and components used in the DAC system and maintenance and replacement emissions – all of which may vary significantly by region due to local infrastructure, supply chains and energy systems.

4.8 Performance of global-scale direct air capture

First, we use the global-scale deployment and cumulative emissions model outlined above to analyse the performance of a base-case scenario for the global scale deployment of direct air capture. In accordance with analysis by the International Energy Agency (IEA)⁵⁴, we assume that currently deployed direct air capture capacity is approximately 0.01 MtCO₂/yr, and that we aim towards expanding capacity to 1 GtCO₂/yr by mid-century on a global basis. Previous work has shown that scaling a technology by this magnitude in the required timescale corresponds to a logistic growth rate of $r = 0.26$ per year.⁵⁵ We assume that direct air capture plants have a lifetime of 30 years.

Figure 4.3 shows the results of applying the logistic growth and cumulative emissions models to this base-case scenario for both L-DAC and S-DAC technologies. As anticipated, global scale deployed direct air capture capacity rises from 0.01 MtCO₂/yr in 2020 to 1 GtCO₂/yr by approximately 2050. The peak deployment rate in this scenario occurs in the year 2046 and corresponds to adding direct air capture capacity at a rate of 65 MtCO₂/yr per year. However, the fastest relative growth occurs in the early decades, when capacity expands from negligible levels highlighting the critical need for early action and investment. The deployment rates fall from this peak through a minimum, but rises again at longer time scales to compensate for deployed plants exceeding their operational lifetime. In this scenario, the DAC deployment rate at long time scales is approximately 33 MtCO₂/year per year, and

⁵⁴ IEA (2024) Direct Air Capture. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture>

⁵⁵ Creutzig et al. (2019): The mutual dependence of negative emission technologies and energy systems. *Environmental Science & Technology* (12).

must be sustained indefinitely to ensure the system reaches the target capacity of 1 GtCO₂/yr. On a globally averaged basis, across different world region energy decarbonisation pathways, L-DAC achieves a cumulative removal of 1.83 GtCO₂ by the year 2050 and S-DAC achieves a cumulative removal of 3.51 GtCO₂. These numbers can be compared against broader CDR projections from recent reports. For instance, the ‘Broken Record’ Report published by the United Nations Environment Programme (UNEP)⁵⁶ projected that novel CDR methods including BECCS, DACCS and enhanced weathering could potentially achieve up to 4.2 GtCO₂ removal per year by 2050 in the most ambitious 1.5 C pathways. In comparison, the state of CDR report⁵⁷ estimates a CDR gap of 0.4-5.4 GtCO₂ per year by 2050, depending on the scenario. The focus of this work is on DAC alone and hence naturally results in lower cumulative removals compared to the broader estimates references that encompass multiple novel CDR methods. The difference in cumulative removals between L-DAC and S-DAC in our work reflects the varying effectiveness in these technologies across different regional energy decarbonisation pathways. In all regional scenarios, the deployment of S-DAC shows a net removal of carbon dioxide from the atmosphere by 2050. Whereas L-DAC is less effective in all world regions, and even results in positive emissions in the Middle East region and has marginal performance in the Asia region.

Scaling L-DAC according to this scenario would mean adding significant DAC capacity at a time when the carbon intensity of energy supply is still too high in some world regions to enable negative emissions by mid-century. It is notable that even in this scenario, which represents a significant growth rate, there is a large delay between the time at which we decide to initiate a wide-scale deployment of direct air capture, and the time at which meaningful carbon removal from the atmosphere is achieved. When wide-scale deployment begins in 2020, negative emissions do not begin to significantly accumulate until approximately 2042 for the L-DAC system (22 year delay), and 2035 for the S-DAC system (15 year delay). The delay in achieving CO₂ removal can be attributed to two factors: (i) the deployed capacity at early times is small, and the translation of capacity into removals is poor because of energy system effects, and (ii) there are significant positive emissions at early phases of the deployment, significantly counteracting removals which are being achieved.

⁵⁶ **UNEP (2023)** Broken Record: Temperatures hit new highs, yet world fails to cut emissions (again). <https://www.unep.org/resources/emissions-gap-report-2023>

⁵⁷ **Smith, S. M., Feden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox E., Edwards M., R., Fuss, S., Johnstone, I., Muller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (2024)** (eds.) The State of Carbon Dioxide Removal 2024 – 2nd Edition. DOI 10.17605/OSF.IO/F85QJ

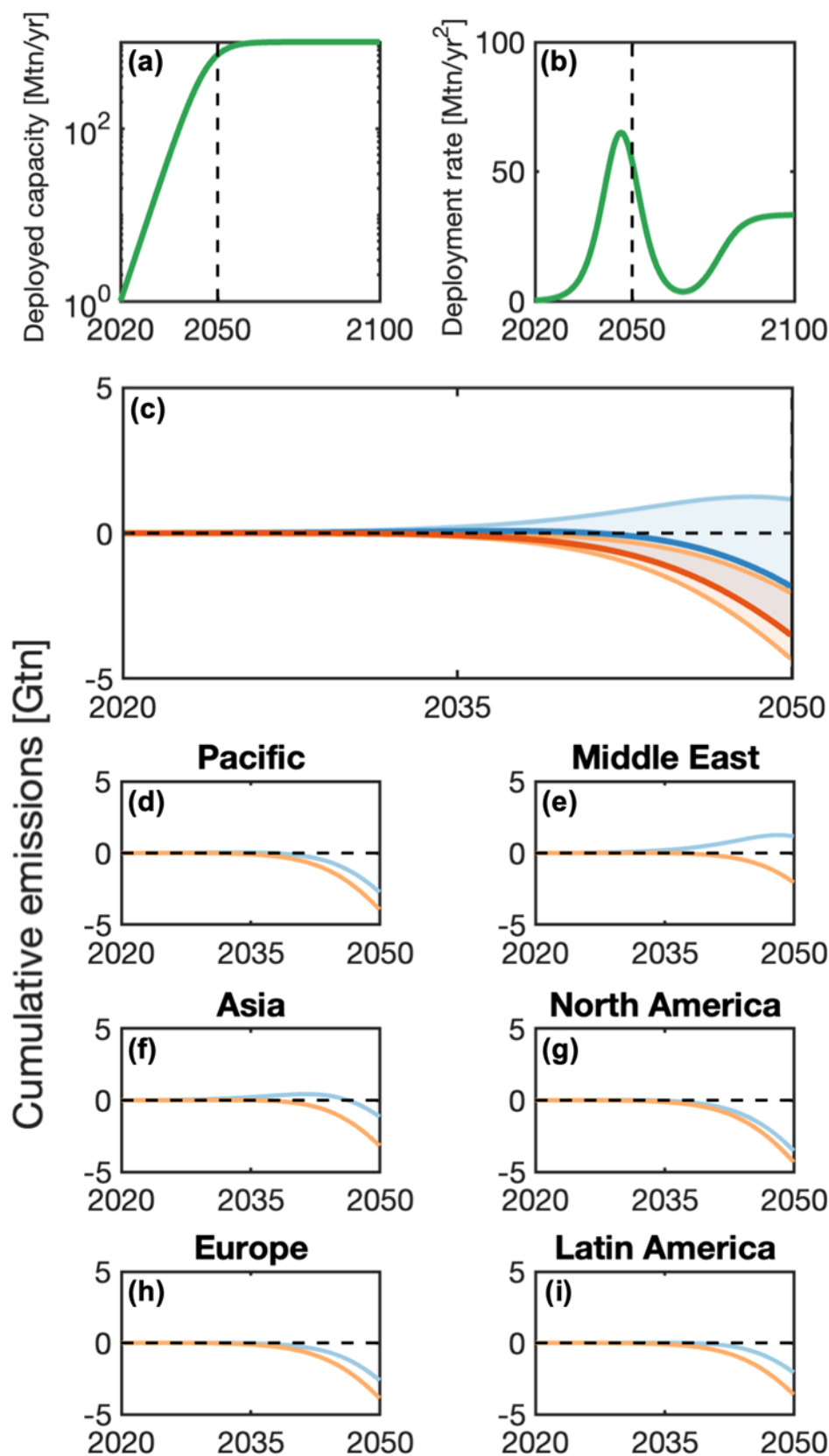


Figure 4.3: performance of a global-scale 1 GtCO₂/yr deployment of direct air capture for the period 2020–2050 in six world regions. **(a)** deployed direct air capture capacity. **(b)** deployment rate of direct air capture capacity in units of MtCO₂/year per year. **(c)** global-average cumulative emissions of L-DAC (blue) and S-DAC (orange) deployments. Shaded regions correspond to variability observed in

individual regional scenarios. (d)-(i) regional cumulative emissions scenarios for L-DAC (blue) and S-DAC (orange) deployments.

4.9 Sensitivity to long-term energy system decarbonisation pathways

The energy system decarbonisation pathways used as an input to this analysis are only provided until the year 2050. However, we have seen that the carbon intensity of the energy system and the rate of decarbonisation are the dominant factors in determining the performance of a direct air capture system over time. Therefore, we aim towards understanding the long-term behaviour of a global-scale direct air capture system in response to possible long-term energy decarbonisation pathways. In the following, we project the cumulative emissions performance of a global-scale direct air capture system in the period 2020–2100. Since this represents a significant extrapolation of the time horizon of the analysis, we consider sensitivity to several possible scenarios:

- ▶ **No decarbonisation after 2050:** a worst-case scenario where the global energy system does not decarbonise any further after the year 2050. In this scenario, the carbon intensity of energy supply at 2100 is assumed to be equal to the global average carbon intensity of energy supply at 2050 (0.057 kgCO₂-eq/kWh).
- ▶ **Net-zero by 2100:** an intermediate scenario where the global energy system achieves net-zero carbon emissions in the year 2100. In this scenario, the carbon intensity of energy supply at 2100 is assumed to be 0 kgCO₂-eq/kWh
- ▶ **Net-negative in 2100:** a best-case scenario where the global energy system achieves net-negative emissions in the year 2100. In this scenario, the carbon intensity of energy supply at 2100 is assumed to be -0.3 kgCO₂-eq/kWh. The value is within the range for carbon intensity of energy generated from bioenergy with carbon capture and storage (BECCS), which is estimated to fall within the range [-1, -0.6] kgCO₂-eq/kWh.⁵⁸ This assumption does not imply that DAC is directly powered by BECCS or that BECCS is infinitely scalable, but rather explores a case in which a substantial share of global energy is provided by net negative sources.

⁵⁸ **Garcia-Freites et al. (2021):** The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UKs net-zero emission target. *Biomass & Bioenergy* (151).

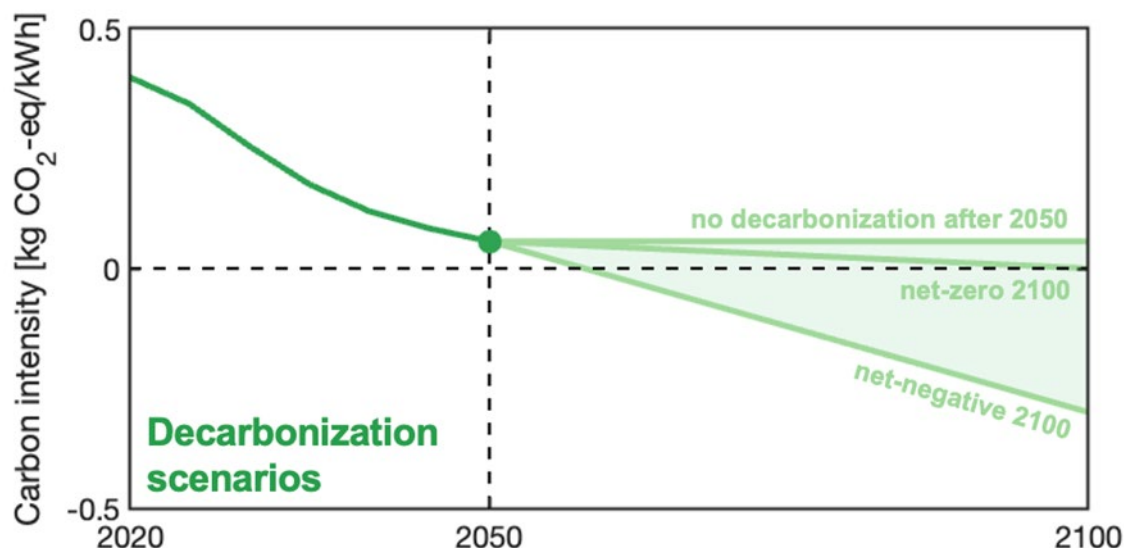


Figure 4.4: global-average carbon intensity of energy supply scenarios in the period 2020–2100. In the period 2020–2050, the projection is based on the EnerOutlook energy & emissions to 2050 scenario. In the period 2050–2100, we consider sensitivity to three possible long-term decarbonisation scenarios, including (i) no further decarbonisation after 2050, (ii) net-zero emissions by 2100, and (iii) net-negative emissions by 2100.

The energy supply carbon intensity scenarios are shown in Figure 4.4. Using these potential energy system decarbonisation scenarios as an input, we have extrapolated the calculation of the cumulative emissions of the global-scale deployment of direct air capture until the year 2100 for the base-case deployment scenario detailed previously. The results of this calculation are shown in Figure 4.5. We find that both L-DAC and S-DAC technologies perform similarly on a long-term basis, but that S-DAC provides a greater amount of carbon removal in all scenarios. The cumulative removal achieved by 2100 using L-DAC is 35–46 GtCO₂, and the cumulative removal achieved by 2100 using S-DAC is 45–50 GtCO₂.

The long-term performance of S-DAC is less sensitive to long-term energy decarbonisation pathways than an equivalent deployment of L-DAC. Therefore, the removal which we can expect to achieve via a global-scale S-DAC system is more reliable and does not depend as heavily on sustained long-term energy system decarbonisation efforts. Whereas for a global-scale L-DAC system, we would require sustained long-term synergy with energy system decarbonisation to ensure the best performance – exposing significant risk for the deployment of L-DAC at the global scale. It is important to note that this analysis does not incorporate potential technological learning or future improvements in DAC system performance e.g., reductions in energy demand.

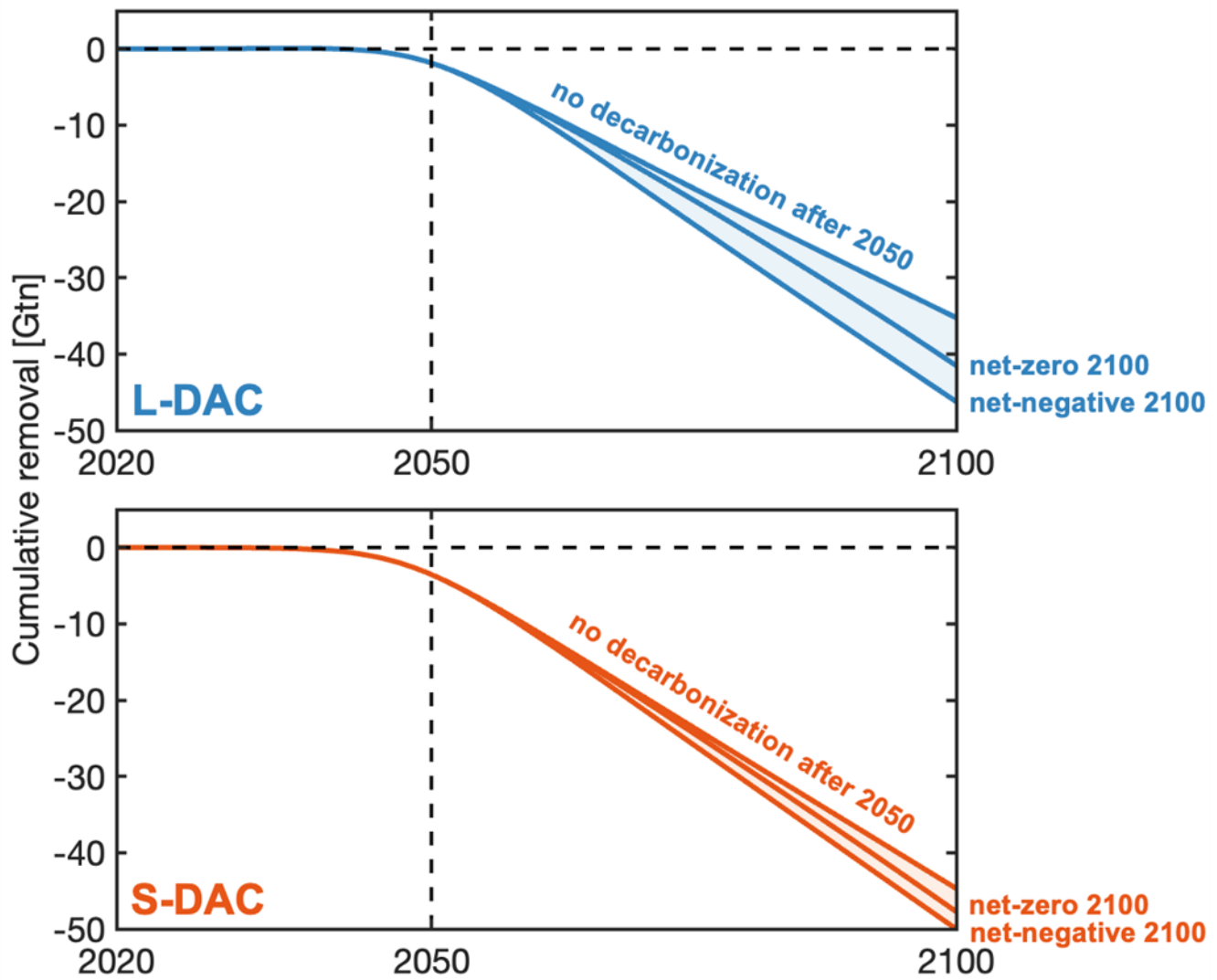


Figure 4.5: Sensitivity of performance for a global-scale deployment of direct air capture using either L-DAC or S-DAC technology to long-term energy system decarbonisation pathways. Sensitivity is considered to three possible long-term decarbonisation pathways, including: (i) no further decarbonisation after 2050, (ii) net-zero emissions by 2100, and (iii) net-negative emissions by 2100.

4.10 Sensitivity to global growth rate

The analysis outlined above corresponds to a base-case scenario where the logistic growth rate is constant and assumed to be $r = 0.26 \text{ yr}^{-1}$. In the following, we consider the sensitivity of the global-scale direct air capture system performance to a variety of global growth trajectories by considering scenarios with different logistic growth rates. As previously, in all scenarios we consider an initially deployed removal capacity of $1 \text{ MtCO}_2/\text{yr}$, a maximum deployed removal capacity of $1 \text{ GtCO}_2/\text{yr}$, and a plant lifetime of 30 years. We have analysed the sensitivity of the performance of the system to logistic growth ranges in the range $0.1\text{--}0.4 \text{ yr}^{-1}$, where $r = 0.1 \text{ yr}^{-1}$ would correspond to slow-moderate growth, and $r = 0.4 \text{ yr}^{-1}$ would correspond to extremely rapid wide-scale growth. The results of this calculation are shown in Figure 4.6.

The peak deployment rate shows the maximum rate at which DAC systems need to be installed and operational to meet the targeted global capacity by a certain year. It is expressed in MtCO₂/year per year, showing how the deployment rate itself must increase over time. Hence, higher growth rates require more rapid scaling up of deployment efforts to achieve the global carbon removal targets within specified timeframes.

As shown in Table 4-2 and Figure 4.6, as the growth rate increases, the required peak deployment rate to achieve the corresponding deployment trajectory increases linearly. For a growth rate of $r = 0.1 \text{ yr}^{-1}$, the peak deployment rate is 27 MtCO₂/yr², which increases to 100 MtCO₂/yr² at a growth rate of $r = 0.4 \text{ yr}^{-1}$. Further, as the growth rate increases, the required year in which the peak deployment rate needs to be achieved becomes earlier. The peak deployment year for a growth rate of $r = 0.1 \text{ yr}^{-1}$ is 2090, and the peak deployment year for a growth rate of $r = 0.4 \text{ yr}^{-1}$ is 2037. For greater growth rates, the required peak deployment rate is higher and this needs to be achieved within a shorter time frame (i.e., observe an earlier peak deployment year in Table 4-2).

Table 4-2: Peak deployment rate of DAC systems and timing.

Growth rate (per year)	Peak deployment rate (MtCO ₂ /year per year)	Peak deployment year (year)	Cumulative emissions achieved by 2050 (GtCO ₂)	
			L-DAC	S-DAC
0.1	27	2090	Zero	Zero
0.4	100	2037	5.1	9.2

With respect to cumulative emissions, as the growth rate increases, the cumulative carbon removal achieved by the year 2050 increases substantially (Table 4-2). For a growth rate of $r = 0.1 \text{ yr}^{-1}$, the cumulative removal achieved by the year 2050 is essentially zero for both L-DAC and S-DAC systems. Whereas, on a globally averaged basis, the cumulative removal by the year 2050 with a growth rate of $r = 0.4 \text{ yr}^{-1}$ is 5.1 GtCO₂ for the L-DAC system, and 9.2 GtCO₂ for the S-DAC system. Therefore, at a global-scale, S-DAC system benefits substantially more from accelerated growth efforts than a global-scale L-DAC system.

From the perspective of maximising environmental effectiveness, it is always favourable to achieve as high of a growth rate as possible – provided that the regional context enables sufficiently low carbon intensity of energy supply that this is advantageous. The results illustrate that direct air capture could have a meaningful contribution to meeting global climate targets in the long-term. However, this would likely need wide-scale deployment of direct air capture to commence immediately.

There will be an upper bound on the achievable growth rate for the global-scale deployment of direct air capture. This upper bound depends on two factors: (i) capacity constraints of supply chains for direct air capture equipment and infrastructure, and (ii) rate at which supply chains can scale up to achieve higher deployment rates. Both factors will depend on real-world supply chain constraints and market factors. We recommend that a key aspect of future work should determine what these supply chain constraints are likely to be feasible. This can be

used to develop reasonable assumptions about the carbon removal potential of direct air capture. This will minimise risk and ensure that sufficient contingencies are considered when forming high-level decarbonisation strategies which include direct air capture technology.

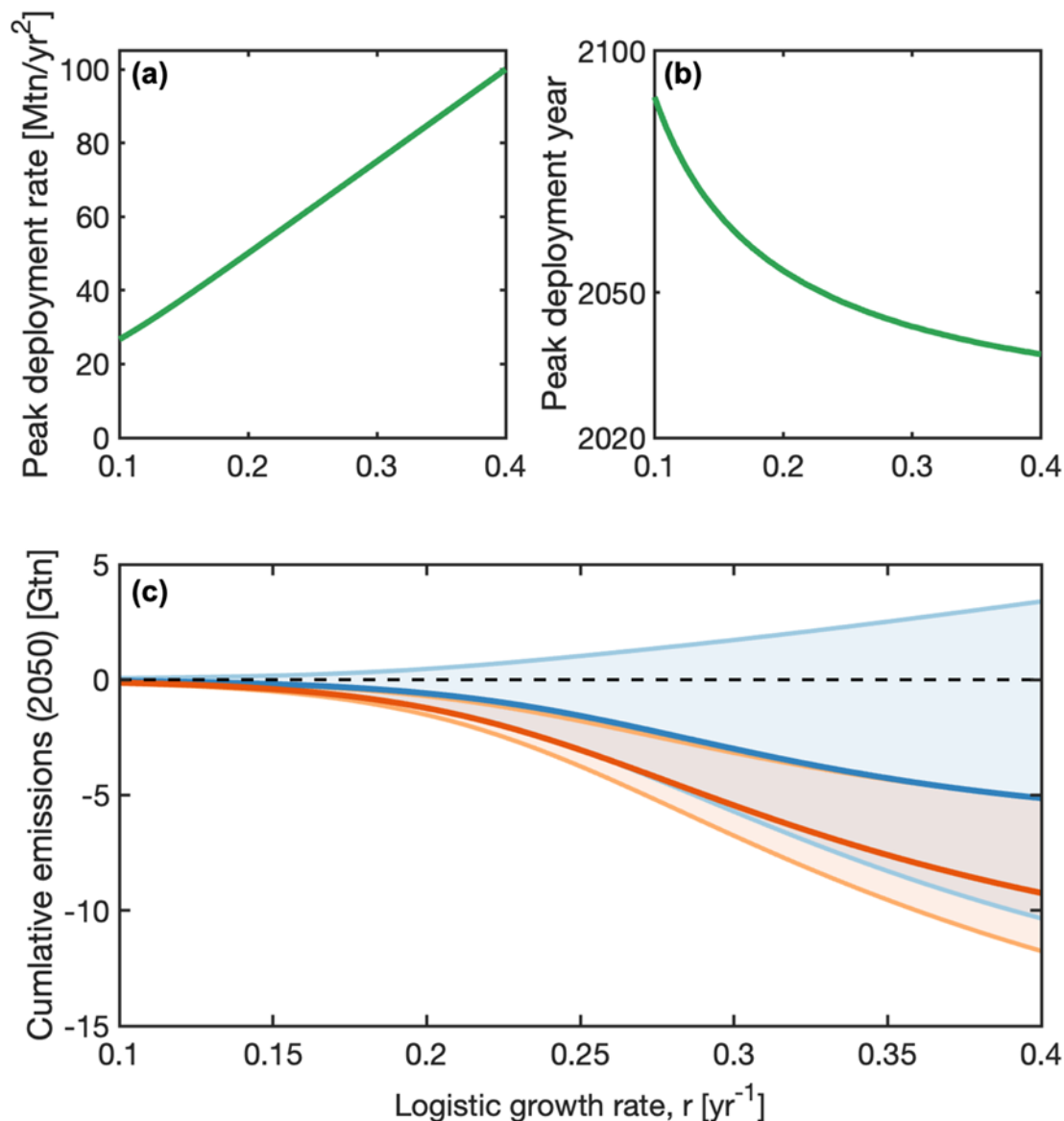


Figure 4.6: Sensitivity of performance for a global-scale 1 GtCO₂/yr deployment of direct air capture to logistic growth rates in the range $r = 0.1 - 0.4 \text{ yr}^{-1}$. (a) peak deployment rate. (b) peak deployment year. (c) cumulative emissions in the year 2050 for L-DAC (blue) and S-DAC (orange) systems. Shaded regions correspond to variability observed in individual regional scenarios.

4.11 Regional decarbonisation requirements

Energy system decarbonisation is central to enabling deep reductions in CO₂ emissions from all sectors (e.g., provision of green hydrogen, electric vehicles), including ensuring the timely removal of significant amounts of CO₂ from the atmosphere via direct air capture deployment. We observe that the performance of both L-DAC and S-DAC processes is strongly dependent on the carbon intensity of energy supply used throughout the deployment and operation periods. World regions which decarbonise significantly and rapidly show strong direct air capture performance (i.e., achieves meaningful CO₂ removal at both the process and global scale, high carbon removal efficiency). In contrast, regions which do not decarbonise to a great enough extent, and/or at a fast enough rate, perform poorly. In the following, we aim towards quantifying the required energy system decarbonisation pathway for each world region which can enable an environmentally effective deployment of a large-scale direct air capture system.

We approach determining the required energy system decarbonisation pathways as an optimisation problem to determine the slowest possible energy decarbonisation trajectory which enables at least net-zero cumulative emissions from a wide-scale deployment of direct air capture in each world region. Therefore, the determined energy decarbonisation pathway represents a minimum ambition which defines the boundary between direct air capture being feasible, or not, to enable negative emissions in each world region. The objective of the problem is:

$$\max_{I_{\text{grid}}(t_1), \dots, I_{\text{grid}}(t_N)} \sum_{i=0}^N I_{\text{grid}}(t_i)$$

where we aim to find the slowest possible decarbonisation pathway which will enable an effective deployment of direct air capture by maximising the area underneath the energy decarbonisation profile. In each world region, we constrain the solution to start from the current day carbon intensity:

$$I_{\text{grid}}(t_0) = \mathcal{J}_{0,\text{region}}$$

we also constrain the decarbonisation pathway to always, at least, decrease as time progresses:

$$I_{\text{grid}}(t_{i+1}) \leq I_{\text{grid}}(t_i), \forall i$$

we aim to calculate the slowest possible decarbonisation pathway which enables at least net-zero cumulative emissions from the direct air capture system in the year 2050:

$$(\text{Cumulative emissions})_{2050} = 0$$

where the cumulative emissions of the direct air capture system are calculated between the period 2020–2050 using the global-scale deployment and cumulative emissions model described previously (Section 4.2). We apply the calculation to each world region, including the Pacific, Middle East, Asia, North America, Europe, and Latin America regions. We consider the base-case deployment scenario developed

previously, where direct air capture capacity is scaled from 1 MtCO₂/yr in 2020 to 1 GtCO₂/yr in 2050 by expansion with a logistic growth rate of $r = 0.26 \text{ yr}^{-1}$ and a plant lifetime of 30 years. We calculate separate regional decarbonisation pathways for both L-DAC and S-DAC deployments, since their interactions with the energy system in terms of cumulative carbon removal performance are distinctly different.

The outcome of this calculation is shown in Figure 4.7. For each world region, the blue shaded area corresponds to the minimum decarbonisation pathway to enable an environmentally effective deployment of L-DAC, and the orange shaded area corresponds to the minimum decarbonisation pathway to enable net zero DAC deployment of S-DAC. In the Pacific, Middle East, and Asia regions the current carbon intensity of energy supply is too high to enable environmentally effective direct air capture deployment using either L-DAC or S-DAC technology. Therefore, significant further decarbonisation efforts are required between 2020–2050 to make these regions suitable for wide-scale deployment of direct air capture. In the North America, Europe, and Latin America regions, only small-moderate further efforts are required to enable an environmentally effective deployment of L-DAC, and no further efforts are required to enable wide-scale S-DAC. However, since the calculated decarbonisation pathways represent a minimum ambition to enable net-zero cumulative emissions from wide-scale direct air capture, it is necessary in all cases to decarbonise to a greater extent than the recommended pathway to enable a highly efficient deployment of DAC that can achieve significant levels of carbon removal.

By comparing the projected decarbonisation pathway in each world region with the minimum required pathway, we can see that the Pacific, North America, Europe, and Latin America regions are on track to deliver an energy system which is suitable for wide-scale deployments of both L-DAC and S-DAC. Whereas the Middle East and Asia regions need to significantly accelerate energy system decarbonisation efforts if they are to create a suitable environment for direct air capture.

The results of this exercise highlight a clear need for synergy between direct air capture deployment and wider energy system decarbonisation, whether through integration with national grids or through the development of dedicated low-carbon energy supplies in regions where bespoke systems may be more viable. Moreover, a wide-scale deployment of direct air capture will inevitably depend on energy provision from national energy networks. While the focus in this work is how DAC deployment interacts with various levels of grid carbon intensity, it is crucial to consider additional synergies. For instance, DAC can play a significant role in addressing residual emissions from hard-to-abate sectors. The implications for energy systems are varied in the sense that regions with abundant fossil fuels might integrate DAC with carbon capture and storage (CCS) technologies to manage emissions, whereas regions with higher renewable energy penetration may find it easier to incorporate DAC into their energy systems.

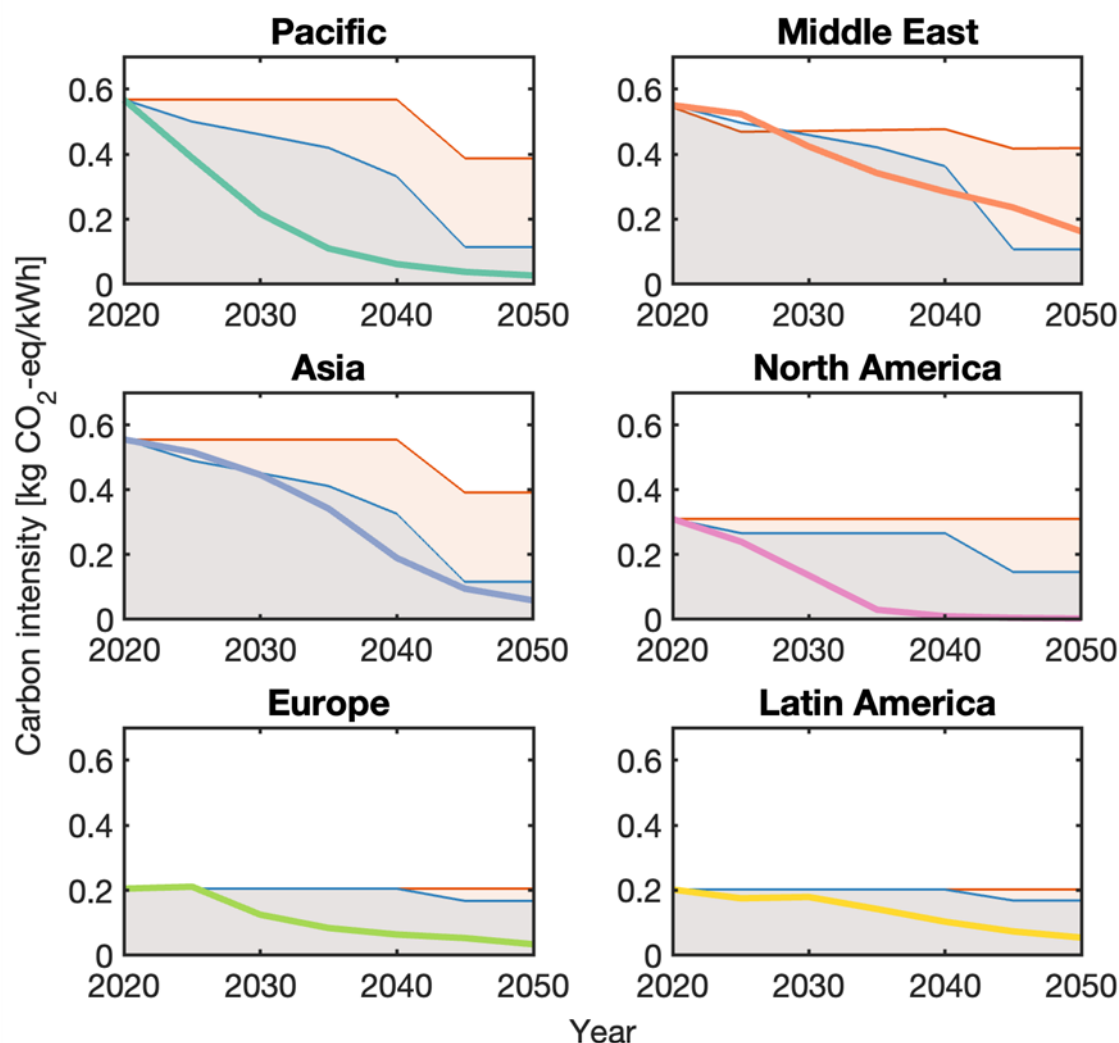


Figure 4.7: Minimum required decarbonisation pathways to enable at least net-zero deployment of direct air capture in six world regions. Shaded blue areas correspond to the minimum decarbonisation pathway to enable L-DAC deployment, and shaded orange areas correspond to the minimum decarbonisation pathway to enable S-DAC deployment. The solid lines correspond to the actual projected decarbonisation pathway in each world region according to the EnerOutlook energy & emissions to 2050 scenario by Enerdata.

To achieve the carbon removal efficiency needed to meet global climate goals and ensure environmental effectiveness, direct air capture deployment requires the timely supply of low-carbon energy. Therefore, direct air capture does not act as a substitute technology which can support sluggish efforts towards wider decarbonisation in the energy system – and can only be enabled to provide services in decarbonisation strategies when integrated in the correct context. The purpose of direct air capture is to provide greenhouse gas removal, to (i) account for hard-to-abate industrial emissions, (ii) account for decentralised emissions (especially in transport and agriculture), and (iii) reduce high atmospheric carbon dioxide concentrations caused by historical unabated emissions. Direct air capture is explicitly not positioned as an approach to compensate for poor efforts towards decarbonisation of the energy system.

4.12 Conclusions and key recommendations

- ▶ Direct air capture processes deployed today perform poorly in terms of average carbon dioxide removal efficiency, and the duration of process operations required to offset construction emissions, particularly when assessed using region-wide average energy system carbon intensities. However, performance may be substantially better at strategically selected sites with access to low-carbon energy.
- ▶ The suggestion to delay DAC deployment until 2030 in regions with high carbon intensity power grids aims to leverage potential advancements in energy system decarbonisation which could result in more efficient cumulative CO₂ removal DAC operations. However, the actual effectiveness of such a strategy is highly dependent on the specific DAC technology used and the rate at which the energy system decarbonises. It is equally important to recognise the value of early deployment for accelerating technology learning, identifying supply chain constraints, and enabling the development of supportive infrastructure and markets. Therefore, strategic early deployment can play a critical role even if immediate carbon removal performance is suboptimal.
- ▶ Global-scale direct air capture deployment can achieve significant amounts of negative emissions in the period 2020–2100. Deployment of a 1 GtCO₂/yr system can enable 35–50 GtCO₂ removal cumulatively by the end of the century. Our model assumes performance based on current DAC configurations, it does not explore alternative technology archetypes or future technology improvements. The carbon removal outcomes are particularly sensitive to the carbon intensity of the energy system over time, underscoring the importance of long-term energy decarbonisation. These results also highlight the importance of strategic early deployment – not only to deliver removals but to advance technology learning and supply chain development, even if initial deployments achieve lower efficiencies.
- ▶ The carbon removal performance of a global-scale direct air capture deployment shows a strong correlation to the growth rate achieved throughout the deployment of the system. Low peak deployment rates yield a system which achieves essentially zero cumulative removals by mid-century, while high peak deployment rates can yield a large amount of cumulative removals. Further practical research on supply chain constraints to establish achievable deployment trajectories for large-scale direct air capture is a significant priority towards establishing the role of direct air capture for providing timely carbon removal.
- ▶ Energy system decarbonisation efforts in the Pacific, North America, Europe, and Latin America regions are on track to deliver a platform which can enable environmentally effective wide-scale direct air capture. The Asia and Middle East regions need to accelerate energy system decarbonisation efforts if

these regions are to play a major role in global-scale direct air capture deployment or opt for DAC systems powered by dedicated low-carbon energy sources.

5 Durability of direct air capture

5.1 Storage lifetime

When a direct air capture process captures carbon dioxide from the air, there are a wide variety of possible sinks for captured carbon, including carbon storage pathways and carbon utilisation pathways⁵⁹. Depending on the choice of sink, the amount of time for which carbon dioxide is prevented from re-entering the atmosphere can vary significantly. This period is characterised by the storage time (t_{store}), which is defined as the amount of time between when an amount of carbon dioxide is captured, and when that carbon dioxide is returned to the atmosphere.

5.2 Geological carbon sequestration

Captured CO₂ can be directed towards sequestration in geological formations. Saline aquifers and exhausted oil/gas fields can be used as storage mediums.⁶⁰ Traditional carbon sequestration acts to store CO₂ in these formations through a series of mechanisms following injection:⁶¹

- ▶ **Structural trapping:** the physical trapping of carbon dioxide in the geological formation by an impermeable cap rock.
- ▶ **Residual trapping:** the isolation of small pockets of injected carbon dioxide as pockets of undissolved fluid.
- ▶ **Solubility trapping:** dissolution of carbon dioxide in the brine fluid already in place within the geological formation.
- ▶ **Mineral trapping:** chemical reaction of dissolved carbon dioxide with the minerals in the structure of the rock, permanently trapping the injected carbon dioxide underground as a solid.

These trapping mechanisms proceed in sequence over long geological time scales. After thousands of years, most of the injected carbon dioxide will be permanently

⁵⁹ The classification of timeframes as "storage" or "utilization" depends on the permanence of the carbon stored. **Storage** generally refers to the long-term sequestration of CO₂, typically in geological formations or other stable reservoirs, where the carbon is expected to remain trapped for thousands of years or more. **Utilisation**, on the other hand, involves using captured CO₂ and converting it into products, which may eventually result in the re-emission of the CO₂ into the atmosphere (e.g., fuels and chemicals). Some utilisation pathways using mineralisation can create products (e.g., building materials) with longer lifetimes of up to 100 years.

⁶⁰ **Aminu et al. (2017):** A review of developments in carbon dioxide storage. *Applied Energy* (208).

⁶¹ **Kelemen et al. (2019):** An overview of the status and challenges of CO₂ storage in minerals and geological formations. *Frontiers in Climate* (1).

stored as a mineral solid within the geological structure. In complement to this traditional approach, technologies are also emerging to achieve significant amounts of mineralisation in a much shorter period.⁶² For example, over a period of a few years, the company CarbFix has been scaling up their technology based on injection into basalt rock formations to achieve carbon mineralisation.⁶³

It is now widely accepted that geological carbon sequestration represents an essentially permanent storage for captured carbon dioxide which has a very low leakage rate.⁶⁴ In accordance with this, previous chapters of this report have assumed that all captured carbon dioxide is directed towards geological storage ($t_{\text{store}} \rightarrow \infty$).

5.3 Carbon utilisation pathways

As well as storing captured carbon dioxide in geological formations, attention is growing on pathways which seek to utilise captured carbon in chemical processes which convert it into useful products. There are a wide variety of carbon-based products that incorporate captured CO₂ or benefit from CO₂ utilisation processes, including: wood products, steel, concrete, plastics, fuels, and chemical feedstocks. For each potential utilisation product, there is a finite storage lifetime associated with their function as a carbon sink. In this context, the captured carbon which is embodied in the product is re-emitted to the atmosphere at the end of the products use phase – defined by the product lifetime.

The product lifetimes associated with a range of potential utilisation products are presented in Figure 5.1.⁶⁵ We can see that the portfolio of possible products which

⁶² **Raza et al. (2022)**: Carbon mineralization and geological storage of CO₂ in basalt: Mechanisms and technical challenges. *Earth-Science Reviews* (229).

⁶³ **Matter et al. (2011)**: The CarbFix pilot project—storing carbon dioxide in basalt. *Energy Procedia* (4).

⁶⁴ **Krevor et al. (2023)**: Subsurface carbon dioxide and hydrogen storage for a sustainable energy future. *Nature Reviews Earth & Environment* (4).

⁶⁵ **Smith et al. (2006)**: “Methods for calculating forest ecosystem and harvested carbon with standard estimates for first types of the United States”. General Technical Report NE-343, United States Department of Agriculture; **Johnston & Radeloff (2019)**: “Global mitigation potential of carbon stored in harvested wood products”. *Proceedings of the National Academy of Sciences* (115); **Murakami et al. (2010)**: “Lifespan of commodities, part I. The creation of a database and its review”. *Journal of Industrial Ecology* (4); **Pauliuk et al. (2013)**: “The steel scrap age”. *Environmental Science & Technology* (47); **Huang et al. (2016)**: “Changing patterns and determinants of infrastructures”. *Resources, Conservation and Recycling* (123); **Yang et al. (2014)**: “Carbonation and CO₂ uptake of concrete”. *Environmental Impact Assessment Review* (46); **Galan et al. (2010)**: “Sequestration of CO₂ by concrete carbonation”. *Environmental Science & Technology* (44). **Penaloza et al. (2019)**: “The influence of system boundaries and baseline in climate impact assessment of forest products”. *International Journal of Life Cycle Assessment* (24); **Deetman et al. (2020)**: “Modelling global material stocks and flows for residential and service sector buildings towards 2050”. *Journal of Cleaner Production* (245); **Penazola et al. (2018)**: “Climate impacts from road bridges: effects of introducing concrete carbonation and biogenic carbon storage in wood”. *Structure and Infrastructure Engineering* (14); **Hertwich et al. (2019)**: “Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics – a review”. *Environmental Research Letters* (14); **Miatto et al. (2019)**: “A spatial analysis of material stock accumulation and demolition waste potential

can result from different carbon utilisation pathways can have a range of different lifetimes. The longest lifetime product is concrete used in buildings, which can have a lifetime of several decades and may be regarded as a form of carbon storage but at a lower durability/permanence compared to geological CO₂ storage. The shortest lifetime products are urea and synthetic fuels, which can potentially be consumed as feedstocks to other processes within only weeks of being produced.

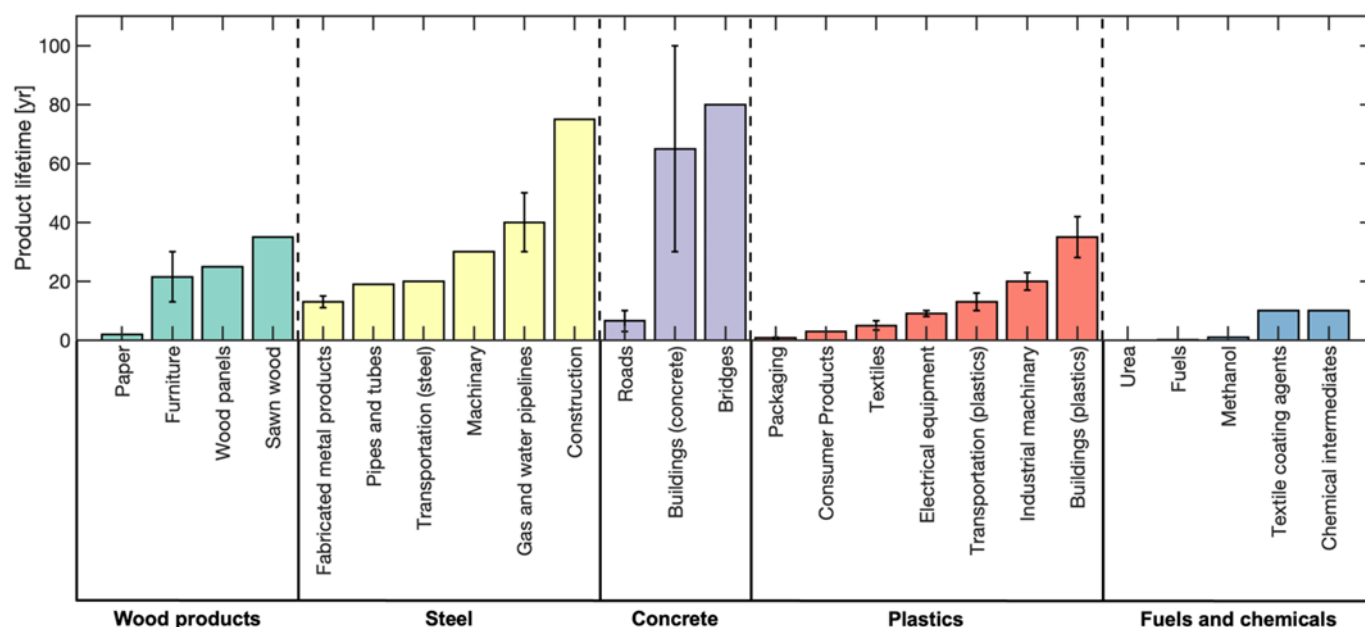


Figure 5.1: Product lifetimes for a variety of potential carbon-based products resulting from chemical conversion of captured carbon dioxide in carbon utilisation pathways. Products are categorised into five main groups: (i) wood products, (ii) steel, (iii) concrete, (iv) plastics, and (v) fuels and chemicals. Error bars represent uncertainty in the product lifetime (where available).

Because (i) carbon dioxide used to generate utilisation products is eventually re-emitted to the atmosphere at the end of the products use phase, and (ii) different products vary in terms of lifetime, we can anticipate that a direct air capture systems using carbon utilisation pathways will have distinctly different cumulative emissions dynamics compared to pathways using geological storage as the carbon sink.

Particularly, we need to understand:

- ▶ How the cumulative emissions dynamics behave for a system in which the carbon sink is inherently temporary.
- ▶ How the product lifetime affects the cumulative emissions over a range of timescales (decades to centuries).

of buildings: A case study of Padua”. *Resources, Conservation and Recycling* (142); **Geyer et al. (2017)**: “Law, production, use and fate of all plastics ever made”. *Science Advances* (3); **Vora et al. (2021)**: “Levelling the cost and carbon footprint of circular polymers that are chemically recycled to monomers”. *Science Advances* (7); **Lee (2020)**: “Modelling the fate of chemicals in products”. Springer Theses. **IEA (2019)**: “Putting CO₂ to use. Creating value from emissions”.

5.4 Cumulative emissions with a temporary carbon sink

The global-scale cumulative emissions model, described in Chapter 4, can be extended to describe carbon sinks with a finite storage lifetime. In this context, the cumulative emissions associated with the global-scale deployment of direct air capture are described by the following time series model:

$$\begin{aligned} & (\text{Cumulative emissions})_{t_n} \\ &= \Delta t \cdot \sum_{i=1}^n [\dot{C}(t_i) E_{\text{DAC}} t_{\text{life}}] - [C(t_i) \eta_{\text{CDR}} (I_{\text{grid}}(t_i))] + [y_{\text{store}} C(t_i - t_{\text{store}})] \end{aligned}$$

where t_{store} is the (finite) storage lifetime (in years) of the temporary carbon sink, and y_{store} is a binary variable defined as follows:

$$y_{\text{store}} = \begin{cases} 0, & \text{if } t < t_{\text{store}} \\ 1, & \text{if } t \geq t_{\text{store}} \end{cases}$$

The cumulative emissions model outlined here accounts for four contributions to the overall emissions of the direct air capture value chain:

- Negative emissions associated with the capture of carbon dioxide from the atmosphere, which is either stored temporarily (e.g., utilisation products) or permanently (i.e., geologically stored).
- Positive emissions associated with the construction of direct air capture processes. This source of emissions is attributed to the time at which capture capacity is added to the global-scale direct air capture system throughout deployment.
- Positive emissions associated with the operational emissions of direct air capture processes. This source of emissions is distributed over time according to the operational capacity of the current direct air capture system, and its efficiency with respect to changes in the energy provision system.
- Positive emissions associated with the re-emission of captured carbon dioxide to the atmosphere once the product lifetime is exceeded. This source of emissions is distributed over time, delayed with respect to the captured carbon profile in accordance with the storage lifetime.

The logistic growth model established in Chapter 4 is used to describe the deployed capacity ($C(t)$) and deployment rate of capacity ($\dot{C}(t)$) of direct air capture as functions of time throughout its global-scale deployment.

5.5 Effect of product lifetime on cumulative emissions

We have analysed the effect of the product lifetime of a temporary carbon sink on the dynamic cumulative emissions dynamics of a global-scale deployment of direct air capture deployment. In the following, we consider the base-case deployment scenario presented in Chapter 4. Direct air capture capacity is scaled globally from 1 MtCO₂/yr in 2020, to 1 GtCO₂/yr by mid-century according to logistic growth with a growth rate of $r = 0.26 \text{ yr}^{-1}$. The lifetime of a direct air capture plant is assumed to be 30 years.

Sensitivity of the cumulative emissions is considered with respect to the three long-term energy system decarbonisation scenarios presented in Chapter 4. Specifically, we consider:

- (i) No further decarbonisation after 2050,
- (ii) Net-zero by 2100,
- (iii) Net-negative by 2100.

Details of these energy decarbonisation scenarios are provided in Chapter 4. In this analysis, the carbon intensity of energy supply profiles is further extended to cover the period 2100–2200 by considering no further change in the profiles after 2100 (i.e., the carbon intensity remains constant after 2100). In this context, we acknowledge significant uncertainty in projecting energy system decarbonisation over such a significant time horizon. However, it is necessary for understanding the behaviour of CO₂ utilisation products as temporary carbon sinks by analysing the cumulative emissions over a long time-horizon to encompass all the relevant emissions mechanisms.

The outcome of this calculation is presented in Figure 5.2 for product lifetimes in the range 0.1–100 years, where representative product lifetimes (e.g., similar to some of those in Figure 5.1) were chosen to illustrate its impact on cumulative emissions. We can see that for all product lifetimes, the carbon balance of the system trends towards becoming positive. This can be understood from the perspective of a carbon balance on the system over time scales much longer than the product lifetime. Carbon is initially captured from the atmosphere, causing negative emissions temporary period. Depending on the product lifetime, an equivalent amount of carbon is re-emitted into the atmosphere. The balance of captured and re-emitted carbon is zero over any timescale longer than the product lifetime. Additionally, there are positive emissions in the system associated with the operation of the direct air capture value chain itself. Therefore, the net balance of carbon emissions is always positive over long time scales, and we can conclude that all carbon utilisation pathways lead to a net addition of carbon to the atmosphere over long timescales. Although, this analysis does not consider the counterfactual emissions that would arise from using conventional fossil-based production routes – the pathways remain net-positive in absolute terms. The time when the system reaches net positive in emissions depends on the lifetime of the utilisation product. It is not possible to

design a net-zero or net-negative emissions system based solely on carbon utilisation which achieves.

For products which have longer lifetimes, we observe transient dynamics in the cumulative emissions of the system over moderate timescales. We see that the system can be temporarily carbon negative, before eventually trending back towards positive emissions. The magnitude of this temporary removal, and the duration for which it is sustained, both increase as a function of increasing product lifetime. However, for the reasons outlined above, the emissions of the system will always be positive over long timescales.

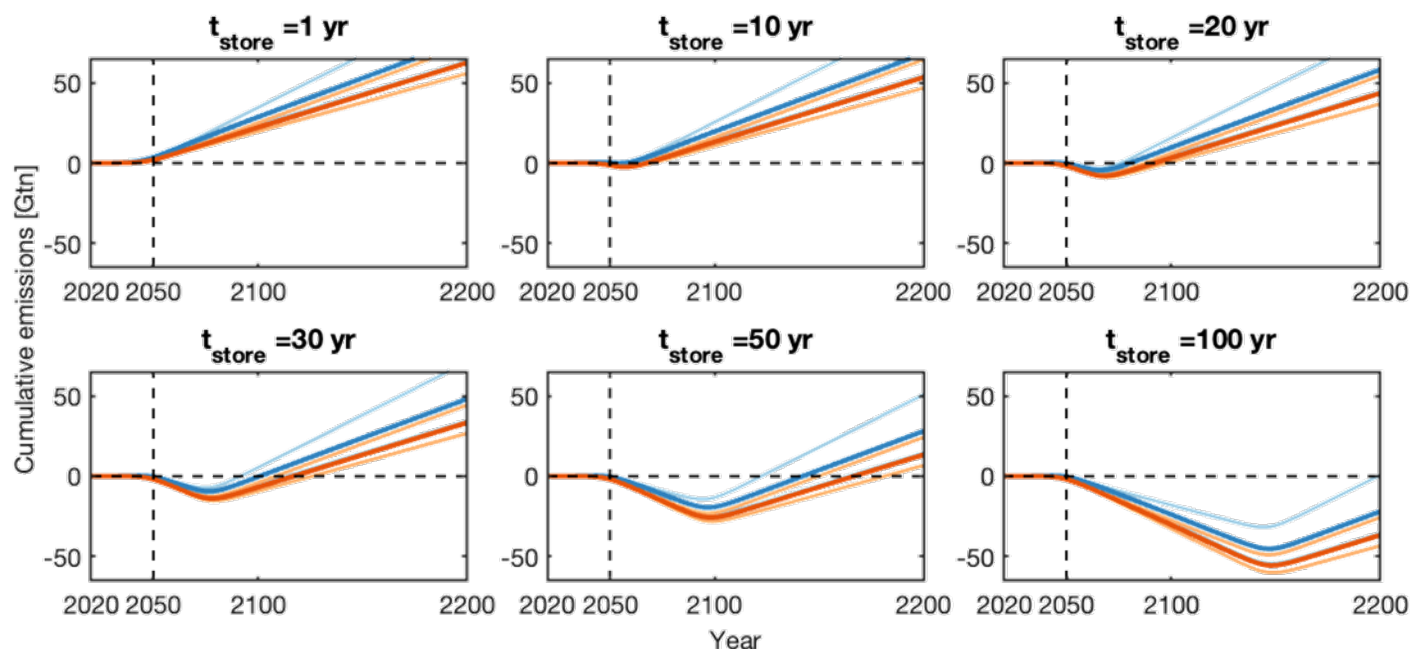


Figure 5.2: Cumulative emissions for a global-scale direct air capture system with a temporary carbon sink. We consider six distinct product lifetimes in the range 1–100 years. On the x-axis, direct air capture capacity is scaled globally from 1 MtCO₂/yr in 2020 to 1 GtCO₂/yr by 2050.

If the emissions associated with the direct air capture value chain are small, carbon utilisation can represent a mechanism for the circular use of carbon-based products with a potentially significantly reduced amount of carbon emissions as compared to conventional production of such products. However, it is important to draw a distinction between this use-case, and the aim of achieving durable carbon removal from the atmosphere.

We conclude that the only route towards achieving durable net-negative emissions using direct air capture value chains over long timescales is to couple direct air capture to a carbon sink with an indefinite storage lifetime, i.e., permanent storage. The only carbon sink that we currently know of which satisfies this criterion is geological carbon sequestration. Therefore, net-negative emissions can only be facilitated by the wide-scale use of geological carbon sequestration as the sink for the carbon dioxide from direct air capture processes.

5.6 Mixed-sink systems

We have previously considered two pathway options for the carbon dioxide recovered by a direct air capture process: (i) geological carbon sequestration, and (ii) carbon dioxide utilisation products. We have seen that geological carbon sequestration represents an approach towards net-negative emissions, and the carbon utilisation always causes net-positive emissions over long timescales when applied in isolation.

However, it is likely that a mature direct air capture system will employ a “mixed sink” approach, whereby some portion of the captured carbon is sent towards temporary embodiment in utilisation pathways, and the remaining captured carbon is sent towards permanent geological sequestration. Before conducting any formal analysis, we know that such a strategy can be effective for resulting in net-negative system emissions.

When we direct 100% of captured carbon towards geological carbon storage, we observe that the cumulative emissions of the system can become significantly negative over time – provided that the regional context of energy supply decarbonisation is favourable (see Chapter 4). This implies that we have some finite “carbon budget” which we can afford to re-emit into the atmosphere without causing net-positive emissions overall. In this context, we can incorporate some amount of carbon utilisation into the downstream portfolio of the value chain without negating the environmental effectiveness of the whole system. The use of the carbon budget afforded by geological carbon sequestration can be used to generate value through two key mechanisms: (i) products from utilisation pathways are valuable in the sense that they provide a low-carbon alternative to an end user, and (ii) the products may generate economic returns for the DAC system operators. However, it is important to note that CCU derived from DAC CO₂ face higher costs compared to conventional products and hence, CCU products may not be competitive without financial incentives or supportive policies⁶⁶.

Thus, the two mechanisms to generate economic value for DAC include:

- (i) Through geological carbon sequestration, which can generate revenue from the sale of CO₂ removal credits on the voluntary carbon market (VCM) which is driven by the demand to offset emissions by individuals, businesses and governments. Revenue also includes compliance markets where companies and governments meet regulatory obligations⁶⁷. Refer to Box 2.
- (ii) Conversion of CO₂ into utilisation products, where value is driven by the current market demand. However, CCU products, especially using DAC-derived CO₂, will be significantly more expensive than their conventional

⁶⁶ Hepburn et al., (2019) The technological and economic prospects for CO₂ utilisation and removal. <https://doi.org/10.1038/s41586-019-1681-6>

⁶⁷ IEA (2023) Unlocking the potential of direct air capture: Is scaling up through carbon markets possible? <https://www.iea.org/commentaries/unlocking-the-potential-of-direct-air-capture-is-scaling-up-through-carbon-markets-possible>

counterparts. Any additional uptake would require supportive financial incentives and policy.

Therefore, exploring different combinations of pathways for direct air capture can act to de-risk the financial burden of developing direct air capture projects.

Box 2: Voluntary Carbon Markets

Voluntary Carbon Markets (VCM) allow carbon emitters to offset their unavoidable emissions by purchasing carbon credits generated by projects that remove or reduce GHG emissions from the atmosphere. Each credit corresponds to one metric ton of CO₂eq reduced, avoided or removed. Companies or individuals can use these credits to compensate for their emissions, at which point the credit is retired and is no longer in circulation. Voluntary carbon markets are self-regulated and operate across geographical borders and sectors. In contrast, compliance carbon markets are regulated by governments and often limited to specific regions or sectors.

Demand for DAC carbon credits: Recent growth in DAC projects has been largely driven by strong private sector demand for DAC carbon removal credits, which are often used to meet voluntary corporate net-zero commitments. Major purchasers of DAC credits include companies such as Airbus, Shopify, Microsoft. Further, advanced market commitments (AMC) from Frontier (founded by Stripe, Alphabet, Shopify, Meta and McKinsey) and NextGen (a joint venture between South Pole and Mitsubishi Corporation) committed to significant future purchases.

Examples of Policy Mechanisms Supporting DAC⁶⁸:

1. **US 45Q tax credit:** this provides a tax credit per ton of CO₂ captured and stored, making it more economically viable for projects to attract investment.
2. **US funding for DAC hubs:** the US government has committed substantial funding to develop DAC hubs, which are specialised facilities to advance the technology and create economies of scale.
3. **UK DAC and Greenhouse Gas Removal (GGR) demonstrator funding:** this is a programme that the UK government launched to support the development and demonstration of carbon removal technologies including DAC. These programs provide financial assistance to pilot projects, helping to address initial scalability and cost challenges.

Article 6 of the Paris Agreement and VCMs: Carbon removal credits could also be generated and exchanged under Article 6 of the Paris Agreement, which allows countries to voluntarily cooperate to enhance the ambition of their Nationally Determined Contributions (NDCs).⁶⁹ Although the full operationalisation of Article 6 is still under negotiation within the United Nations Framework Convention on

⁶⁸ Smith, S. M., et al. (2024) (eds.) The State of Carbon Dioxide Removal 2024 – 2nd Edition. DOI 10.17605/OSF.IO/F85QJ

⁶⁹ Bednar, B., et al. (2023) The Role of Carbon Dioxide CDR in Contributing to the Long-Term Goal of the Paris Agreement 2023. Swedish Environmental Research Institute

Climate Change (UNFCCC), there are emerging examples of cooperation, such as the declaration of intent between Switzerland and Iceland on DACCS. However, there are technical barriers to overcome. For instance, the latest IPCC Guidelines for National Greenhouse Gas Inventories do not yet include an accounting methodology for DACCS.

5.7 Cumulative emissions of mixed-sink systems

In a mixed sink system, a fraction of the captured carbon dioxide (θ_U) is directed towards utilisation pathways where it is temporarily embodied in carbon-based products. The remaining fraction of the captured carbon, $(1 - \theta_U)$, is directed towards permanent geological carbon sequestration. The cumulative emissions model presented above for systems with temporary carbon sinks can be extended to model a mixed sink system. In this context, the cumulative emissions associated with the global-scale deployment of direct air capture are described by the following time series model:

$$(\text{Cumulative emissions})_{t_n} = \Delta t \cdot \sum_{i=1}^n [\dot{C}(t_i) E_{\text{DAC}} t_{\text{life}}] - [C(t_i) \eta_{\text{CDR}} (I_{\text{grid}}(t_i))] + \theta_U [(1 + \alpha(\epsilon_a - 1)) y_{\text{store}} C(t_i - t_{\text{store}}) + C(t_i) \epsilon_U]$$

where θ_U is the fraction of captured carbon dioxide directed towards carbon utilisation, ϵ_U is the emissions factor of converting captured carbon dioxide into the utilisation product (tCO₂-eq/tCO₂-utilised), α is the abatement factor which defines the percentage of product expiration emissions which can be captured for storage at the point of product use, and ϵ_a is the emissions factor of abatement (tCO₂-eq/tCO₂-abated). The cumulative emissions model outlined here accounts for six contributions to the overall emissions of the direct air capture value chain:

- Negative emissions associated with the capture of carbon dioxide from the atmosphere.
- Positive emissions associated with the construction of direct air capture processes. This source of emissions is attributed to the time at which capture capacity is added to the global-scale direct air capture system throughout deployment.
- Positive emissions associated with the operational emissions of direct air capture processes. This source of emissions is distributed over time according to the operational capacity of the current direct air capture system, and its efficiency with respect to changes in the energy provision system.
- Positive emissions associated with the re-emission of captured carbon dioxide to the atmosphere once the utilisation product lifetime is exceeded. Re-emissions are discounted according to the abatement factor (*e.g.* by the application of post-combustion carbon capture). This source of emissions is distributed over time, delayed with respect to the captured carbon profile in accordance with the storage lifetime.

- ▶ Positive emissions associated with the conversion of captured carbon dioxide into the product produced by the utilisation pathway. These emissions encompass the total life cycle emissions of the utilisation pathway from cradle-to-grave. This source of emissions is distributed over time according to the operational capacity of the current direct air capture system, and the proportion of captured carbon dioxide directed towards the utilisation pathway.
- ▶ Positive emissions associated with the abatement of re-emitted carbon dioxide once the product lifetime is exceeded. This refers to the emissions and energy consumption related to capturing CO₂ that is re-released from utilisation products at the end of their lifetime. This source of emissions is distributed over time, delayed with respect to the captured carbon profile in accordance with the storage lifetime.

5.8 Case-studies of mixed sink systems

To analyse the performance of mixed sink systems, we have formulated three case studies of proposed carbon utilisation pathways. All three chosen pathways fall under the category of air-to-fuel processes, where captured carbon dioxide is converted into fuel for either industrial use, or for use in transport applications. Air-to-fuels is a promising concept for reducing the emissions associated with the use of carbon-based fuels. In an air-to-fuels value chain, the emissions associated with the end-use of the produced fuel are associated with carbon dioxide which was itself originally obtained from the atmosphere. Therefore, use of the produced fuel (e.g., combustion) does not cause a net-positive emission to the atmosphere. The only remaining emissions are those associated with the CO₂ capture and conversion parts of the value chain. Provided that these value chain emissions are small, we can understand that air-to-fuels is a promising pathway towards utilisation of carbon-based fuels, in a circular manner, with potentially significantly reduced overall emissions⁷⁰. The three case studies which we have analysed are detailed in the following:

1) Methane production (unabated NGCC)

Carbon dioxide is captured from the air via DAC, and a proportion of the captured carbon is directed towards a methanation process which converts it into methane. The produced methane is then sent to a Natural Gas Combined Cycle (NGCC) power plant, where it is combusted to generate electricity and the CO₂ from the NGCC is

⁷⁰ **Ganzer, C. & Mac Dowell, N. (2020)** A comparative assessment framework for sustainable production of fuels and chemicals explicitly accounting for intermittency. *Sustainable Energy & Fuels*; **Gonzalez-Garay, A. et al. (2022)** Unravelling the potential of sustainable aviation fuels to decarbonise the aviation sector. *Energy & Environmental Science* 15, 3291-3309.; **Freire Ordóñez, D. et al. (2022)** Evaluation of the potential use of e-fuels in the European aviation sector: a comprehensive economic and environmental assessment including externalities. *Sustainable Energy & Fuels* 6, 4749-4764.; **Barnosell, I. & Pozo, C. (2024)** The impacts of the European chemical industry on the planetary boundaries. *Sustainable Production and Consumption* 44, 188-207.; **Mitchell, S., Martín, A. J., Guillén-Gosálbez, G. & Pérez-Ramírez, J. (2024)** The Future of Chemical Sciences is Sustainable. *Angewandte Chemie International Edition* 63, e202318676.

emitted (i.e., unabated). The remainder of the carbon captured by DAC is directed towards geological storage.

In this value chain, there are negative emissions associated with the capture of carbon dioxide from the atmosphere (i.e., DAC), and there are positive emissions associated with the construction/operation of direct air capture plants, the construction/operation of methanation plants, and the combustion of methane in NGCC plants.

The comparable conventional production pathway for methane in this context is the extraction of naturally occurring methane from geological reserves, and subsequent combustion in NGCC plants.

2) Methane production (abated NGCC)

This case study is identical to the case study presented above for the unabated production and use of methane, with the addition of a post-combustion carbon capture (PCC) unit fitted to the flue gas outlet of the NGCC plants. In accordance with United States Department of Energy benchmarking studies, we assume that the PCC units recover 90% of the carbon dioxide eluted in the flue gas of the NGCC plants.⁷¹ We assume that all carbon dioxide captured by the PCC units is directed towards geological carbon storage.

3) Aviation fuel production

Carbon dioxide is captured from the air, and a proportion of the captured carbon is directed towards a Fischer-Tropsch (FT) process which converts it into jet fuel (i.e., kerosene). The produced jet fuel is then utilised in aircraft, where it is combusted. The remainder of the captured carbon from DAC that does not undergo conversion is directed towards geological storage.

In this aviation fuel value chain, there are negative emissions associated with the capture of carbon dioxide from the atmosphere, and there are positive emissions associated with the construction/operation of direct air capture plants, the construction/operation of FT plants, and the combustion of jet fuel in aircrafts.

The comparable conventional production pathway for jet fuel in this context is the extraction of oil from geological reserves, and subsequent blending of various petroleum distillation products to produce jet fuel. The produced jet fuel is then combusted in aircrafts. Note that this analysis does not include avoided emissions from displacing conventional fossil-derived products, as the focus is on absolute environmental effectiveness of DAC value chains.

Schematic representations of the value chains for each of the case studies described above are provided in Figure 5.3. All lifecycle assessment data used as inputs for the case studies is tabulated in Appendix 5.

⁷¹ **Fout et al. (2015):** Cost and performance baseline for fossil energy plants volume 1a: bituminous coal (PC) and natural gas to electricity. Revision 3. National Energy Technology Laboratory Report.

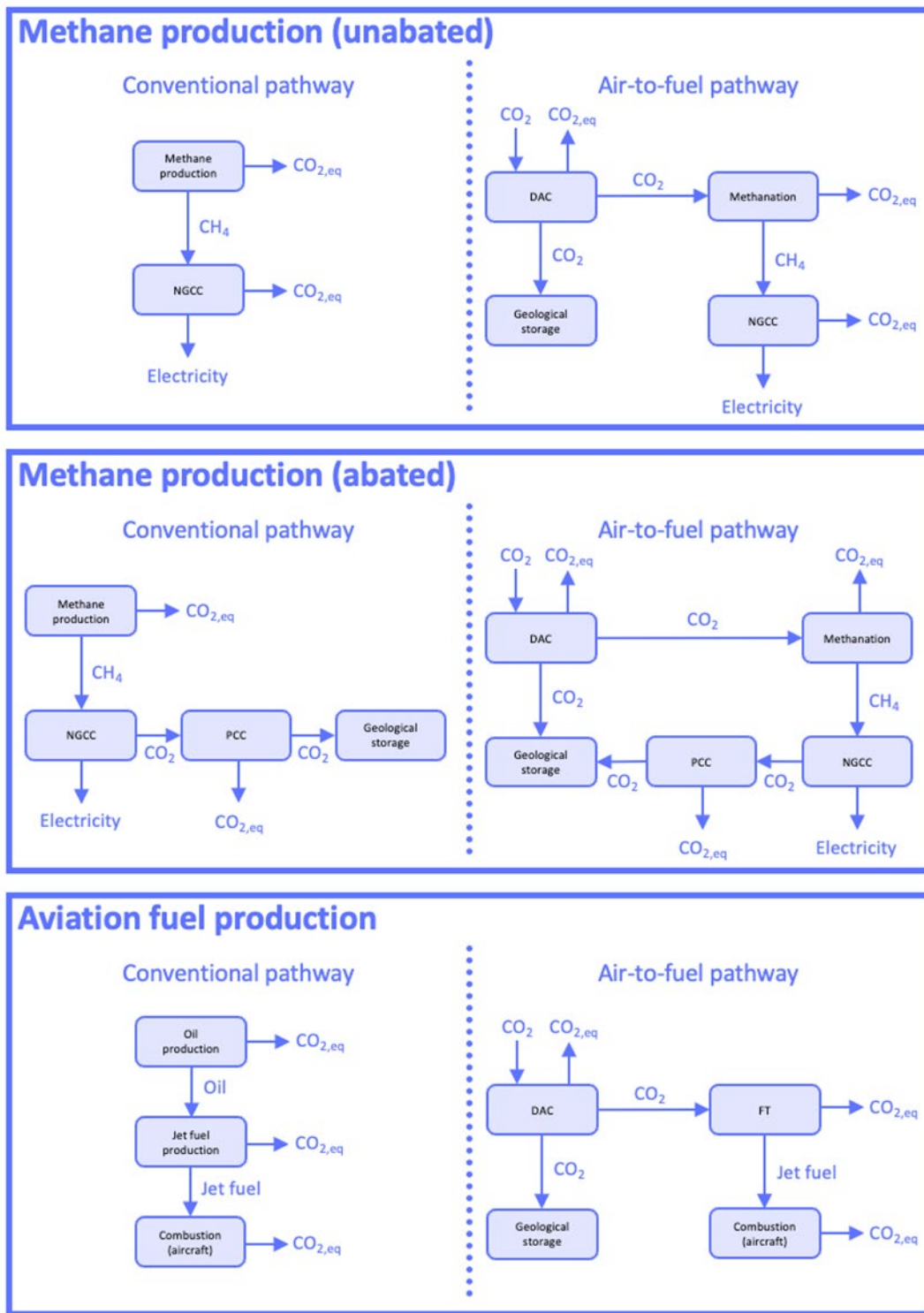


Figure 5.3: Schematics of value chains for conventional and air-to-fuel pathways towards: (i) methane production (unabated NGCC), (ii) methane production (abated NGCC), and (iii) aviation fuel production. DAC = direct air capture, NGCC = natural gas combined cycle, PCC = post-combustion carbon capture, FT = Fischer-Tropsch.

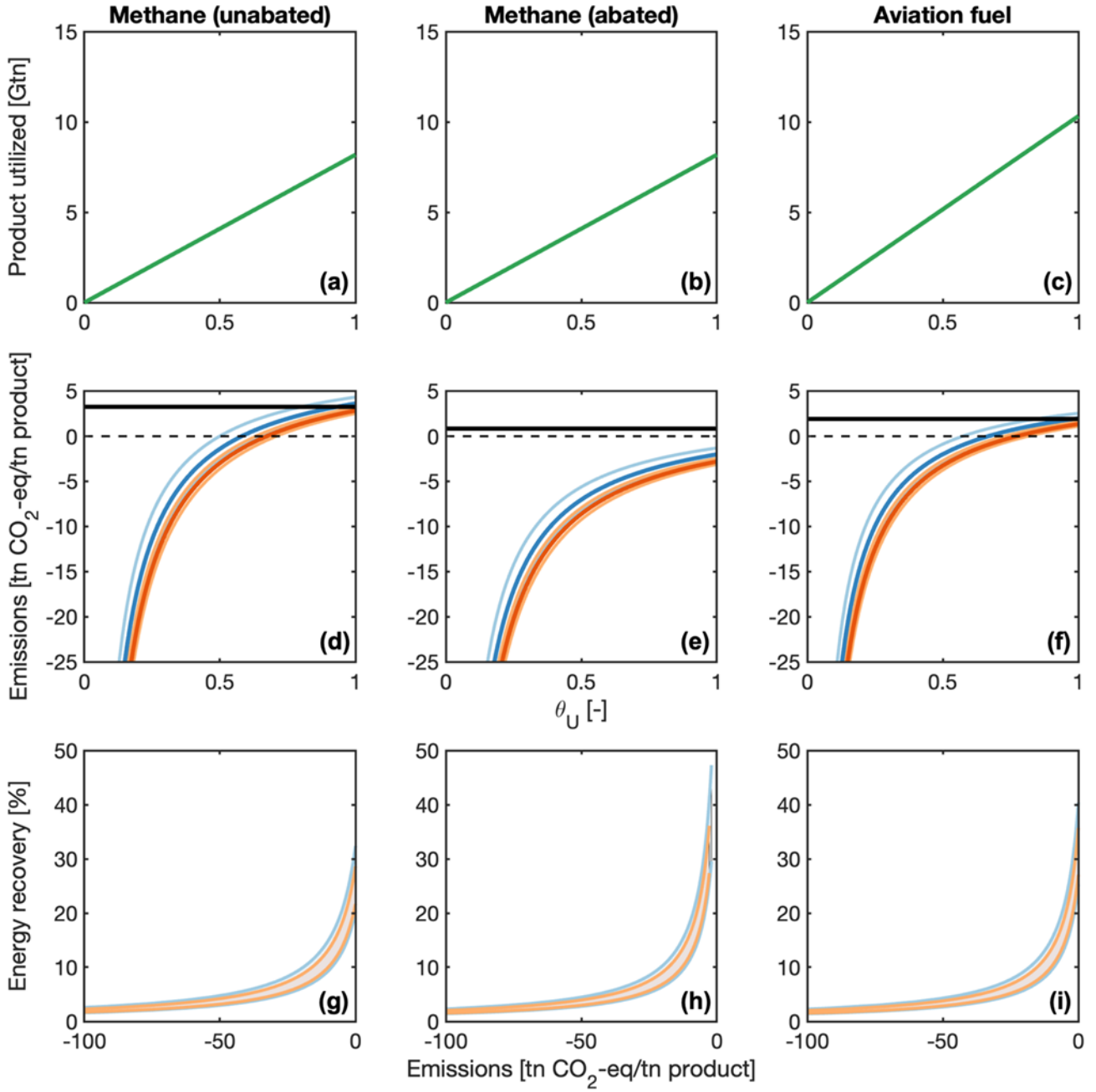


Figure 5.4: Performance of mixed-sink systems with embedded air-to-fuel value chains for: (i) methane production used in unabated NGCC, (ii) methane production used in abated NGCC, and (iii) jet fuel production. (a) – (c): cumulative amount of product utilisation by 2100 as a function of the utilised fraction (θ_U). (d) – (f): average emissions factor in the period 2020–2100 as a function of the utilised fraction (θ_U). (g) – (i): average energy recovery factor in the period 2020–2100 as a function of the emissions factor. Blue lines correspond to L-DAC processes. Orange lines correspond to S-DAC processes. Shaded regions represent uncertainty arising from regional energy decarbonisation scenarios. Black lines correspond to the emissions factor of conventional production pathways.

For each case study, we consider the global-scale deployment base-case presented in Chapter 4. Global direct air capture capacity is scaled from 1 MtCO₂/yr in 2020 to 1 GtCO₂/yr by mid-century according to logistic growth with a growth rate of $r = 0.26 \text{ yr}^{-1}$. The lifetime of direct air capture plants is assumed to be 30 years. We

predict the system performance in the period 2020–2100, considering sensitivity to the three long-term global energy decarbonisation pathways set out in Chapter 4: (i) no further decarbonisation after 2050, (ii) net-zero 2100, (iii) net-negative 2100. The outcome of this calculation is shown in Figure 5.4. For each case study, we present the cumulative amount of product utilised and the average emissions factor in the period 2020–2100 as functions of the utilised fraction (θ_U). We also provide the average energy recovery in the period 2020–2100 as a function of the average emissions factor. The average energy recovery corresponds to the amount of energy extracted as useful work by end-use of the product as a proportion of the energy supplied to the direct air capture value chain.

For the unabated methane production and combustion pathway, 50–71% (L-DAC: 50–65%, S-DAC: 63–71%) of captured carbon dioxide can be directed towards methane production with net-zero system emissions overall. This pathway cumulatively generates 4.1–5.8 Gt of methane by 2100. This is equivalent to a cumulative energy output of 29,000–41,000 TWh in the period 2020–2100 (*ca.* 1–1.5 times the current annual world electricity consumption).⁷²

For the abated methane production and combustion pathway, all of the captured carbon dioxide from DAC can be directed towards methane production while achieving net-negative system emissions overall. This system cumulatively produces 8.2 Gt of methane by 2100. Compared to the unabated methane usage case, the relative power output per amount of methane utilised is lower because of the parasitic energy consumption of the post-combustion capture process on the NGCC plants.⁷³ However, the cumulative net power generation is greater than the unabated case because of the larger amount of methane produced without causing positive system-wide emissions (*ca.* 48,000 TWh). The higher power output of this pathway is also associated with the co-benefit of achieving a net-removal of carbon dioxide from the atmosphere. The system cumulatively achieves 11–26 GtCO₂ removal by 2100 (L-DAC: 11–22 GtCO₂, S-DAC: 20–26 GtCO₂). This is equivalent to a removal of 0.06–0.14 kgCO₂/kWh. For reference, it is estimated that bioenergy with carbon capture and storage (BECCS) achieves a carbon removal of approximately 0.6–1 kgCO₂/kWh.⁷⁴ Therefore, BECCS does represent a stronger level of environmental effectiveness relative to power output. However, the direct air capture system has the significant benefit that arable land is not required in the value chain – and therefore does not present any competition against other uses for such land (*e.g.* growing crops).

It should be noted that the energy generated by both considered air-to-methane pathways is accompanied by a significant energy penalty consumption associated with operation of the direct air capture plants. The energy provision corresponding to the cumulative carbon dioxide capture represented in these scenarios is 82,000–

⁷² Oh et al. (2021): “Performance and cost analysis of natural gas combined cycle plants with chemical looping combustion”. ACS Omega (6); IEA (2023): “World Energy Outlook 2023”.

⁷³ Zhang et al. (2014): “Post-combustion carbon capture technologies: Energetic analysis and life cycle assessment”. International Journal of Greenhouse Gas Control (27).

⁷⁴ Garcia-Freites et al. (2021): “The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UKs net-zero emission target”. Biomass & Bioenergy (151).

141,000 TWh (L-DAC: 82,000–131,000 TWh, S-DAC: 107,000–141,000 TWh).⁷⁵ For L-DAC, this corresponds to an energy recovery efficiency of 22–32% (methane production with unabated NGCC) and 30–47% (methane production with abated NGCC). For S-DAC, this corresponds to an energy recovery efficiency of 22–28% (methane production with unabated NGCC) and 27–36% (methane production with abated NGCC). For reference, batteries can have energy recovery efficiencies in the range 30–80%.⁷⁶ Therefore, air-to-methane pathways can act as a competitive option for energy storage in this context. As an energy storage medium, produced methane has the distinct advantage of being highly transportable around the world (*e.g.* as liquified natural gas). Considering the energy requirements for this pathway are greater than the amount of energy produced, air-to-methane is not a competitive pathway with BECCS for power generation. However, abated air-to-methane pathways can perform a service to the energy sector as a carbon negative long-distance energy vector.⁷⁷ As an energy storage medium, produced methane has the potential for much longer energy storage lifetime than conventional batteries via underground gas storage.

For the aviation fuel pathway, 57–81% (L-DAC: 57–75%, S-DAC: 73–81%) of captured carbon dioxide can be directed towards fuel production with net-zero system emissions overall. This pathway cumulatively generates 5.9–8.4 Gt of jet fuel by 2100. Globally, the annual demand for jet fuel is approximately 0.5 Gt/yr.⁷⁸ Therefore, the cumulative production by this pathway represents enough jet fuel to power flights for approximately 12–17 years in the period 2020–2100 – with net-zero emissions in the fuel production and use value chain. Therefore, we can conclude that while such a pathway represents a route towards net-zero aviation fuel, the chosen capacity of the system would not be sufficient to satisfy demand.

For all of the presented case studies, there is a trade-off between the cumulative emissions of the system and its capacity to produce fuels. As the utilised fraction decreases, the production capacity of the system decreases linearly. However, the corresponding improvement in the environmental effectiveness follows an exponentially increasing trend. We also see that the energy recovered by the system as useful work declines exponentially with increasing environmental effectiveness. Ultimately, the fraction of utilised carbon dioxide in a global-scale direct air capture system will be determined by external demands on the system with respect to the market pressures to produce useful products, or to achieve greater environmental effectiveness. While we account for the energy requirements for DAC, the energy intensity and variability of the downstream conversion processes are not explicitly modelled. The results presented assume alignment with long-term energy pathways.

⁷⁵ IEA (2022): Direct air capture: A key technology for net zero.

⁷⁶ Eftekhari (2017): Energy efficiency: a critically important but neglected factor in battery research. *Sustainable Energy & Fuels* (1).

⁷⁷ Yao, J., Bui, M., Mac Dowell, N. (2019) Grid-scale energy storage with net-zero emissions: comparing the options. <https://doi.org/10.1039/C9SE00689C>

⁷⁸ Chèze et al. (2011): Forecasting world and regional aviation jet fuel demands to the mid-term (2025). *Energy Policy* (39).

These case studies demonstrate that utilisation of captured carbon in direct air capture value chains is a realistic approach towards achieving net-zero or net-negative emissions overall. These pathways allow for the production of products which have both economic and social value and can serve to at least partially offset the costs associated with operating direct air capture plants. For the cases of unabated methane usage and aviation fuel usage, we see that when the system is constrained by realistic deployment trajectories and energy supply scenarios that it is not possible to achieve net-zero usage of such products without directing at least some fraction of the captured carbon towards permanent storage via geological sequestration.

Further, we can see that even when a large fraction of captured carbon from a global-scale deployment of direct air capture is directed towards a single utilisation pathway, that the contribution which can be made to global demand for these products is marginal. We therefore conclude that it is unlikely that such value chains will be established at a large scale, as the significant decrease in carbon removal potential of the direct air capture system is likely not offset by the marginal contribution towards the global-scale supply of these fuels. In these cases, we contend that efforts would be better dedicated towards focussing on durable geological storage for carbon captured by direct air capture as the primary driver towards wide-scale deployment.

5.9 Conclusions and key recommendations

- ▶ The only permanent sink for captured carbon dioxide is storage in geological formations. Any deployment of direct air capture which achieves net-negative emissions must direct at least some portion of the captured carbon dioxide towards storage in geological formations. This is necessary to offset the operational emissions of direct air capture.
- ▶ There are a wide variety of carbon-based products which can be made by using captured carbon dioxide as a feedstock. Different carbon-based products have widely different lifetimes (weeks – decades). All possible carbon utilisation pathways lead to positive emissions overall at long time scales. However, carbon utilisation pathways can enable a temporary overall carbon removal. Longer product lifetimes give a larger and more sustained temporary carbon removal than products with shorter lifetimes.
- ▶ Mixed-sink systems represent an approach towards enabling a degree of carbon utilisation in direct air capture systems while maintaining negative emissions overall. In a mixed sink system, a portion of the captured carbon dioxide is directed towards carbon utilisation pathways. The remaining captured carbon dioxide is directed towards geological carbon storage.
- ▶ Air-to-fuel value chains as a component of mixed sink direct air capture systems can enable the use of low-emission fuels in a circular manner. However, there is a strong trade-off in such a system between the capacity to generate fuel products, and the environmental effectiveness.

6 Land footprint of direct air capture

6.1 Land requirements of direct air capture

A key consideration for the wide-scale deployment of any greenhouse gas removal technology is the amount of land which will be occupied by the process equipment, and the land which will be occupied by infrastructure which supports the operation of the process equipment – *e.g.* infrastructure required for the provision of electricity, heat, and water. In general, direct air capture processes have previously been asserted to have a low land footprint requirement in comparison to other greenhouse gas removal technologies (*e.g.* Afforestation: 270,000 km²/(GtCO₂/yr), Bioenergy with Carbon Capture and Storage: 2,500,000 km²/(GtCO₂/yr)), requiring approximately 7,000 to 100,000 km²/(GtCO₂/yr).⁷⁹ The range depends on several factors, including the type of energy source used, the specific DAC technology employed and the configuration of the capture systems. For instance, a DAC system powered by natural gas generally has a smaller land footprint compared to one that relies entirely on renewable energy, due to the additional land needed for solar PV or wind power generation.⁸⁰ Additionally, the spacing and arrangement of contactors, the scale of deployment and the need for infrastructure such as CO₂ transport and storage can further influence the total land requirement. Further, direct air capture does not require the use of arable land for achieving greenhouse gas removal. While this reduces direct competition with agriculture and may lower biodiversity concerns compared to land-intensive methods like BECCS or afforestation, it is important to note that its deployment can be constrained by other location-specific factors. These include proximity to low-carbon energy, access to CO₂ transport and storage infrastructure and climatic conditions that influence process performance. However, previous assessments of the land requirements of direct air capture processes have not considered the large-scale provision of resources for a real-world deployment. Therefore, the indirect land footprint associated with the provision of key resources has not yet been accurately characterised to understand the requirements of such a deployment.

⁷⁹ **NASEM (2019)**: Negative emission technologies and reliable sequestration: A research agenda, National Academies of Sciences, Engineering, and Medicine; **Smith et al. (2015)**: Biophysical and economic limits to negative CO₂ emissions. *Nature Climate Change* (6).

⁸⁰ **Sendi, M., Bui, M., Mac Dowell, N., Fennell, P. (2024)** Geospatial techno-economic and environmental assessment of direct environmental assessment of different energy options for solid sorbent direct air capture; **NASEM (2019)** Negative emission technologies and reliable sequestration: A research agenda, National Academies of Sciences, Engineering, and Medicine.

6.2 Categories of land footprint for direct air capture

The land footprint of a direct air capture system is comprised of two main contributions. First, the direct land footprint associated with the direct air capture processes themselves. Second, the indirect land footprint associated with infrastructure to provide resources for process operations – particularly the provision of electricity, heat, and water. In this assessment, we consider three categories of land footprint associated with the deployment of a large-scale direct air capture system:

- ▶ **Process equipment (direct):** the land occupied by air contactors and regeneration equipment.
- ▶ **Contactor spacing (direct):** the land occupied by the space between deployed air contactors. It is necessary to space air contactors apart from each other so that the CO₂-lean air outlet from an air contactor is not fed to the input of another air contactor. There needs to be sufficient space between contactors to allow for the CO₂-lean air outlet from an air contactor to re-equilibrate with the CO₂ present in air.
- ▶ **Resource provision (indirect):** the land occupied by infrastructure dedicated to the provision of operational resources/utilities required for direct air capture operation, including: (i) electricity, (ii) heat, and (iii) water.

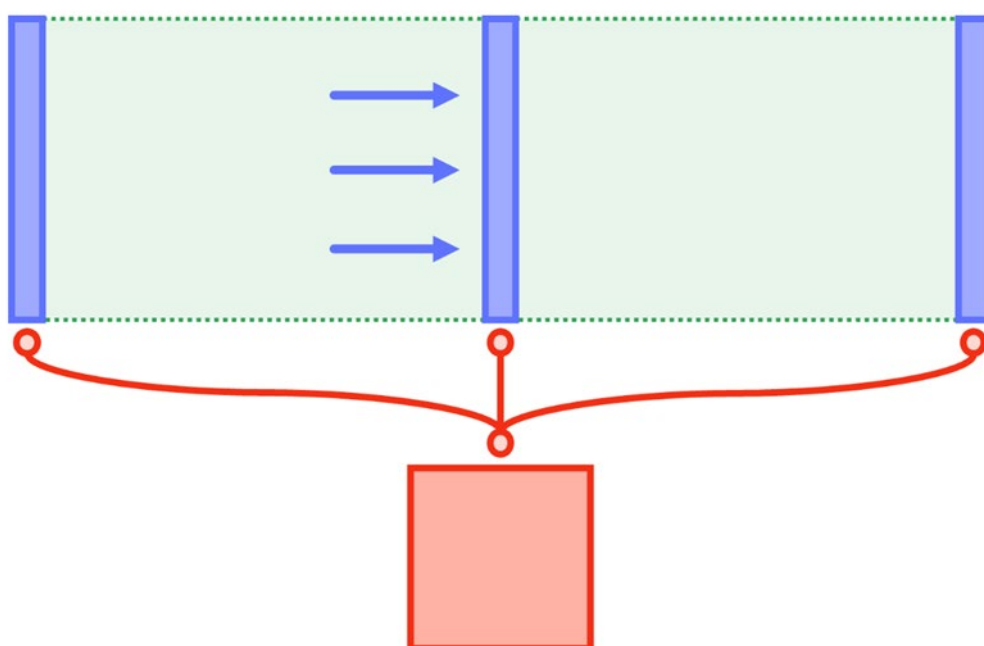


Figure 6.1: Schematic representation of the direct and indirect land footprint of a direct air capture system. **Blue:** direct land footprint of air contactors and regeneration equipment. **Green:** direct land footprint of spacing required between air contactors to allow for mixing with atmospheric air. **Red:** indirect land footprint of operational resource provision, including (i) electricity, (ii) heat, and (iii) water.

6.3 Land footprint model for large-scale direct air capture

We have calculated the land footprint requirements of a large-scale direct air capture system, accounting for: (i) direct land footprint of air contactors and regeneration equipment, (ii) direct land footprint of air contactor spacing, and (iii) indirect land footprint of operational resource provision. We calculate the land footprint using the following model:

$$L(t) = C(t)[F_{\text{DAC}} + E_{\text{total}}(F_{\text{heat}}(t)\theta_{\text{heat}} + F_{\text{elec}}(t)(1 - \theta_{\text{heat}})) + WF_{\text{water}}]$$

where $L(t)$ is the total land footprint of the direct air capture system (m^2) at time t (yr), $C(t)$ is the total deployed capacity of direct air capture (tCO_2/yr), F_{DAC} is the specific land footprint of direct air capture process equipment and contactor spacing (m^2 per tCO_2/yr), $F_{\text{heat}}(t)$ is the specific land footprint of heat supply (m^2/W), $F_{\text{elec}}(t)$ is the specific land footprint of electricity supply (m^2/W), F_{water} is the specific land footprint of water supply (m^2 per $\text{tH}_2\text{O}/\text{yr}$), E_{total} is the total energy usage of direct air capture (J/tCO_2), W is the water usage of direct air capture ($\text{tH}_2\text{O}/\text{tCO}_2$), and θ_{heat} is the fraction of energy input to direct air capture as heat.

All data used as inputs to this model are provided in Appendix 6, including: (i) specific land footprint of direct air capture process equipment and contactor spacing, (ii) energy requirements of direct air capture, (iii) water requirements of direct air capture, (iv) fraction of energy supplied as heat, (v) specific land requirement of technologies for the provision of electricity, heat, and water, and (vi) global-scale pathways for resource provision changes in the period 2020–2050.

6.4 Performance of direct air capture technologies

S-DAC processes have a lower direct land footprint than L-DAC processes associated with air contactors, regeneration equipment, and contactor spacing (L-DAC: 7 km^2 per MtCO_2/yr , S-DAC: 5 km^2 per MtCO_2/yr).⁸¹ However, L-DAC processes have a lower specific energy requirement than S-DAC processes (L-DAC: $5.5\text{--}8.8 \text{ GJ}/\text{tCO}_2$, S-DAC: $7.2\text{--}9.5 \text{ GJ}/\text{tCO}_2$).⁸² Despite this, S-DAC systems can exhibit higher carbon removal efficiency under certain conditions, particularly when cleaner electricity is available or when process co-benefits (e.g., water recovery) are factored in. Therefore, while L-DAC may require less energy per tonne of CO_2 captured, this does not always translate to superior environmental performance. This highlights the importance of considering energy quantity, energy quality (i.e., high/low temperature heat, electricity) and carbon intensity in evaluating land and climate impacts. So, although, we can anticipate that L-DAC processes have a lower indirect land footprint than S-DAC processes, it is not clear whether it is beneficial to have a lower direct land

⁸¹ NASEM (2019): Negative emission technologies and reliable sequestration: A research agenda.

⁸² IEA (2022): Direct air capture: A key technology for net zero.

footprint or indirect land footprint without calculating the total land footprint of the direct air capture system.

We also note that L-DAC processes utilise a greater proportion of their total energy input as heat than S-DAC processes (L-DAC: 80–100%, S-DAC: 75–80%).⁸³ L-DAC processes require an input of water to facilitate process operations (0–50 tH₂O/tCO₂), while S-DAC processes can be a net-producer of water when operating under favourable conditions by capturing moisture from the air as a co-product to the captured carbon dioxide (–2 to 0 tH₂O/tCO₂). The amount of water captured or required varies, depending on the DAC technology, ambient temperature and humidity.⁸⁴ For instance, S-DAC could potentially supply sufficient water for its own use or for other purposes. However, S-DAC faces challenges in humid climates as the system removes more water than CO₂, which can directly affect the techno-economic performance of DAC (i.e., reduces CO₂ productivity and increases the levelized cost of DAC).⁸⁵ Further, it could necessitate more frequent maintenance and hence increase operational costs. In contrast, the dependence of L-DAC poses a challenge on water resources especially in regions where water is scarce.⁸⁵

All the above serves to highlight the complexity in anticipating the indirect land footprint of direct air capture systems in the absence of an explicit calculation. Further, the assessment should seek to integrate realistic resource provision pathways for electricity, heat, and water such that any change in the indirect land footprint throughout the deployment period of direct air capture can account for both: (i) the change in land footprint associated with the expansion of direct air capture capacity, and (ii) the change in land footprint associated with any change to the specific land requirement for the provision of operational resources/utilities (e.g., heat, electricity, cooling).

6.5 Land requirements of operational resource provision

As we have seen above, the land requirements of the processes and equipment used to provide operational resources is a key contribution to the total land footprint of a direct air capture system. The specific land footprint associated with the provision of resources can vary over time, depending on the mix of technologies being utilised at the global-scale for the provision of these resources – with each resource provision technology yielding a distinct land requirement specific to the amount of resource supplied. It is important to note that while the grid electricity involves a mix of technologies, the land footprint attributed specifically to DAC should only include the land required for dedicated energy generation, as grid infrastructure is shared by various users and not exclusively tied to DAC operations.

In terms of electricity provision, the NZE scenario assumes that the use of fossil fuel-based electricity supply is largely phased out over the period 2020–2050. As well as

⁸³ IEA (2022): Direct air capture: A key technology for net zero.

⁸⁴ NASEM (2019): Negative emission technologies and reliable sequestration: A research agenda.

⁸⁵ Sendi, M., Bui, M., Mac Dowell, N. & Fennell, P. (2022) Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment. *One Earth* 5, 1153–1164.

an increase in the total amount of electricity consumption within the considered period, the IEA's NZE scenario expects that wind and solar PV will significantly emerge as the dominant sources of electricity by 2050. In terms of heat supply, most industrial heat is currently provided by the combustion of fossil fuels (coal, oil, and gas). However, in the period 2020–2050 it is projected that there will be a significant shift towards abated fossil fuel combustion (*i.e.* with post-combustion carbon capture and storage), and the wide-scale utilisation of other technologies, including hydrogen, bioenergy, solar thermal, and geothermal heating. Figure 6.2 (top) shows the projected global resource provision mix in the International Energy Agency Net Zero Emissions by 2050 scenario (NZE) for the provision of electricity and heat.⁸⁶ The trend seen is primarily driven by the increasing reliance on renewable and low-carbon technologies, which generally have higher land requirements than fossil-based systems.

As mentioned, the NZE scenario assumes that fossil fuel-based electricity supply will largely be phased out by 2050. In this scenario, developing nations are expected to follow a similar trajectory despite their current reliance on coal and natural gas.⁸⁷ However, it is important to note that the expectation that developing nations will completely phase out coal and other fossil fuels by 2050 can be seen as unrealistic, given their current heavy reliance on these energy sources and the socio-economic challenges involved in transitioning to low-carbon alternatives.⁸⁸ Additionally, the NZE scenario assumes a rapid and large-scale deployment of decarbonisation technologies. Thus, the projections are based on ideal assumptions about the achievable pace and scale of global decarbonisation. However, these idealised deployment rates may not fully reflect the complexities of real-world energy transitions, which may be subject to challenges such as supply chain and regulatory bottlenecks, as well as financial or policy-related barriers. The scenario assumptions represent a source uncertainty in the results of this work.

Figure 6.2 (bottom) shows a projection of the specific land footprint of electricity and heat provision in the period 2020–2050 by integrating these resource supply pathways with the specific land footprint of each resource provision technology.⁸⁹ The overall specific land requirement of electricity supply increases significantly from 0.054 m²/W in 2020 to 0.096 m²/W in 2050 (+77%). This increase is primarily driven by the wide-scale expansion of wind power for electricity provision, which has a high specific land requirement (0.345 m²/W). However, it is important to note that the

⁸⁶ IEA (2023): World Energy Outlook 2023.

⁸⁷ IEA (2023): World Energy Outlook 2023.

⁸⁸ Patrizio, P., Pratama, Y. W. & Mac Dowell, N. (2020) Socially equitable energy system transitions. *Joule* 4, 1700-1713. Patrizio, P. et al. (2018) Reducing US coal emissions can boost employment. *Joule* 2, 2633-2648.

⁸⁹ Denholm & Margolis (2008): "Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States". *Energy Policy* (9); NREL (2009): "Land-use requirements of modern wind power plants in the United States"; Tester et al. (2021): "The evolving role of geothermal energy for decarbonizing the United States". *Energy & Environmental Science* (14); Schneider et al. (2013): "Measures of the environmental footprint of the front-end nuclear fuel cycle". *Energy Economics* (40); Wu et al. (2021): "Unveiling land footprint of solar power: A pilot solar tower project in China". *Journal of Environmental Management* (280); Jordaan et al. (2017): "Understanding the life cycle surface land requirements of natural gas-fired electricity". *Nature Energy* (2).

land footprint for electricity is highly dependent on the energy type. For example, solar PV requires $0.0154 \text{ m}^2/\text{W}$, nuclear requires $0.00027 \text{ m}^2/\text{W}$ and natural gas requires $0.0178 \text{ m}^2/\text{W}$. The specific land footprint requirement of heat supply increases less significantly in the considered period, from $0.034 \text{ m}^2/\text{W}$ in 2020 to $0.048 \text{ m}^2/\text{W}$ in 2050 (+40%). Therefore, we can understand that while resource provision changes in terms of electricity and heat supply will act to significantly reduce the carbon emissions associated with the provision of these resources, that the land footprint requirement is increased as a consequence. Generally, care should be taken as to not double count land footprints in cases where both electricity and heat are provided by a single power generation plant, e.g., combined heat and power (CHP) plants.

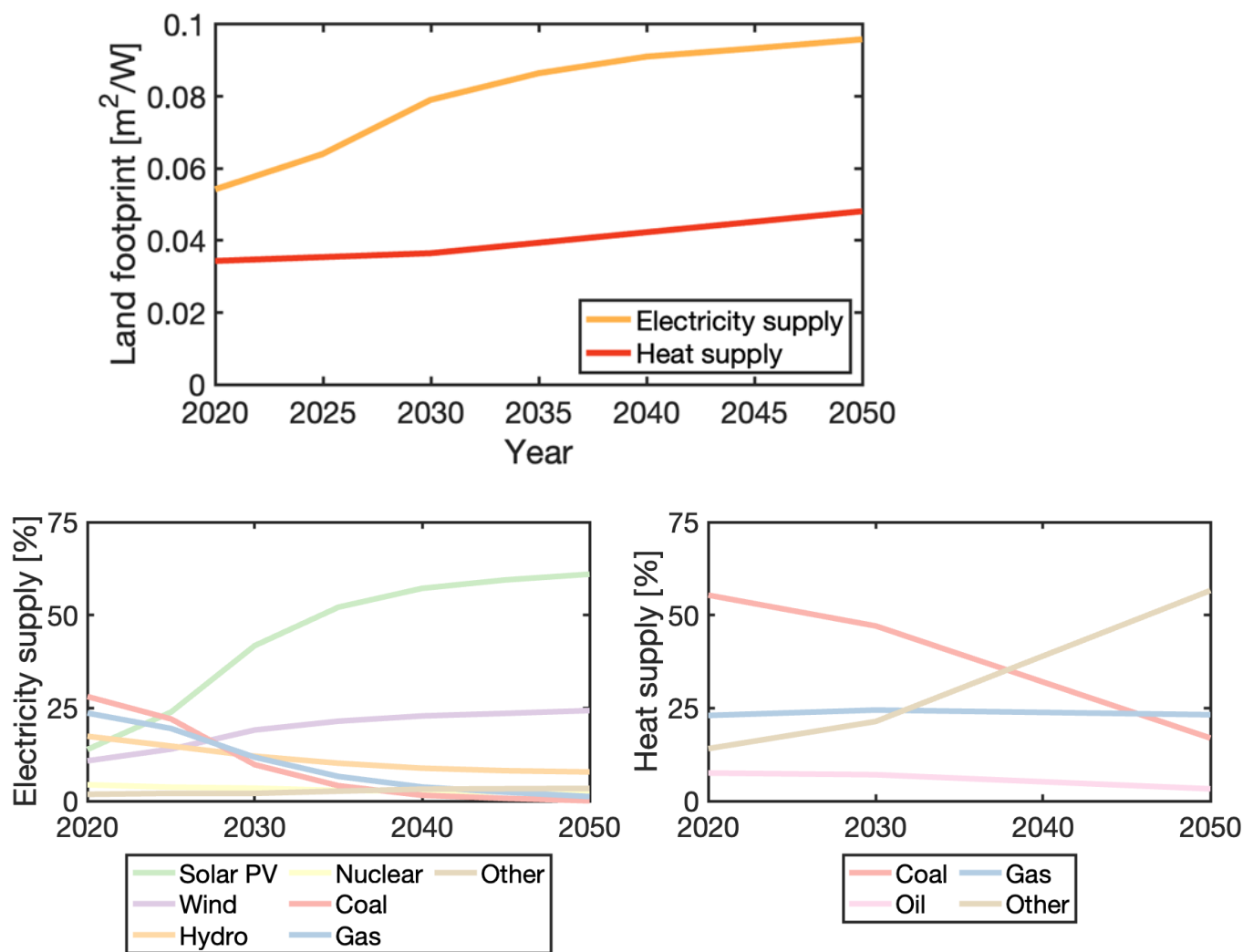


Figure 6.2 (Top): Projected specific land footprint requirements of electricity and heat supply in the period 2020–2050 according to the global technology mix in the International Energy Agency Net Zero Emissions by 2050 (NZE) scenario. **(Bottom):** Pathways for the global provision of electricity and heat in the period 2020 – 2050, as projected in the International Energy Agency Net Zero Emissions by 2050 (NZE) scenario. Electricity is provided by solar PV, wind, hydroelectric (hydro), nuclear, coal, gas, and other technologies (other renewables and battery storage). Heat is provided by coal, oil, gas, and other technologies (hydrogen combustion, bioenergy, solar thermal, and geothermal heating).

6.6 Land footprint of global-scale direct air capture

We calculate the land footprint requirements of a global-scale deployment of direct air capture. In the following, we consider the base-case deployment scenario outlined in Chapter 4 as a basis. Here, global direct air capture capacity is scaled from 1 MtCO₂/yr in 2020 to 1 GtCO₂/yr by mid-century according to logistic growth with a growth rate of $r = 0.26 \text{ yr}^{-1}$.

There are several sources of uncertainty in the calculation of the land footprint requirements of direct air capture, including: (i) the total amount of energy usage, (ii) the proportion of energy supplied as heat, and (iii) the amount of water usage. To acknowledge this uncertainty, we compare land footprint requirements across different scenarios by considering both a best-case and a worst-case scenario. It is important to note that minimising land requirement does not necessarily correspond to ‘best case scenario’. For instance, using energy sources with lower land footprints such as combined cycle gas turbine (CCGT) or nuclear power, might reduce the land requirement but could be less desirable from a sustainability and public acceptance perspective. Therefore, the land footprint requirements are reported as a range to reflect trade-offs and varying priorities in energy source selection for DAC projects. The minimum land usage scenario assumes:

- ▶ **Minimum amount of energy usage per tonne of carbon dioxide captured.**
Using a smaller amount of energy results in a lower indirect land footprint associated with the provision of energy.
- ▶ **Maximum proportion of energy supplied as heat.** Heat provision always has a lower land footprint than electricity provision in the resource provision pathway. This is because heat is often delivered via fossil fuels, which require less land compared to renewable energy sources. Therefore, utilising a maximum amount of the required energy as heat minimises the indirect land footprint associated with the provision of heat, but may increase fossil fuel use.
- ▶ **Minimum amount of water usage per tonne of carbon dioxide captured.**
Using a smaller amount of water results in a lower indirect land footprint associated with the provision of water.

In the maximum land usage scenario, we assume the converse case with maximum energy usage, minimum proportion of energy supplied as heat, and maximum water usage. While the scenarios presented here represent fixed assumptions on energy and water usage, it is important to acknowledge that ongoing technological advancements may lead to reductions in energy intensity, improved sorbent performance, faster cycle times, or innovations in modular renewable energy technologies. Such improvements could significantly reduce both the direct and indirect land footprint of DAC systems. However, these potential improvements are subject to uncertainty and have not been explicitly modelled in this analysis. As such,

the land footprint estimates should be interpreted as indicative values based on current performance characteristics rather than fixed projections.

In Figure 6.3 we show the outcome of this calculation. For the 1 GtCO₂/yr system deployed by the year 2050, we estimate that the total land footprint requirement is 10,900–16,600 km²/(GtCO₂/yr) for L-DAC processes and 12,900–16,400 km²/(GtCO₂/yr) for S-DAC processes. These estimates are consistent with the range of previous work on direct air capture, where DAC systems powered entirely by solar energy required 80,000–100,000 km² per 1 GtCO₂ removed per year. Considering an energy mix with 25% solar power reduced the requirement to approximately 21,600 km²/(GtCO₂/year), whereas systems relying solely on natural gas required significantly less land, around 7000 km²/(GtCO₂/year).⁹⁰

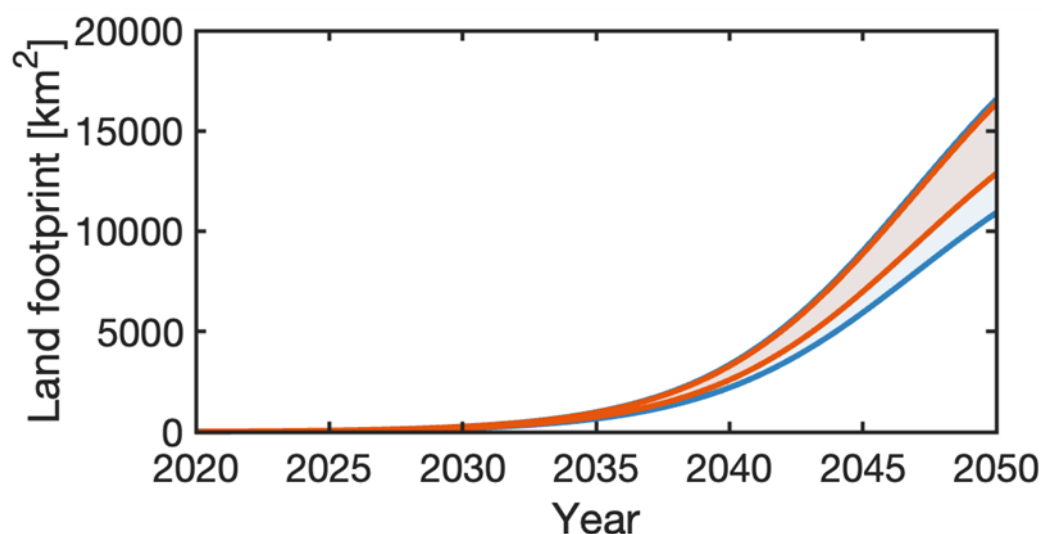


Figure 6.3: Projected land footprint requirements for a global-scale deployment of a 1 GtCO₂/yr direct air capture system in the period 2020–2050. Blue lines correspond to the land footprint requirement of an L-DAC system. Orange lines correspond to the land footprint requirement of an S-DAC system. Shaded regions correspond to uncertainty arising from resource provision scenarios.

Our estimates are within a range that seems to reflect a diverse global energy technology mix that incorporates a variety of energy sources, unlike earlier studies that assessed one specific type of energy source in isolation. Notably, the calculated land footprint represents a significantly smaller requirement than that for equivalent amounts of other carbon removal approaches. For an equivalent CO₂ removal capacity, the DAC energy system (including energy supply) only requires 4–6 % of the land required by afforestation, or 0.4–0.7% of the land used by bioenergy with carbon capture and storage (BECCS). These percentages were derived based on a comparison of land footprints from a previous study,⁹⁰ where the land area for DAC was compared to the land needed for afforestation and BECCS to remove 1 GtCO₂ per year. Therefore, we contend that direct air capture represents an option with excellent efficiency in terms of land footprint compared to other greenhouse gas removal pathways – particularly noting that there is no requirement for arable land. The land footprint of coupling DAC with renewable energy sources can also vary

⁹⁰ NASEM (2019): “Negative emission technologies and reliable sequestration: A research agenda”.

between the different types of renewables (e.g., concentrated solar power, wind turbines, or solar PV), and also combining renewables with energy storage to provide high-capacity factors can also significantly influence the land footprint of the DAC system⁹¹.

We can see that the total land footprint requirement of the system increases throughout the considered period. This increase is attributed to two factors: (i) the deployed capacity of direct air capture increases throughout the period, and (ii) the specific land requirement associated with the provision of electricity and heat increases throughout the period, especially as the energy system decarbonises. Therefore, as time goes by, the land requirement for a given amount of direct air capture deployment may increase, particularly when relying more on renewable energy sources, which generally have a larger land footprint when compared to fossil fuels.

In Figure 6.4 we show a breakdown of the land footprint requirements of the 1 GtCO₂/yr L-DAC and S-DAC systems in the year 2050 in terms of the land required for process equipment, contactor spacing, and resource provision in both the best-case (minimum land use) and worst-case (maximum land use) scenarios. We can see that the direct land footprint requirement of process equipment (air contactors and regeneration equipment) is very small in comparison to the overall system land footprint (L-DAC: 0.01–0.15%, S-DAC: 1.08–1.37%). The requirements for contactor spacing and the indirect land requirements of resource provision are much larger. L-DAC processes require 29.9–45.4% of total land footprint for contactor spacing, and 54.5–70.0% of total land footprint for resource provision. S-DAC processes require 20.6–26.2% of total land footprint for contactor spacing, and 72.4–78.3% of total land footprint for resource provision. This difference in spacing arises from the distinct air flow dynamics and design configurations of L-DAC and S-DAC systems. For instance, L-DAC systems typically use large, fan-driven contactor units that require wider spacing to avoid re-ingestion of CO₂-depleted air, whereas many S-DAC systems use passive or modular designs with smaller units that can be spaced more tightly without compromising performance.

The higher land requirement for resource provision is based on an energy land intensity factor, which varies depending on the type of energy source used. L-DAC processes can achieve a lower overall land footprint than S-DAC processes in the best-case scenario, but the land footprint is similar for the worst-case scenario. This difference is largely due to the type of energy required for each process. L-DAC processes can be mostly powered by low temperature heat energy (80–100% of total energy input), and if provided by fossil fuels, requires a relatively small land footprint. In contrast, electricity provision, particularly when sourced from renewable energy, tends to require much more land.

⁹¹ Sendi, M., Bui, M., Mac Dowell, N., Fennell, P. (2024) Geospatial techno-economic and environmental assessment of direct environmental assessment of different energy options for solid sorbent direct air capture. *Cell Reports Sustainability* 1, 100151.

<https://doi.org/10.1016/j.crsus.2024.100151>

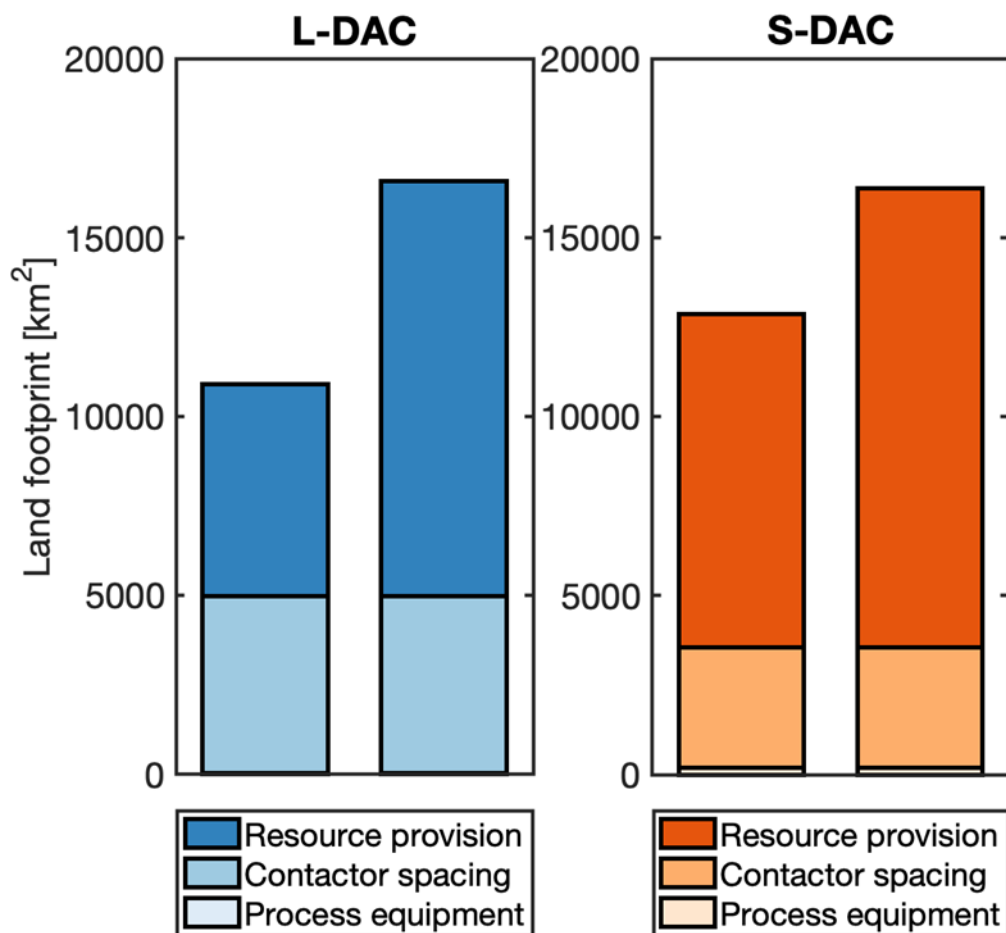


Figure 6.4: Breakdown of land footprint requirements for a global-scale direct air capture system, with capture capacity of 1 GtCO₂/yr, in terms of (i) the direct land footprint of process equipment, (ii) the direct land footprint of air contactor spacing, and (iii) the indirect land footprint associated with the provision of resources (electricity, heat, and water). Left bars correspond to the best-case scenario in terms of resource provision uncertainty. Right bars correspond to the worst-case scenario in terms of resource provision uncertainty.

It is important to note that the land footprint associated with resource provision is not simply a function of whether heat or electricity is used, but rather the type of energy source that provides this energy. In our worst-case scenario, we assume maximum energy usage, where there was also a minimum proportion of energy supplied as heat and maximum water usage. This scenario is linked to the assumption that electricity is provided by renewable energy sources, which generally have a higher land requirement compared to fossil fuels. On the other hand, fossil-fuel based energy, which has a lower land requirement, can reduce the overall land footprint when used to provide heat.

Considering the distinctions between the types of energy sources and their respective land requirements, we can see that L-DAC processes can achieve lower land requirements when compared to S-DAC processes. This is due to L-DAC relying more on heat which can be provided by fossil fuels, and in turn lower the land footprint. In contrast, S-DAC relies more on electricity, which has a higher land footprint, especially when the electricity is being sourced from renewables.

Finally, we note that a proposed approach for reducing the land footprint requirements of direct air capture systems is to use the inter-contactor spacing as land for other purposes, as suggested by Sendi et al. (2024)⁹², such as siting infrastructure for the provision of resources. Applying this strategy to the cases presented above (shown in Figure 6.4) would result in a reduction of the total land footprint requirement of 30–45% for L-DAC processes, and 21–26% for S-DAC processes. Such a strategy would only be applicable in practice if the proposed infrastructure to be placed in the inter-contactor spacing can be sufficiently low-lying as to not disrupt the re-equilibration of CO₂-lean air from contactor outlets with atmospheric air. It is currently not clear if this would be possible in practice, and further practical research is needed to determine the feasibility of this strategy.

This analysis shows the importance of considering the type of energy source in evaluating the land footprint of DAC systems. This suggests that future efforts to optimise DAC systems should evaluate and consider the trade-offs between energy source, land use and overall system efficiency.

6.7 Land footprint requirements in regional contexts

The analysis outlined above estimates that the land footprint requirement of large-scale direct air capture is approximately 10.9–16.6 km²/(MtCO₂/yr) for L-DAC processes and 12.9–16.4 km²/(MtCO₂/yr) for S-DAC processes. We now aim towards understanding what this land footprint requirement means in practice within the context of national and international published targets for the large-scale deployment of direct air capture as a pillar of decarbonisation strategies.

The International Energy Agency's Net Zero Emissions by 2050 (NZE) scenario estimates that approximately 1 GtCO₂/yr of direct air capture capacity is required by 2050. This corresponds to 10,900–16,400 km² of land requirement globally (L-DAC: 10,900–16,600 km², S-DAC: 12,900–16,400 km²), or 0.0084–0.013% of total global land. For reference, capturing 1 GtCO₂/yr using bioenergy with carbon capture and storage (BECCS) would require approximately 1.9% of total global land, a significant proportion of which would be arable land.⁹³ This highlights the role of direct air capture as a pathway towards carbon removal with a significantly low land footprint, as compared to other carbon removal pathways.

As a national case study of land footprint requirements for carbon removal by direct air capture, we consider the United Kingdom. The United Kingdom Climate Change Committee's (CCC) balanced pathway estimates that the United Kingdom requires

⁹² Sendi, M., Bui, M., Mac Dowell, N., Fennell, P. (2024) Geospatial techno-economic and environmental assessment of direct air capture. Cell Reports Sustainability 1, 100151. <https://doi.org/10.1016/j.crsus.2024.100151>

⁹³ NASEM (2019) Negative Emissions Technologies and Reliable Sequestration: A research agenda. <https://doi.org/10.17226/25259>

approximately 5 MtCO₂/yr of direct air capture capacity by 2050.⁹⁴ This corresponds to 55–82 km² of land requirement (L-DAC: 55–83 km², S-DAC: 65–82 km²), or 0.023–0.034% of total UK land area. This land footprint requirement is represented on a map of the United Kingdom in Figure 6.5. For reference, capturing 5 MtCO₂/yr using BECCS would require approximately 5.1% of total UK land area. While a range of other durable CDR options are under development, BECCS is used here as a comparator, given its prominent role in UK decarbonisation plans⁹⁴ and the relatively mature state of analysis regarding its land use implications. As such, it provides a meaningful benchmark for understanding the scale of land footprint for DAC in national contexts. The CCC balanced pathway indicates that the UK requires a total of 58 MtCO₂/yr carbon removal capacity. If this entire capacity were to be supplied by direct air capture, such a system would require 0.26–0.40% of total UK land area. If this entire capacity were to be supplied by BECCS, such a system would require 59.5% of total UK land area⁹⁵. This deployment of BECCS would certainly rely on international imports of biomass to satisfy the input requirements, given the infeasibly large total land footprint requirement as a proportion of total UK land area. For instance, Drax, a biomass power station in the UK, is predominantly sourcing biomass from the United States and Canada.⁹⁶ The company plans to integrate CCS to transition into a full-scale BECCS facility, further emphasising the reliance on international biomass supply chains. A large-scale direct air capture system could therefore enable national independence in achieving sufficient levels of carbon removal, which is a notable co-benefit of such a system. This highlights the key role that direct air capture systems can play in national contexts with low land area availability relative to the amount of carbon removal required in decarbonisation pathways.

The UK's national ambition of 5 MtCO₂/yr for carbon removal by direct air capture results in a relatively modest total land footprint requirement. However, the required land footprint is large enough that it would be necessary to establish a distributed system where direct air capture capacity is constructed wherever suitable land is available. In the context of the UK's geography, this would be particularly challenging as the planned carbon dioxide transport and storage infrastructure is concentrated at the coastline⁹⁷ – where there is limited availability of suitable land. This kind of distributed system would therefore require a complex national network of resource provision and carbon dioxide transport and storage infrastructure. Therefore, if large-scale direct air capture capacity is to be established, it is necessary to start planning for such a national network at an early stage to ensure that: (i) sufficient amounts of land are reserved and available, and (ii) the necessary supporting infrastructure for

⁹⁴ **Climate Change Committee (2025)** [The Seventh Carbon Budget](#), United Kingdom.

⁹⁵ This land requirement for BECCS was calculated using data from NASEM (2019), where references estimated that capturing 12 GtCO₂/yr using BECCS would be approximately 380-700 million hectares of land. The range depends on various factors such as biomass productivity and whether afforestation is also a part of the carbon removal strategy.

⁹⁶ **Drax Group plc (2023)** Drax ESG Performance Report 2023. <https://www.drax.com/wp-content/uploads/2024/03/Final-Signed-ESG-2023-Supplement.pdf>

⁹⁷ **UK Research and Innovation (2023)** Enabling Net Zero: A Plan for UK Industrial Cluster Decarbonisation. https://www.ukri.org/wp-content/uploads/2023/09/IUK-131023-UKRI_EnablingNetZero.pdf

the provision of resources and the transport/storage of carbon dioxide is planned for so that it is available in the correct locations and at the correct time as the system scales. By nature, this is a highly complex deployment problem requiring the integration of multiple synergistic systems. Successfully achieving this deployment will require sustained, long-term, national-scale planning, and certainly should not be neglected.

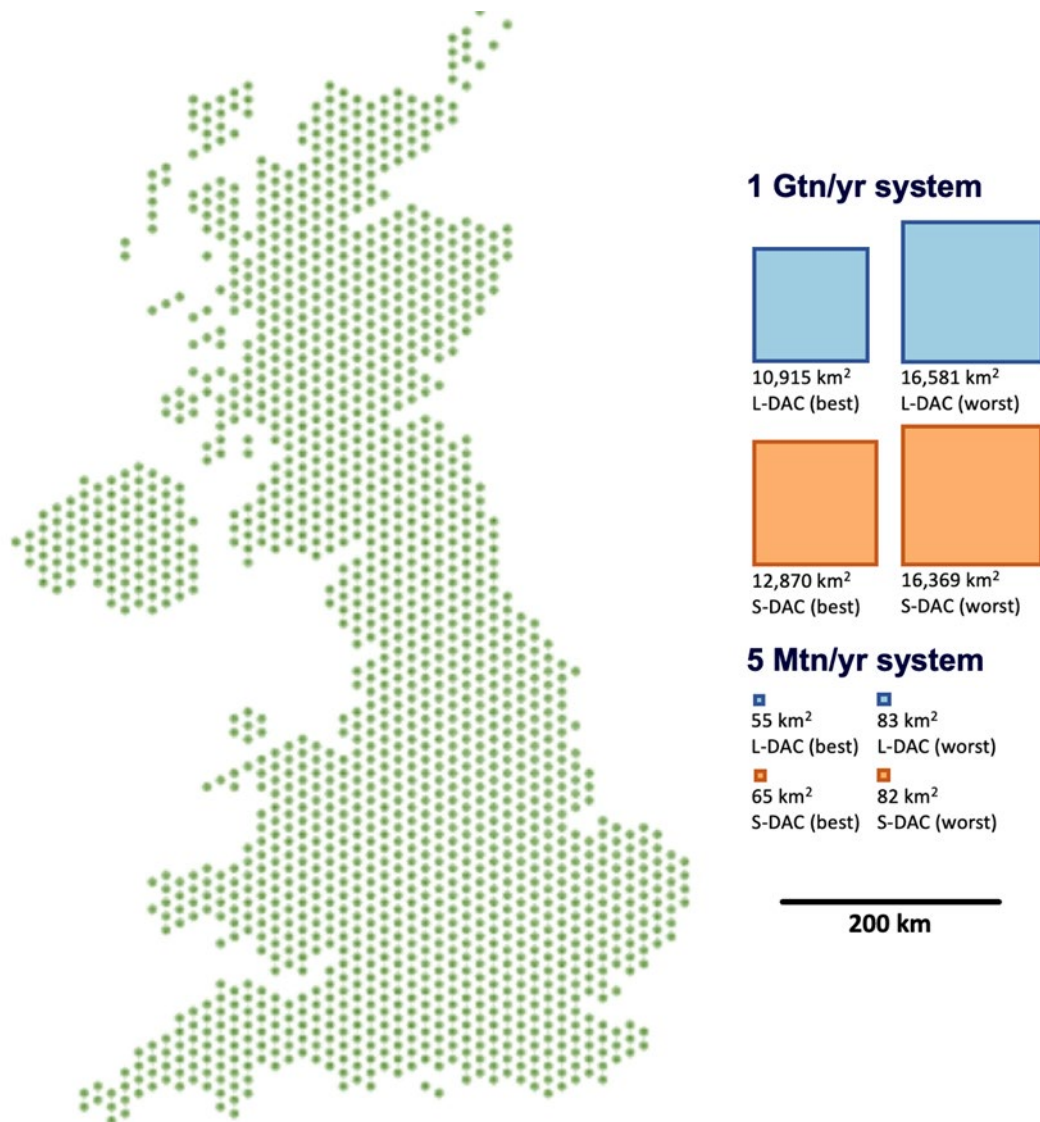


Figure 6.5: Land footprint requirements of 1 GtCO₂/yr (global-scale ambition) and 5 MtCO₂/yr (UK national ambition) direct air capture systems to scale with the United Kingdom.

Finally, a proposed research priority for direct air capture which has been established recently is the co-location and integration of direct air capture processes within the existing energy systems at industrial clusters. However, large-scale deployment of DAC systems presents challenges that could make this co-location strategy less feasible. For instance, while the land footprint of DAC is smaller than what would be needed for biomass-based CDR technologies such as BECCS, DAC systems will still have substantial land requirements. Furthermore, the energy requirements for DAC from sustainable energy sources such as wind or solar are often decentralised and

spread out across large geographic areas. This means that DAC facilities might need to be located closer to these renewable energy sources rather than concentrated near industrial clusters. Lastly, the logistics of CO₂ transport and storage is also a key siting factor. Industrial clusters typically have well established infrastructure, including pipelines and storage facilities which could be adapted to accommodate large-scale CCS. Given these key considerations, large-scale direct air capture deployment requires a dedicated and whole-systems approach to energy system planning and integration.

6.8 Conclusions and key recommendations

- ▶ The land footprint requirements of direct air capture systems are affected by the direct land footprint of the direct air capture plant itself, and the indirect land footprint required to site supporting infrastructure for the provision of electricity, heat, and water.
- ▶ Among available pathways for achieving greenhouse gas removal, direct air capture has a low total land footprint. Large-scale direct air capture systems have a total land footprint requirement of 10.9–16.6 km²/(MtCO₂/yr). The land footprint requirement is highly sensitive to the direct air capture technology selection, and to the energy requirements for the operation of direct air capture.
- ▶ The reduction of energy usage of direct air capture technologies can be used as a strong engineering factor for improving the overall performance of a direct air capture system. The use of energy with lower carbon intensity can enable lower value chain emissions and leads to improved environmental effectiveness. Low energy usage is the strongest available factor for reducing the land footprint requirements of direct air capture systems.
- ▶ Whole-systems planning of wide-scale direct air capture deployment is needed to ensure the availability of land, low-carbon energy provision, and carbon dioxide transport and storage infrastructure are in the correct locations and times.
- ▶ Shared use of land for air contactor spacing with infrastructure for resource provision can reduce the land footprint requirements of direct air capture by 21–45%. Further practical research efforts are required to establish if this approach is feasible.

7 Techno-economics of direct air capture

7.1 Scales of techno-economics

When assessing the techno-economics of greenhouse gas removal pathways, it is important to consider the economic performance of the available technologies at two key scales:

- ▶ **Process scale:** assessment of the capital and operating costs of an individual direct air capture process (i.e., at site level) using current state-of-the-art technology.
- ▶ **System scale:** assessment of the total system cost associated with large-scale deployment of direct air capture for CO₂ removal.

When deploying direct air capture at large scales, technology learning will inevitably take place and act to reduce capital costs of direct air capture processes deployed throughout the deployment period. There are the system scale marginal costs, where the cost dynamics of the system change over time given the established system which is in place. For example, marginal costs in an established system are substantially lower than in an emerging system, because barriers to investment have already been overcome. These effects can lead to substantial differences in the assessment of techno-economics of direct air capture at each scale. For this reason, it is important to understand the techno-economic performance of direct air capture processes at both scales.

7.2 Process-scale techno-economics of direct air capture

We have reviewed available studies from academic literature which have provided techno-economic assessments of both L-DAC and S-DAC processes. We have identified 9 studies reporting techno-economic assessment for L-DAC processes,⁹⁸

⁹⁸ **Fasihi et al. (2019)**: “Techno-economic assessment of CO₂ direct air capture plants”. *Journal of Cleaner Production* (224); **Keith et al. (2018)**: “A process for capturing CO₂ from the atmosphere”. *Joule* (2); **Kiani et al. (2020)**: “Techno-economic assessment of CO₂ capture from air using conventional liquid-based absorption process”. *Frontiers in Energy Research* (8); **McQueen et al. (2021)**: “A review of direct air capture (DAC): Scaling up commercial technologies and innovating for the future”. *Progress in Energy* (3); **NASEM (2019)**: “Negative emissions technologies and reliable sequestration: A research agenda”; **Zeman et al. (2014)**: “Reducing the cost of Ca-based direct air capture of CO₂”. *Environmental Science & Technology* (48); **Mazzotti et al. (2013)**: “Direct air capture

and 4 studies reporting techno-economic assessment for S-DAC processes.⁹⁹ Note that we only include studies in this review of the literature which report sufficient detail to individually attribute both capital and operating costs of direct air capture on the basis of the cost to capture a single tonne of carbon dioxide.

In Figure 7.1, we present the capital costs (CAPEX) and operating costs (OPEX) of L-DAC and S-DAC processes based on techno-economic assessments available in the literature. The techno-economic dataset represented in Figure 7.1 is tabulated in Appendix 7. The reported studies generally show that the capital costs of L-DAC processes are lower than the capital costs of S-DAC processes. This finding is in agreement with the findings in previous Chapters which asserts that L-DAC processes achieve a higher system productivity than S-DAC processes. A higher productivity implies lower capital costs, because less process equipment volume is required to achieve an equivalent carbon dioxide capture rate.

We can see that both L-DAC and S-DAC processes attribute a higher proportion of the overall cost towards capital costs over operating costs. Already, we can understand that this has implications for system scale techno-economic performance of a direct air capture system. At early times in deployment, when the expansion of the technology is fast in the system, the capital investment will be high. This means that significant early upfront investment will be required before benefits are manifested through long-term operation of the system. However, once the system is established, the cost of operating the system will be relatively low. Therefore, while the total capture cost of an individual DAC plant appears to be large, the marginal cost of operating the system at long time scales has the potential to be substantially lower.

The reported literature studies show that the operating costs of L-DAC processes are generally higher than that of S-DAC processes. L-DAC processes have a lower specific energy requirement for operation than S-DAC processes. However, the energy which needs to be provided for the operation of L-DAC processes is almost entirely high temperature heat (i.e., 300–900°C). Whereas, for S-DAC processes, energy provided for operations is a mixture of electricity and low temperature heating (i.e., 80–100°C). Therefore, while L-DAC processes require a smaller amount of energy, the energy carrier which is required for operations comes at a higher cost. The available data demonstrates that the balance of these effects is that the operating costs of L-DAC processes are greater than the operating costs of S-DAC processes.

of CO₂ with chemicals: Optimization of a two-loop hydroxide system using a counter current air-liquid contactor". *Climate Change* (118); **American Physical Society (2018)**: "Direct air capture of CO₂ with chemicals"; **Daniel et al. (2022)**: "Techno-economic analysis of direct air carbon capture with CO₂ utilisation". *Carbon Capture Science & Technology* (2); **Ozkan et al. (2022)**: "Current status and pillars of direct air capture technologies". *iScience* (25).

⁹⁹ **Fasihi et al. (2019)**: "Techno-economic assessment of CO₂ direct air capture plants". *Journal of Cleaner Production* (224); **McQueen et al. (2021)**: "A review of direct air capture (DAC): Scaling up commercial technologies and innovating for the future". *Progress in Energy* (3); **NASEM (2019)**: "Negative emissions technologies and reliable sequestration: A research agenda"; **Ozkan et al. (2022)**: "Current status and pillars of direct air capture technologies". *iScience* (25).

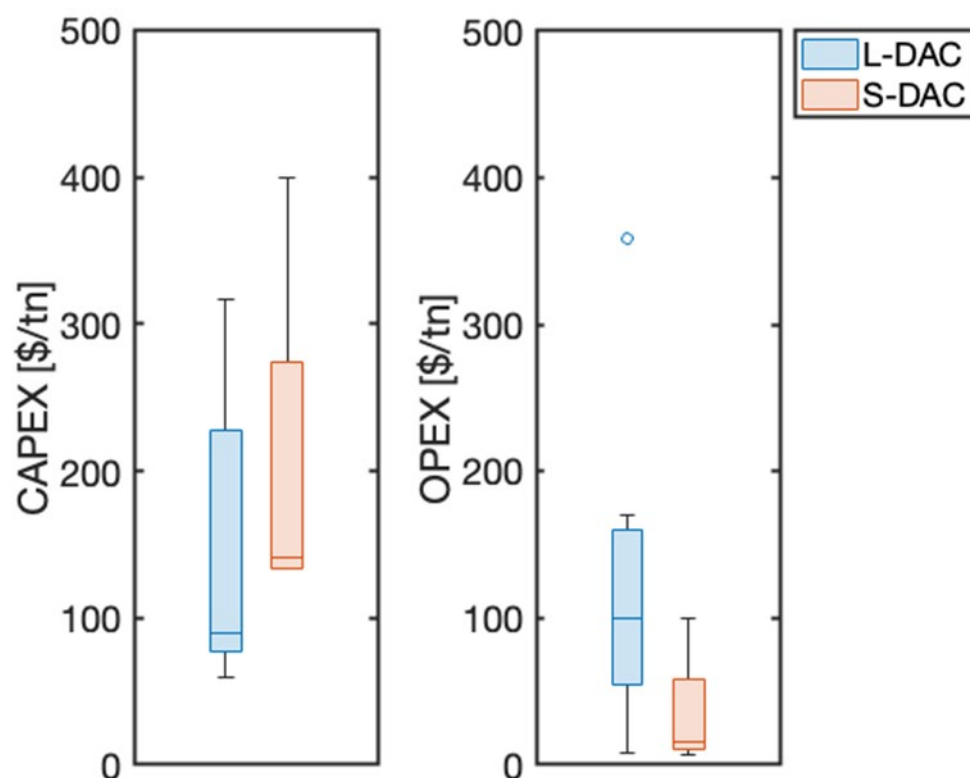


Figure 7.1: Capital costs (CAPEX) and operating costs (OPEX) in units of \$/t CO₂ capture for L-DAC and S-DAC processes based on techno-economic analysis studies presented in the academic literature. Source of data.^{98, 99} The boxplots represent the distribution of reported values: the central line shows the median. Note that outliers beyond 1.5x the interquartile range are excluded from the box plots.

7.3 Operating costs of direct air capture processes

We note that the operating costs reported in several of the literature studies for direct air capture processes are very low (L-DAC: 7–359 \$/tCO₂, S-DAC: 6–100 \$/tCO₂). It has been shown in previous studies that the minimum thermodynamic work associated with the separation of carbon dioxide from atmospheric air is 0.468 GJ/tCO₂ (corresponding to 75% recovery, at a product purity of 95%).¹⁰⁰

Assuming a historically typical energy cost of 0.06 \$/kWh,¹⁰¹ and a thermodynamic efficiency of 100%, the minimum energy cost of direct air capture is approximately 7.8 \$/tCO₂. However, it must be noted that this represents a best-case scenario and is not practically achievable. Therefore, this figure represents an absolute lower bound on the cost of the provision of energy to operate a direct air capture process. Despite this, studies in the literature have reported operating costs below/around this value. We contend that *such an estimate is not realistic*, particularly considering

¹⁰⁰ Herzog (2022): Greenhouse gas removal technologies: Chapter 6 – direct air capture. <https://doi.org/10.1039/9781839165245-00115>

¹⁰¹ Huisman & Killiç (2013): A history of European electricity day-ahead prices. Applied Economics (45).

that the figure provided above does not account for the costs of other operational expenses (*e.g.* water provision, sorbent costs, *etc.*).

We can calculate an approximate operational cost of energy provision corresponding to the performance of state-of-the-art direct air capture technologies using the concept of equivalent work. The equivalent work is an approach for calculating the amount of electrical work which is equivalent to the provision of a given amount of heat and electricity to a process. Currently available technologies achieve a total energy usage of 5.5–9.5 GJ/tCO₂ (L-DAC: 5.5–8.8 GJ/tCO₂, S-DAC: 7.2–9.5 GJ/tCO₂).¹⁰² For L-DAC processes, 80–100% of this energy is supplied as high-temperature heat (*ca.* 900°C). For S-DAC processes, 75–80% of the energy is supplied as low-temperature heat (*ca.* 100°C). The operational cost of energy provision for current direct air capture technology can then be estimated as:

$$C_E = C_{\text{elec}} \times W_{\text{EQ}}$$

where C_E is the operational cost of energy provision (\$/tCO₂), C_{elec} is the unit cost of electricity (\$/kWh), and W_{EQ} is the equivalent work of the direct air capture process (kWh/tCO₂). The equivalent work of a direct air capture process is calculated as:¹⁰³

$$W_{\text{EQ}} = (1 - \theta_{\text{heat}})E_{\text{tot}} + \eta_{\text{turb}} \left(1 - \frac{T_L}{T_H}\right) \theta_{\text{heat}} E_{\text{tot}}$$

where E_{tot} is the total energy usage of a direct air capture process (kWh/tCO₂), θ_{heat} is the proportion of total energy supplied as heat, T_L is the ambient temperature (K), T_H is the temperature at which heat is supplied to the direct air capture process (K), and η_{turb} is the thermodynamic efficiency of a hypothetical turbine which interconverts between thermal and electrical work. Here, in accordance with previous studies, we assume a turbine efficiency of $\eta_{\text{turb}} = 0.75$.¹⁰⁴

Using this approach and acknowledging uncertainty present in the performance of direct air capture processes with respect to the amount of energy used and the proportion of energy supplied as heat, we can estimate the operational cost of supplying energy for current direct air capture technologies. **We estimate that the operational cost of providing energy is approximately 43–97 \$/tCO₂ (L-DAC: 53–97 \$/tCO₂, S-DAC: 43–63 \$/tCO₂).** We can see that the operational cost of energy provision is indeed lower for S-DAC processes than for L-DAC processes, which is in agreement with the literature studies. However, the outcome of this exercise confirms that reported estimates for the operating costs of direct air capture processes in the available literature are often too optimistic. We note that this estimate does not include other contributions to the operating cost of direct air capture, such as those of water provision and sorbent production. While these are generally less significant than energy costs, particularly at current performance levels, they may become more relevant depending on regional siting conditions,

¹⁰² IEA (2022): Direct air capture: A key technology for net zero.

¹⁰³ Young et al. (2021): The impact of binary water-CO₂ isotherm models on the optimal performance of sorbent-based direct air capture processes. *Energy & Environmental Science* (14).

¹⁰⁴ Danaci et al. (2021): Guidelines for techno-economic analysis of adsorption processes. *Frontiers in Chemical Engineering* (2).

sorbent longevity, and future system configurations. However, we assert that by assuming modest energy efficiency improvements in direct air capture technology that the figures presented here represent a reasonable estimate of the operating costs of current direct air capture technologies once these additional operating expenses are accounted for.

7.4 Uncertainty in process scale techno-economics

It is clear that the capital and operating costs presented in Figure 7.1 demonstrate that there is significant uncertainty regarding the techno-economic performance of direct air capture processes. The methodologies applied in the available studies are often inconsistent with one another in terms of several key assumptions:

- ▶ **Energy sources:** the technology portfolio which is selected for the provision of energy (electricity and heat), and the cost factors which are attributed to energy provision.
- ▶ **Contactor sizing:** the throughput basis used to determine the technical performance of the direct air capture process. This choice impacts the techno-economic performance through the effect of economies of scale.
- ▶ **Mass transfer performance:** the assumed rates of sorption and desorption of carbon dioxide from the sorbent within the direct air capture process. This parameter has a significant impact on the estimated capital cost of the process. However, sufficient data to model this accurately is scarcely available in the literature.¹⁰⁵
- ▶ **Economic assumptions:** the choice of economic parameters, *e.g.* the plant lifetime and capital recovery factor. These assumptions generally impact the capital cost, and it is challenging to systematically determine what values are most appropriate.

Variability in the assumptions used in the literature studies doubtless arises from the lack of centralised and authoritative guidelines for conducting techno-economic analysis of direct air capture processes. For liquid-sorbent based processes, there appears to have been no attempts towards standardisation of techno-economic procedure. While published literature has made efforts towards guidelines for techno-economic assessment of solid-sorbent based carbon capture processes in

¹⁰⁵ **Low et al. (2023):** Analytical review of the current state of knowledge of adsorption materials and processes for direct air capture. *Chemical Engineering Research and Design* (189); **Sabatino et al. (2021):** A comparative energy and costs assessment and optimization for direct air capture technologies. *Joule* (5).

general,¹⁰⁶ there has been little specific guidance offered on the application of these guidelines in the context of direct air capture.

Such wide variability in estimations of techno-economic performance is troubling from the perspective of trying to draw definitive conclusions through a comparison of data. Furthermore, current techno-economic analyses are largely speculative because direct air capture is not yet deployed at a large enough scale to yield real-world data against which to benchmark techno-economic assumptions. In this context, standardised guidelines for conducting techno-economic assessments of both L-DAC and S-DAC processes would be extremely valuable, with an aim towards achieving a higher level of reliability between independent bodies of work in the academic literature. This is a necessary pre-condition to gaining a deeper understanding of current cost estimates of direct air capture technologies, and to understand any barriers which are present in developing engineering approaches to reduce costs as the technology develops.

7.5 System scale techno-economic model

To predict the system scale techno-economic performance of direct air capture, we deploy a discrete time series model. The modelling approach again uses the logistic growth deployment model (see Chapter 4) as a basis for predicting the global scale deployment of direct air capture over time. Within this approach, we can calculate the total cumulative system cost over time as:

$$G(t_n) = \Delta t \cdot \sum_{i=1}^n \dot{C}(t_i) G_{\text{CAPEX}}(t_i) t_{\text{life}} + C(t_i) G_{\text{OPEX}}$$

where G is the total cumulative system cost (\$), C is the deployed capacity of direct air capture (tCO₂/yr), $\dot{C}$ is the deployment rate of direct air capture capacity (tCO₂/yr²), G_{CAPEX} is the capital cost of direct air capture (\$/tCO₂), G_{OPEX} is the operating cost of direct air capture (\$/tCO₂), t_{life} is the direct air capture plant lifetime (yr), and Δt is the time step size.

The modelling approach accounts for the following contributions to the total cost of a direct air capture system:

- **Capital costs:** the costs associated with constructing new direct air capture plants to add capacity to the existing direct air capture system. This cost is distributed over time according to the deployment rate of direct air capture described in the logistic growth modelling approach.
- **Operating costs:** the costs associated with operating currently deployed direct air capture plants. This cost is applied at each time step, according to

¹⁰⁶ Danaci et al. (2021): Guidelines for techno-economic analysis of adsorption processes. *Frontiers in Chemical Engineering* (2).

the deployed capacity of direct air capture at each time described in the logistic growth modelling approach.

7.6 System scale techno-economic scenarios

Acknowledging the deep uncertainty observed above regarding the process scale techno-economic performance of direct air capture, we proceed with analysis of the techno-economic performance at the system scale with an approach which aims to integrate uncertainty in our predictions at long timescales.

For each direct air capture technology, we consider a deployment trajectory corresponding to the base-case scenario outlined in Chapter 4. Global-scale direct air capture capacity is scaled from 1 MtCO₂/yr in the year 2020, to 1 GtCO₂/yr by mid-century according to logistic growth with a growth rate of $r = 0.26 \text{ yr}^{-1}$. We assume that direct air capture plants have a lifetime of 30 years.

Significant sources of uncertainty in the prediction of techno-economic performance at long timescales include: (i) capital costs of direct air capture, (ii) operating costs of direct air capture, (iii) the carbon intensity of energy supplied to direct air capture at long times (e.g., grid electricity), and (iv) the rate at which capital costs will reduce over time through technology learning as we transition towards mass manufacturing of plants and/or process units (i.e., technology learning rate). In the following analysis, we consider three scenarios encompassing a (i) best-case scenario (lowest costs), (ii) an intermediate scenario, and (iii) a worst-case scenario (highest costs).

The key assumptions underpinning each of the scenarios are as follows:

- ▶ **Capital costs:** capital costs in the intermediate scenario are assumed as the median of the capital costs reported in the literature studies. The best-case and worst-case capital costs are taken as the lower and upper quartile, respectively, from the distribution of capital costs reported in the literature studies (Figure 7.1).
- ▶ **Operating costs:** operating costs are assumed from the calculations presented above regarding the operational costs of direct air capture based on energy usage analysis. The best-case and worst-case values are assumed to be the endpoints of the ranges provided above, and the intermediate value is assumed to be the mean of this range (Section 7.3).
- ▶ **Grid carbon intensity:** the long-term carbon intensity of energy supply scenarios utilised here are identical to those outlined in Chapter 4. The global carbon intensity of energy supply in the period 2020–2050 is obtained from the EnerOutlook Energy and Emissions to 2050 pathway (Box 1).¹⁰⁷ In the period 2050–2100 we consider three possible long-term energy system carbon intensity pathways: (i) no further decarbonisation after 2050 (NFD), (ii) net-zero emissions by 2100 (NZ-2100), and (iii) net-negative emissions by 2100 (NN-2100). Here, the best-case scenario corresponds to the NN-2100

¹⁰⁷ Enerdata (2023) Energy & emissions projections 2050 - EnerOutlook.

pathway, the intermediate scenario corresponds to the NZ-2100 pathway, and the worst-case scenario corresponds to the NFD pathway.

- **Technology learning:** capital costs will reduce over time during the wide-scale deployment of direct air capture. Previous work has shown that technology learning rates for direct air capture should fall within the range 10–20%, where 10% corresponds to slow-moderate learning, and 20% corresponds to fast technology learning.¹⁰⁸ Here, the best-case scenario assumes a learning rate of 20%, the intermediate scenario assumes a learning rate of 15%, and the worst-case scenario assumes a learning rate of 10%.

All techno-economic assumptions relating to the scenarios outlined above are tabulated in Appendix 8.

7.7 Total direct air capture system cost

In Figure 7.2 we show the total system cost for DAC deployment over time, reflecting the system value of DAC technologies, i.e., their cumulative cost and performance at global scale, under long-term deployment trajectories. We also provide plots of the cumulative amounts of carbon dioxide captured and removed over time by the global-scale system. By 2100, the total system cost for wide-scale L-DAC deployment is \$3.4–9.9 trillion (intermediate scenario: \$5.1 trillion). For wide scale S-DAC deployment, the total system cost by 2100 is \$3.3–9.2 trillion (intermediate scenario: \$4.6 trillion). We note that the cost estimates presented do not include additional system-level costs such as CO₂ transport and storage (T&S), monitoring, reporting and verification (MRV), permitting or infrastructure buildout. Therefore, the values presented should be interpreted as indicative system-scale capture costs, rather than comprehensive full-chain removal costs.

We can see that the total system cost develops over time in three main phases:

- **Phase 1:** exponential increase in the total cost over time. This increase is driven by significant capital investment in wide-scale expansion of the technology in the period 2020–2050.
- **Phase 2:** a relative plateau in the total cost over time. In this phase, the dominant contribution towards total cost is the operating costs of the established direct air capture system.
- **Phase 3:** essentially linear increase in total cost over time. There is a constant cost per unit time associated with maintaining the existing direct air capture system. There are contributions to this cost from both the operating cost of existing plants, and the capital investment required to construct new direct air capture plants as older plants exceed their lifetime and retire from the system.

¹⁰⁸ McQueen et al. (2021): A review of direct air capture (DAC): Scaling up commercial technologies and innovating for the future. *Progress in Energy* (3).

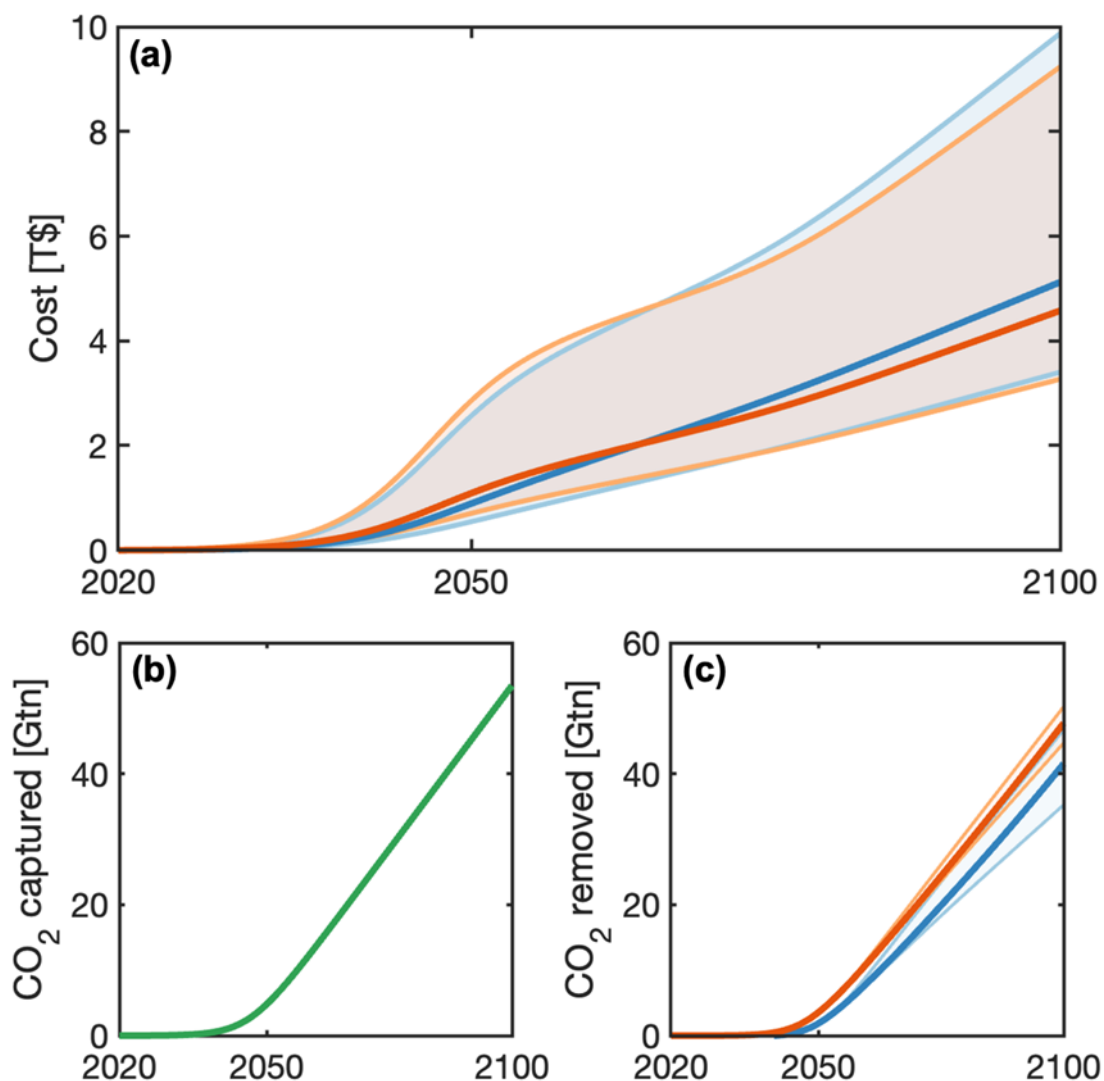


Figure 7.2: total system cost in the period 2020–2050 for a 1 GtCO₂/yr deployment of direct air capture using either L-DAC or S-DAC technology. **(a)** total system cost over time. Blue line corresponds to the total cost of the L-DAC system in the intermediate scenario. Orange line corresponds to the total cost of the S-DAC system in the intermediate scenario. The shaded regions correspond to the uncertainty observed in the best-case and worst-case techno-economic scenarios. **(b)** cumulative amount of carbon dioxide captured over time. **(c)** cumulative amount of carbon dioxide removed over time. Blue line corresponds to the total cost of the L-DAC system in the intermediate scenario. Orange line corresponds to the total cost of the S-DAC system in the intermediate scenario. The shaded regions correspond to the uncertainty observed in the best-case and worst-case techno-economic scenarios.

7.8 Conclusions and key recommendations

- ▶ There is significant uncertainty in current cost estimates of direct air capture technologies. Standardised methodologies for the techno-economic assessment of direct air capture processes are a significant priority towards improving reliability and comparability of cost estimates.
- ▶ Operating cost estimates in several published techno-economic studies are infeasibly low. The operating cost of current direct air capture technologies is at least 43–97 \$/tCO₂, based solely on the cost of energy provision.
- ▶ Capital costs of direct air capture processes can be expected to fall significantly (*c.a.* 79%) in the period 2020–2050 *via* technology learning. Cost reductions can be facilitated by a transition towards mass manufacturing of standardised direct air capture plants and/or process units.
- ▶ Technology learning is expected to be faster for S-DAC technology than L-DAC technology, owing to greater suitability towards standardised mass manufacturing.
- ▶ Global-scale deployment of 1 GtCO₂/yr direct air capture capacity is predicted to have a total cumulative system cost of \$3.3–9.2 trillion in the period 2020–2100. This cost represents a very small proportion of expected cumulative global GDP in the same period.
- ▶ Significant public and private sector investment is required to enable the establishment of a large-scale direct air capture system which can enable market-friendly marginal costs in the second half of the century.
- ▶ Significant technology learning to drive down capital costs and deep energy system decarbonisation are necessary pre-conditions to enable low-cost direct air capture.

8 Conclusions and key recommendations

Carbon dioxide removal (CDR) provides an important service in the context of global decarbonisation efforts, by allowing for handling of residual industrial emissions, decentralised emissions, and historical emissions of greenhouse gases. Importantly, CDR should not be viewed as a substitute for emissions reduction. To meet the Paris Agreement targets of limiting global warming to 1.5°C, the mitigation/abatement of GHG emissions should be the priority, but CDR is also an essential technology required to reach net zero emissions by 2050, and eventually become net negative beyond.

Among the available options for CDR, direct air carbon capture and storage (DACCS) represents an attractive option – owing primarily to the small land footprint, low water consumption, ease of monitoring, reporting and verification (MRV) and scalability.

There are currently two leading technologies which are being commercially scaled to achieve DAC: (i) absorption into liquid sorbents (L-DAC), and (ii) adsorption onto solid sorbents (S-DAC). Thus, this analysis will focus on these two options for DAC as both technologies are sufficiently developed (i.e., TRL above 6) and we can envision a wide-scale deployment in the near term. To date, there has been little systematic analysis in the literature towards the concept of the value of DAC systems for providing CDR at the global scale. Specifically, considering the concepts of carbon removal efficiency, timeliness, durability, land footprint and techno-economics of DAC in an integrated manner is central to assessing the potential for achieving carbon removal.

The objective of this study was to evaluate the value of DAC in the energy transition, accounting for key metrics, including carbon removal efficiency, timeliness, durability, land footprint, techno-economic performance. We developed and applied a quantitative technical framework for assessing the impact of these metrics on the value of DAC systems. The backbone of the framework is a prediction of the global-scale deployment trajectory for DAC, facilitated by a logistic growth model. The global-scale deployment trajectory was coupled to a time-series model for the cumulative emissions of the entire DAC system, which accounted for: (i) carbon removal from the atmosphere, (ii) cradle-to-grave life cycle emissions for the construction, operation, and provision of resources for DAC, and (iii) the fate of captured CO₂ through consideration of a variety of possible carbon sinks (both geological storage, and utilisation pathways).

The framework is inherently time dependent and aims to quantify the dynamic impact on atmospheric carbon levels of a wide-scale deployment of DAC in the period 2020 – 2100. Furthermore, the modelling integrates data for energy system decarbonisation pathways to accurately characterise the efficiency and timeliness in several regional contexts, including the Pacific, Middle East, Asia, North America, Europe, and Latin America regions.

The carbon removal efficiency of DAC processes is affected by the life cycle emissions of its value chain from cradle-to-grave. Accounting for these emissions when calculating the net removal achieved by a DAC process is critical to accurately characterising its overall effectiveness. We found that the most significant factor affecting the efficiency of DAC is the provision of energy for process operations. The carbon dioxide removal efficiency of DAC has been correlated as a function of the carbon intensity of energy supply to estimate the performance of DAC technologies in each world region over the considered time horizon. We find that while the global energy system is not suitable for a wide-scale deployment of effective DAC today, predicted energy decarbonisation pathways in the considered period are on-track to enable effective DAC by mid-century in most global regions, including the Pacific, North America, Europe, and Latin America regions. However, the Middle East and Asia regions would need to accelerate decarbonisation efforts.

The timeliness of DAC processes for providing timely carbon removal is challenged by currently high costs and unscaled supply chains. Therefore, the rate at which DAC can scale globally, and the removal which can be achieved through that scale-up, is unclear. Application of the quantitative framework which we have developed shows that wide-scale deployment of both L-DAC and S-DAC with geological CO₂ storage can achieve significant negative emissions by the end of the century. A 1 GtCO₂/yr deployment of L-DAC cumulatively achieves a net CO₂ removal of 35–46 GtCO₂ by 2100, and S-DAC achieves a net-removal of 45–50 GtCO₂ – with the significant uncertainty in the results attributed to uncertainty in the long-term decarbonisation of the global energy system. The results show that there is a significant lag in the system between the time at which wide-scale deployment of DAC is initiated, and the time at which significant carbon removal is achieved.

The timeliness of large-scale DAC deployment will likely be a function of three key factors: (i) time required to establish suitable supply chains and bring down technology costs, (ii) wide-scale deployment is characterised by a period of high construction related emissions in the near-term, and (iii) the global energy systems needs time to sufficiently decarbonise to enable environmentally effective DAC operations. Further, we analysed the sensitivity of the system to possible growth trajectories, and we find that low growth rate scenarios achieve very poor levels of removal during this century. Therefore, we contend that if DAC is to play a role in global efforts towards CDR, immediate and rapid deployment is central to achieving this.

The durability of carbon removal by DACCS is affected by the choice of carbon sink. Carbon storage by geological sequestration is an essentially permanent carbon sink, while utilisation of the captured CO₂ via chemical conversion into carbon-based products is inherently temporary. In this study, we demonstrated how the choice of carbon sink(s) affects the dynamic performance of the overall system in terms of carbon emissions and environmental benefit. With respect to system durability, we find that geological carbon sequestration is the only currently available carbon sink which provides a permanent removal of captured emissions from the atmosphere. There are also a wide variety of potential utilisation pathways available for captured carbon (e.g., fuels, chemicals, plastics), for which the storage lifetime of captured emissions varies widely (weeks, to decades) depending on the product lifetime of the

chosen pathway. We find that all possible utilisation pathways ultimately lead to positive emissions for the entire system at long time scales. This effect is manifested through the balance of captured emissions by DAC and re-emission to the atmosphere at the end of the product lifetime, with the presence of additional positive emissions in the system for the operation and construction of DAC and carbon conversion processes. We find that systems aimed at achieving negative emissions must direct a minimum proportion of captured CO₂ emissions towards geological carbon storage. For instance, for the unabated methane production and combustion pathway, 30–50 % of the CO₂ captured needs to be directed to geological carbon storage. Therefore, there remains significant scope to utilise carbon-based products via DACCS, but we assert that careful systems-level considerations are required to ensure the environmental effectiveness of the overall system.

Among available pathways for achieving greenhouse gas removal, direct air capture has a low total land footprint. Large-scale direct air capture systems have a total land footprint requirement of 10.9–16.6 km²/(MtCO₂/yr). The land footprint requirement is highly sensitive to the direct air capture technology selection, and to the energy requirements for the operation of direct air capture. Low energy usage is the strongest available factor for reducing the land footprint requirements of direct air capture systems. Shared use of land for air contactor spacing with infrastructure for resource provision has the potential to reduce the land footprint requirements of DAC by 21–45%. However, further practical research efforts are required to establish if this approach is feasible.

Technology learning could potentially help drive down capital costs, and deep energy system decarbonisation will be required to enable low-cost DAC. Ultimately, significant public and private sector investment is required to enable the establishment of a large-scale DAC market. This study highlights the importance of whole-systems planning for wide-scale DAC deployment to ensure sufficient availability of land, low-carbon energy provision, and CO₂ transport and storage infrastructure are in the correct locations and times.

It should be noted that requirements for infrastructure, siting, and integration into existing energy systems can vary substantially between DAC technologies. Moreover, siting of DAC plants will also need to account for regional climate since air humidity and temperature will have a significant impact on S-DAC performance and cost.¹⁰⁹ These region-specific factors could lead to different regional feasibility profiles and may alter the land, cost, and energy implications assessed in this report. As such, while this analysis provides a comparative baseline, future research should further explore how siting constraints, technology configurations, and resource dependencies vary across DAC pathways and regions.

¹⁰⁹ Sendi, M., Bui, M., Mac Dowell, N. & Fennell, P. (2022). Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment. *One Earth* 5, 1153-1164.

An, K., Farooqui, A., McCoy, S. T. (2022). The impact of climate on solvent-based direct air capture systems. *Applied Energy* 325: 119895.

Jung, H., Kim, K., Jeong, J., Jamal, A., Koh, D.-Y., Lee, J. H. (2025). Exploring the impact of hourly variability of air condition on the efficiency of direct air capture. *Chemical Engineering Journal* 508: 160840.

Importantly, the logistic growth model used in this study has limitations that should be considered. This model focuses solely on the DAC technology itself and does not account for potential bottlenecks in developing the necessary supporting infrastructure. For instance, it omits key aspects such as the availability of power supply, CO₂ transport, and storage infrastructure which are critical to the successful deployment and operation of DACCS. It also does not consider how DAC deployment would interact with the deployment of other CDR approaches. These factors can significantly impact the overall deployment timeline and capacity, and their omission may lead to an overestimation of the feasibility and speed of DAC scaling. Thus, the results from this work should be considered as the optimistic upper bound of DAC deployment.

Appendix 1: Literature review of direct air capture life cycle assessments

<i>Technology</i>	η_{CDR} [%]	E_{DAC} [tCO ₂ -eq/tCO ₂ -cap]	<i>Basis</i> [tCO ₂ -cap/yr]	t_{BE} [months]	<i>Source</i>
L-DAC	41.3	0.11	1,000,000	95.9	Madhu et al. (2021)
L-DAC	80.3	-	-	-	Chiquier et al. (2022)
L-DAC	60.0	0.0020	1,000,000	1.2	NETL (2021)
L-DAC	62.0	0.0049	1,000,000	2.8	de Jonge et al. (2019)
L-DAC	65.4	-	1,000,000	-	Qiu et al. (2022)
S-DAC	69.7	0.019	1,000,000	9.8	Madhu et al. (2021)
S-DAC	76.1	-	-	-	Chiquier et al. (2022)
S-DAC	67.6	-	-	-	NETL (2021)
S-DAC	70.0	0.0060	100,000	3.1	Terlouw et al. (2021)
S-DAC	97.6	0.0015	368,000,000	0.6	Deutz et al. (2021)
S-DAC	36.2	-	100,000	-	Qiu et al. (2022)

Appendix 2: Carbon intensity of energy supply pathways by world region

Region	Carbon intensity of energy supply [kgCO ₂ -eq/kWh]						
	2020	2025	2030	2035	2040	2045	2050
<i>Pacific</i>	0.568	0.389	0.217	0.110	0.062	0.038	0.027
<i>Middle East</i>	0.551	0.524	0.424	0.342	0.285	0.236	0.162
<i>Asia</i>	0.555	0.516	0.446	0.342	0.190	0.095	0.059
<i>North America</i>	0.310	0.240	0.136	0.030	0.010	0.005	0.003
<i>Europe</i>	0.205	0.211	0.125	0.084	0.064	0.053	0.034
<i>Latin America</i>	0.202	0.175	0.179	0.142	0.103	0.073	0.054

Data source: <https://eneroutlook.enerdata.net/forecast-world-co2-intensity-of-electricity-generation.html>

Appendix 3: Carbon dioxide removal efficiency as a function of carbon intensity of energy supply

The carbon dioxide removal efficiency is correlated as a function of the carbon intensity of energy supply. The correlation has the following linear form:

$$\eta_{\text{CDR}} = \delta_{\text{DAC}} I_{\text{grid}} + \epsilon_{\text{DAC}}$$

where η_{CDR} is the carbon dioxide removal efficiency (-), I_{grid} is the carbon intensity of energy supply (kgCO₂-eq/kWh), and δ_{DAC} and ϵ_{DAC} are coefficients of the correlation. The values of the coefficients for both L-DAC and S-DAC processes are tabulated below.

Technology	δ_{DAC} [kWh/kgCO₂-eq]	ϵ_{DAC} [-]
L-DAC	-4.47	0.964
S-DAC	-2.16	0.973

Appendix 4: Cumulative construction emissions of L-DAC and S-DAC processes

The construction emissions of a direct air capture process are calculated using the following equation:

$$\begin{aligned} & \text{(Cumulative construction emissions)} \\ &= \text{(Embodied emissions)} \times \text{(Capture rate)} \times \text{(Plant lifetime)} \end{aligned}$$

where (Construction emissions) corresponds to the amount of CO₂ (equivalent) emissions associated with construction of a direct air capture process, and (Embodied emissions) are the construction emissions in terms of amount of CO₂ (equivalent) emissions normalised by the amount of CO₂ captured over the plant lifetime.

The construction emissions used as an input to the process-scale cumulative emissions model are taken as the average of the construction emissions reported in available literature studies conducting life cycle assessments for direct air capture processes, corresponding to a process with a capture rate of 1 MtCO₂/yr and a lifetime of 30 years. The resulting construction emissions are tabulated below.

<i>Technology</i>	<i>E_{DAC}</i> [tCO ₂ -eq/tCO ₂ -cap]	<i>Capture rate</i> [tCO ₂ -cap/yr]	<i>t_{life}</i> [yr]	<i>Construction emissions</i> [tCO ₂ -eq]
L-DAC	0.11	-	-	-
L-DAC	0.0020	-	-	-
L-DAC	0.0049	-	-	-
L-DAC (average)	0.039	1,000,000	30	1,168,900
S-DAC	0.019	-	-	-
S-DAC	0.0060	-	-	-
S-DAC	0.0015	-	-	-
S-DAC (average)	0.0088	1,000,000	30	265,000

Where, E_{DAC} is carbon removal operational efficiency and t_{life} is the DAC plant lifetime.

Appendix 5: Life cycle assessment data for analysis of carbon utilisation pathways

Case study	ϵ_0 [tCO ₂ -eq/t product]	ϵ_{II} [tCO ₂ -eq/tCO ₂ -utilised]	α [-]	$\Gamma_{product}$ [t product/tCO ₂ -utilised]	ϵ_a [tCO ₂ -eq/tCO ₂ -abated]
Methane (unabated)	3.25 ¹¹⁰	0.325 ¹¹¹	0	0.153 ²¹	-
Methane (abated)	0.837 ⁷³	0.325 ⁷³	0.9	0.153 ⁷³	0.0387 ¹¹²
Aviation fuel	1.91 ¹¹³	0.153 ⁷⁸	0	0.193 ⁷⁸	-

¹¹⁰ Littlefield et al. (2022): "Life cycle GHG perspective on US natural gas delivery pathways". Environmental Science & Technology (56); Wei and Jinlong (2010): "Methanation of carbon dioxide: an overview". Frontiers of Chemical Science and Engineering (5).

¹¹¹ Federic et al. (2022): "Life cycle analysis of a combined electrolysis and methanation reactor for methane production". Energy Reports (8).

¹¹² Zhang et al. (2014): "Post-combustion carbon capture technologies: Energetic analysis and life cycle assessment". International Journal of Greenhouse Gas Control.

¹¹³ Rojas-Michaga et al. (2023): "Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment". Energy Conversion and Management (292); Xu et al. (2015): "Thermochemical properties of jet fuels".

Appendix 6: Input data for land footprint assessment of direct air capture processes

Technical performance of direct air capture processes:

	L-DAC	S-DAC
Direct land footprint [$\text{km}^2/(\text{MtCO}_2/\text{yr})$]	7	5
Specific energy usage [GJ/tCO_2]	5.5 – 8.8	7.2 – 9.5
Share of energy input as heat [%]	80 – 100	75 – 80
Specific water usage [$\text{tH}_2\text{O}/\text{tCO}_2$]	0 – 50	-2 – 0

Deployed capacity of electricity supply technologies in the period 2020–2050 (TW). “Other” generation types include bioenergy and geothermal power:

Generation type	Year						
	2020	2025	2030	2035	2040	2045	2050
Solar PV	1.09	2.33	5.82	10.1	14.0	16.7	18.5
Wind	0.85	1.36	2.66	4.16	5.60	6.62	7.38
Hydro	1.37	1.44	1.68	1.97	2.16	2.29	2.37
Other	0.14	0.20	0.29	0.51	0.78	0.93	1.03
Nuclear	0.34	0.36	0.48	0.55	0.64	0.69	0.67
Coal	2.21	2.15	1.36	0.80	0.38	0.20	0.02
Gas	1.86	1.90	1.64	1.28	0.92	0.66	0.37

Deployed capacity of electricity supply technologies in the period 2020–2050 (%):

Generation type	Year						
	2020	2025	2030	2035	2040	2045	2050
Solar PV	13.9	23.9	41.8	52.1	57.2	59.5	61.0
Wind	10.8	14.0	19.1	21.5	22.9	23.6	24.3
Hydro	17.4	14.8	12.1	10.2	8.8	8.2	7.8
Other	1.8	2.1	2.1	2.7	3.2	3.3	3.4
Nuclear	4.4	3.7	3.5	2.9	2.6	2.4	2.2
Coal	28.1	22.1	9.8	4.1	1.5	0.7	0.1
Gas	23.6	19.5	11.8	6.6	3.8	2.4	1.2

Land footprint requirement of electricity supply technologies:

Generation type	Land footprint [m^2/W]
Solar PV	0.0154
Wind	0.345
Hydro	0
Other	0.0658
Nuclear	0.000227
Coal	0.0333
Gas	0.0178

Overall weighted land footprint requirement of electricity supply in the period 2020 – 2050:

	Year						
	2020	2025	2030	2035	2040	2045	2050
Land footprint [m^2/W]	0.0542	0.0640	0.0790	0.0864	0.0910	0.0933	0.0958

Deployed capacity of heat supply technologies in the period 2020–2050 (EJ/yr). “Other” generation types include hydrogen combustion, bioenergy, solar thermal, and geothermal heating:

Generation type	Year		
	2020	2030	2050
Coal	39.7	30.6	6.2
Oil	5.4	4.6	1.2
Gas	16.5	15.9	8.5
Other	10.1	13.9	20.7

Deployed capacity of heat supply technologies in the period 2020–2050 (%):

Generation type	Year		
	2020	2030	2050
Coal	55	47	17
Oil	8	7	3
Gas	23	24	23
Other	14	21	57

Land footprint requirement of heat supply technologies:

Generation type	Land footprint [m^2/W]
Coal	0.0333
Oil	0.0333
Gas	0.0178
Other	0.0658

Overall weighted land footprint requirement of heat supply in the period 2020–2050:

	<i>Year</i>		
	2020	2025	2030
<i>Land footprint [m²/W]</i>	0.0343	0.0365	0.0481

Appendix 7: Techno-economic scenarios for system scale direct air capture deployment

L-DAC

Capture cost [\$/tn]	CAPEX [\$/tn]	OPEX [\$/tn]	Source
245	236	9	Fasihi et al. (2019) ¹¹⁴
159	78	81	Keith et al. (2018) ¹¹⁵
908	426	482	Kiani et al. (2020) ¹¹⁶
190	77	113	McQueen et al. (2021) ¹¹⁷
106	81	59	NASEM (2019) ¹¹⁸
571	353	218	Zeman (2014) ¹¹⁹
531	309	222	Mazzotti et al. (2013) ¹²⁰
355	123	232	American Physical Society (2011) ¹²¹
375			Daniel et al. (2022) ¹²²
120	79	40	Ozkan et al. (2022) ¹²³

¹¹⁴ Fasihi et al. (2019): "Techno-economic assessment of CO₂ direct air capture plants". Journal of Cleaner Production (224).

¹¹⁵ Keith et al. (2018): "A process for capturing CO₂ from the atmosphere". Joule (2)

¹¹⁶ Kiani et al. (2020): "Techno-economic assessment for CO₂ capture from air using conventional liquid-based absorption process". Frontiers in Energy Research (8).

¹¹⁷ McQueen et al. (2021): "A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Progress in Energy (3).

¹¹⁸ NASEM (2019): "Negative emissions technologies and reliable sequestration: A research agenda".

¹¹⁹ Zeman (2014): "Reducing the cost of Ca-based direct air capture of CO₂". Environmental Science & Technology (48).

¹²⁰ Mazzotti et al. (2013): "Direct air capture of CO₂ with chemicals: Optimization of a two-loop hydroxide system using a countercurrent air-liquid contactor". Climate Change (118).

¹²¹ American Physical Society (2018): "Direct air capture of CO₂ with chemicals".

¹²² Daniel et al. (2022): "Techno-economic analysis of direct air carbon capture with CO₂ utilisation". Carbon Capture Science & Technology (2).

¹²³ Ozkan et al. (2022): "Current status and pillars of direct air capture technologies". iScience (25)

S-DAC

Capture cost [\$/tn]	CAPEX [\$/tn]	OPEX [\$/tn]	Source
204	196	8	Fasihi et al. (2019) ⁹¹
1094			Krekel et al. (2018) ¹²⁴
565	452	113	McQueen et al. (2021) ⁹⁴
195	175	20	NASEM (2019) ⁹⁵
144	131	14	Ozkan et al. (2022) ¹⁰⁰

¹²⁴ Krekel et al. (2018): "The separation of CO₂ from ambient air - A techno-economic assessment". Applied Energy (218).

Appendix 8: Techno-economic assumptions related to system-scale scenarios

L-DAC scenario inputs:

Scenario	CAPEX [\$/tCO ₂]	OPEX [\$/tCO ₂]	Grid carbon intensity	Learning rate [-]
Best-case	78	53	NN-2100	0.2
Intermediate	90	75	NZ-2100	0.15
Worst-case	228	97	NFD	0.1

S-DAC scenario inputs:

Scenario	CAPEX [\$/tCO ₂]	OPEX [\$/tCO ₂]	Grid carbon intensity	Learning rate [-]
Best-case	133	43	NN-2100	0.2
Intermediate	141	53	NZ-2100	0.15
Worst-case	275	67	NFD	0.1

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