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Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Report
2021-05
December 2021

Global Assessment of Direct Air Capture Costs

IEA GREENHOUSE GAS R&D PROGRAMME

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GLOBAL ASSESSMENT OF DIRECT AIR CARBON CAPTURE AND STORAGE (DACCS) COSTS, SCALE AND POTENTIAL

This study aims to improve the current DACCS cost-performance evidence base by synthesising data from the recent literature and technology developers to explore the economic feasibility of different DACCS technologies (both liquid and solid based systems) across timescales, capacities, configurations, and numerous global siting factors. It also provides recommendations for the integrated assessment modelling (IAM) community and policymakers to inform next steps for DACCS implementation and deployment.

Key Messages

- Although DACCS is more expensive than many carbon mitigation and removal options, careful plant siting and rapid learnings can achieve significantly more competitive DACCS costs.
- First-of-a-kind (FOAK) DACCS projects are likely to range from ~\$400-\$700/net-tCO_2, when global average solar photovoltaics (PV) costs are used, or ~\$350-\$550/net-tCO_2, when lowest-cost renewables are used.
- Significant cost reduction can be achieved for nth-of-a-kind (NOAK) DACCS plants, reaching ~\$194-\$230/net-tCO_2 for 1 MtCO_2/year scale, driven by reduced electricity prices, cost of capital and upfront capital investment. Energy costs can be as much as 50% of long-term liquid DACCS costs. NOAK DACCS costs in the range of ~\$150-\$200/net-tCO_2 may be achieved if very low-cost solar energy is used. Long-term costs were found to be significantly higher than the industry target of \$100/tCO_2 captured, except under ambitious cost-performance assumptions and favourable conditions.
- The lifecycle emissions associated with DACCS range from 7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants (if low carbon energy is used).
- Since no large-scale plant is built to date, inherent uncertainties on most parameters are high. The largest uncertainties requiring major assumptions are on capital costs, plant scaling factors, future cost reductions through learning, and solid adsorbent cost-performance dynamic.
- To date DACCS representation in integrated assessment models (IAMs) has been relatively simplistic. Technical parameters compiled and developed throughout this study can be used for representation of DACCS technologies in future IAM studies. IAM practitioners should consider differentiating between DACCS technologies and considering multiple plant configurations. Practitioners should also take care to ensure consistent treatment of financing costs for all technologies across their models. Furthermore, operating and labour costs are likely to be region dependent and IAMs can use reference tables to estimate how these costs could differ between countries.
- Most current DACCS policy support consists of generic R,D&D funding, and financial support aimed at wider negative emissions technologies (NETs) or carbon capture and storage (CCS) technologies. The US, UK, EU, Canada and Australia are key regions with relatively developed CCS regulations and R&D and demonstration programmes targeting carbon removal or general CCS projects. The 45Q tax credits in the US and California’s Low Carbon Fuel Standard (LCFS) are currently the only financial mechanisms in the world available for large-scale DACCS projects.

Background to the Study

NETs are essential for limiting atmospheric greenhouse gas concentrations and achieving global temperature targets. NETs, including DACCS, can be used to offset emissions from industries that are very difficult to abate, such as aviation, thereby decoupling decarbonisations efforts from the source of emissions. Analyses by IAMs presented in IPCC reports show that 87% of all IAM scenarios consistent with limiting global temperature rise to 2°C and 100% of IAM scenarios limiting temperature rise to 1.5°C require large-scale NETs (1.3 to 29 $GtCO_2$/year) to be deployed in the second half of this century.

DACCS has some advantages over other NETs due to its smaller land and water footprint, as well as potential for easy scalability. NETs interacting with biomass, such as afforestation, soil carbon storage and bioenergy with carbon capture and storage (BECCS), require significant water and arable land. Other chemical NETs, such as enhanced weathering, risk changing the chemistry of oceans and rivers. DACCS avoids many of these limitations as it has a comparatively small land footprint, but does require a sustainable energy source, geological CO_2 storage to operate and is relatively immature technology with as-yet unproven deployment potential. Furthermore, the varying levels of modularity of DACCS systems imply potential for easy scaling up and rapid deployment.

Current information on DACCS costs, performance, and impact of plant siting have several data gaps and significant uncertainties. Despite the climate relevance of DACCS technologies, current capture capacities are only at $ktCO_2$/year levels. Therefore, literature on DACCS is limited to few desk-based models and high-level data shared by technology developers with commercial interests. Consequently, most IAMs either omit DACCS or include it without granularity on specific configurations.

Scope of Work

IEAGHG commissioned Element Energy, UK, to collate and improve current evidence on the costs of DACCS systems and provide recommendations for the IAM community and policymakers to inform next steps. The study consists of the following objectives:

1. Develop a high-level techno-economic model to investigate the costs of DACCS technologies across plant scales and timeframes, as well as identifying significant uncertainties and gaps in the literature.
2. Assess key global siting factors influencing DACCS deployment, such as energy prices and emissions, CO_2 storage and transport availability, regulatory support, land, and water availability.
3. Derive recommendations for the IAM community on integration of DACCS into IAMs.
4. Discuss the required policy incentives in the context of current challenges and progress.

Although it is possible to combine DAC with CO_2 utilisation to produce low-carbon or net-negative products, this study primarily focusses on combination of DAC with dedicated permanent geological storage so as to provide a common reference point for costs of negative emissions. The combination of DAC with use of the CO_2 in enhanced oil recovery (EOR) is also excluded from the analysis.

Findings of the Study

Methods and Approach

To better investigate the current and future DACCS costs under different settings and conditions, a high-level techno-economic model was developed, which calculates the levelised cost of DACCS (LCOD) of each plant configuration, assuming a base plant capacity of 1 $MtCO_2$/year captured. Both liquid solvent and solid sorbent technologies are investigated as FOAK plants commissioning in mid-2020s and long-term NOAK plants, assumed to be in the 2050s. A further distinction is made between plants using pure electricity and hybrid plants requiring both electricity and heat inputs. Lastly, gross LCODs ($/$tCO_2$ captured) calculated in the model are converted to net LCODs ($/$tCO_2$ net removed) by accounting for some of the lifecycle emissions made throughout the DACCS supply chain.

This study uses 2050 as the base year for NOAK calculations, however, this does not imply that NOAK stage is likely to be reached only by 2050. Reaching NOAK status depends on deployment rates of individual technologies and this study does not make an assumption regarding future DACCS deployment. Here, NOAK roughly coincides to 5-7 doublings of initial large-scale production capacity and depending on future support for DACCS, NOAK stage may be reached by as early as 2035.

Key TEA Findings

Current Performance	• Early DACCS projects in the 2020s are likely to range from ~$400-$700/net-tCO_2 stored (when global average solar PV costs are used) depending primarily on scale and type of technology. • Costs drop to ~$350-$550/net-tCO_2 stored with low-cost renewables, therefore early plants are likely to be situated where renewable electricity is most affordable. Liquid DACCS plants get significantly more cost-effective with increasing size due to economies of scale. Solid DACCS costs scale more linearly with size and are likely to be the more cost-effective option for smaller plants (<100$ktCO_2$/year).
Key Cost Influences	• Liquid DACCS costs are most sensitive to upfront capital investment (Capex) and electricity prices. Due to the relatively balanced distribution of costs, most parameters are influential on LCODs, except for consumable prices including capture chemicals. • Solid DACCS prices are most sensitive to adsorbent costs and future adsorbent performance improvements are the single most important factor which will determine cost-effectiveness of solid DACCS. Solid DACCS costs are also more sensitive to plant lifetime and may significantly suffer if lifetime is reduced.
Cost Reduction	• Significant cost reduction can be achieved in the future, with DACCS reaching ~$194-$230/net-tCO_2 for 1 $MtCO_2$/year NOAK plants (~2050), driven by reduced electricity prices, cost of capital and upfront capital investment. Costs are likely to be higher for smaller plants and further cost reduction potential exists for more ambitious renewables and adsorbent cost reduction, with solid technologies having more room for innovation learning as they utilise more novel chemical processes. • Liquid DACCS further benefits from overall improvements in lifecycle emissions. Solid DACCS technologies experience further cost reduction through increases in plant lifetimes (from 10 to 25 years) and cost-performance improvements of adsorbents.

<table>
<tr><td></td><td>

- CO_2 transport and storage costs are found to be ~6-15% of total LCODs and costs may be reduced by \$20-\$25/tCO_2 if plants use shared infrastructure.
- Energy costs are as much as 50% of long-term liquid DACCS costs. DACCS costs in the range of ~\$150-\$200/net-tCO_2 may be achieved in the long-term if very low-cost solar energy is used.
- Long-term costs are found to be significantly higher than the industry target of \$100/tCO_2 captured, except under ambitious cost-performance assumptions and favourable conditions. These favourable conditions may come to exist but commenting on the size of the opportunity is difficult.

</td></tr>
<tr><td>Lifecycle Emissions</td><td>

- Emissions are primarily associated with the energy inputs (electricity and heat) and upstream methane emissions if natural gas is used in the process. Therefore, reducing the carbon intensity of energy sources is of paramount importance.
- The lifecycle emissions associated with DACCS range from 7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants (if low carbon energy is used).

</td></tr>
<tr><td>Energy Demand</td><td>
<table>
<tr><th></th><th>FOAK Liquid DACCS[89]</th><th>NOAK Liquid DACCS[89]</th><th>FOAK Solid DACCS</th><th>NOAK Solid DACCS</th></tr>
<tr><td>Thermal energy cons. (GJ/tCO_2)</td><td>6.8</td><td>0</td><td>10.8 (-)</td><td>4.9 (-)</td></tr>
<tr><td>Electrical energy cons. (GJ/tCO_2)</td><td>2.2 – 3.7</td><td>7.2 – 9</td><td>2.3 (6.6)</td><td>1.6 (3.6)</td></tr>
</table>

- Much of this data is sourced from companies developing DACCS systems. These are largely in line with those in the literature, with the slight exception of solid DACCS, where electricity consumption is at the higher end of the reported ranges in the literature, and the addition of the possibility of electricity-only solid DACCS systems. (Figures in brackets for solid DACCS are an electric-only configuration.)

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<tr><td>Uncertainties</td><td>

- Since no large-scale plant is built to date, inherent uncertainties on most parameters are high. The largest uncertainties requiring major assumptions are on capital costs, plant scaling factors, future cost reductions through learning, and solid adsorbent cost-performance dynamic.

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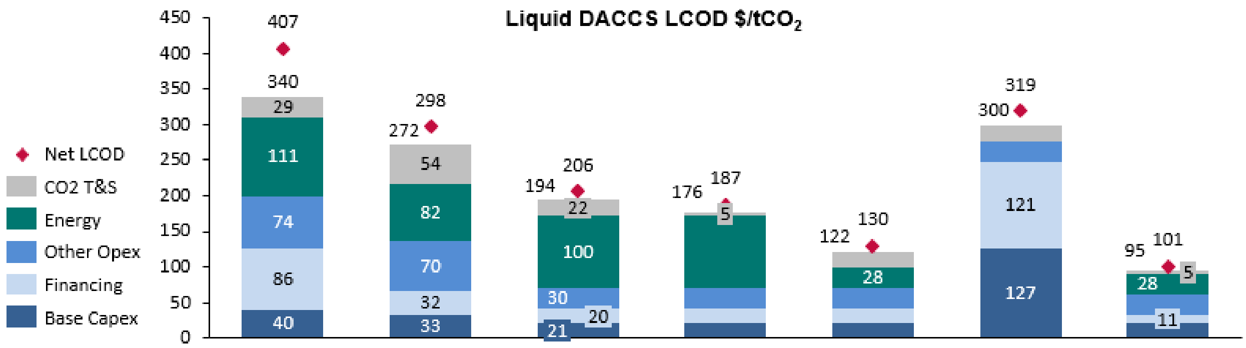
A more detailed cost breakdown of several solid and liquid system configurations as well as the most important assumptions can be found in Figure 1 and Figure 2. DACCS plants operating flexibly to follow renewable generation may access lower-cost electricity, but overall LCODs are expected to be higher than continuous operation. Solar and wind are intermittent energy sources, therefore operating DACCS plants with renewables will either require energy storage, purchasing a portfolio of low-carbon power or operating plants flexibly to match renewable generation. Reducing the operating hours of plants is likely to be technically feasible but would increase the impact of capital costs on LCODs. Operating plants at a 15% load factor, as opposed to 90%, would increase long-term levelised costs of DACCS in 2050s by up to 50%, even if electricity is assumed to be free of charge.

Land and water requirements for DACCS, which depend on the source of energy and regional climate, are not expected to be restrictive in most areas. Land occupied by DACCS plants is relatively inconsequential, estimated to be 2,000 km^2 for a total capacity of 1 GtCO_2/year including space for solar PV. This footprint is estimated to be orders of magnitude smaller than area required to remove the same amount of CO_2 by afforestation and BECCS, and may even reduce further if other power sources, such as nuclear, are used. Similarly, water requirements are not likely to be limiting for most regions, though they will likely influence siting choices. A total DACCS capacity of 1 GtCO_2/year is calculated to consume only 0.16% of agricultural water used globally. In the worst case, supplying water through desalination is estimated to increase LCODs by less than 5%. Moreover, some regions with poor water supplies, such as deserts, may save costs on solar PV generation.

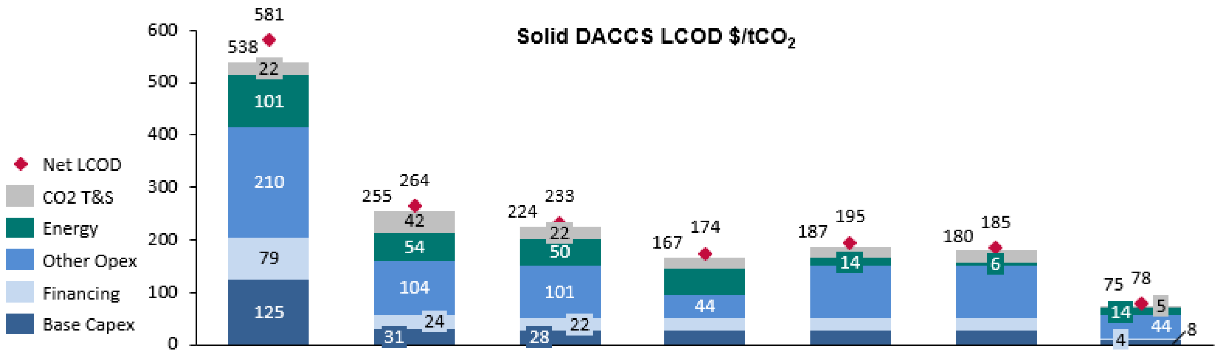
Public acceptance, policy, and regulatory support for DACCS and relevant enabling technologies are often overlooked factors influencing practical feasibility of rapid scaleup. The US, Canada, the UK, Norway, China, Japan, and Australia are countries with some of the most favourable policies supporting CCS. Furthermore, CCS regulatory provisions are most developed in North America, Australia, and the European Union. Considering the close link between CCS and DACCS technologies, these regions may be the most suitable for early deployment.

Carbon capture clusters with access to shared CO_2 infrastructure and low-carbon renewables/gas are ideal sites for future DACCS plants which can reduce LCODs significantly. Electricity price is found to be the most influential parameter for liquid DACCS costs; highly ambitious assumptions with lower cost of capital, lower electricity price and shared CO_2 infrastructure resulted in costs ~\$100/net-tCO_2. For solid DACCS plants adsorbent price is the most important parameter, and very ambitious performance improvements may cut LCODs by 25%. Under similarly highly ambitious assumptions, including additional capital cost reduction through high learning rates, solid DACCS may reach LCODs as low as \$80/net-tCO_2. (Note: the set of assumptions used for those highly ambitious cases currently do not exist or only exist partly in select few geographic locations.)



Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low T&S Cost	5- Low-Cost Solar	6- Flexible Operation	7- Very Ambitious
Maturity	FOAK	NOAK	NOAK	NOAK	NOAK	NOAK	NOAK
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Electric	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Base Case	Base Case	15% Plant Utilisation	Base Case
Electricity Source	Solar PV – Base Case (\$68/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Low (\$14/MWh)	Free Solar PV	Solar PV – Low (\$14/MWh)
CO_2 T&S	Base Case (\$22/tCO_2)	Base Case (\$22/tCO_2)	Base Case (\$22/tCO_2)	In Cluster (\$5/tCO_2)	Base Case (\$22/tCO_2)	Base Case (\$22/tCO_2)	In Cluster (\$5/tCO_2)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%

Figure 1 LCOD for several liquid DACCS system configurations (plant utilisation = load factor, the report has a more detailed, yet simplistic case study of flexible DACCS operation)



Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low-Cost Adsorbent	5- Low-Cost Electricity	6- Low-Cost Energy Hybrid	7- Very Ambitious
Timeline	FOAK 2020s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Hybrid	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Low Sorbent Cost	Base Case	Base Case	Low Sorbent Cost & High Learning Rate
Electricity Source	Solar PV – Base Case ($68/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Low ($50/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)
Heat Source	Nuclear ($19/MWh)	Nuclear ($19/MWh)	-	-	-	Free Waste Heat	-
CO_2 T&S	Base Case ($22/t$CO_2$)	Base Case ($22/t$CO_2$)	Base Case ($22/t$CO_2$)	Base Case ($22/t$CO_2$)	Base Case ($22/t$CO_2$)	Base Case ($22/t$CO_2$)	In Cluster ($5/t$CO_2$)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%

Figure 2 LCOD for several solid DACCS system configurations

Global Siting Factors

Initially it may appear as if DACCS technologies can be deployed anywhere, with key factors being access to low carbon energy and CO_2 storage resources. This study did not identify many other constraints on overall DACCS potential. However, many other factors such as environmental footprint, downstream CO_2 processing, and legal and policy environments will likely influence specific siting decisions. This study investigated these global siting factors qualitatively and, in some cases, quantitatively.

Dedicated geologic storage space is not likely to restrict global DACCS potential but will influence where DACCS can be deployed cost effectively. Sedimentary basins capable of storing CO_2 over very long periods of time are relatively well distributed around the world and all major CO_2 emitting countries are believed to have access to such storage spaces. Modest estimates calculate global storage potential to be over three times the total greenhouse gas emissions since the beginning of the Industrial Revolution.

CO_2 transport and storage costs can be significantly reduced by using shared infrastructure. CO_2 transport and storage costs for stand-alone plants are found to be 6-15% of total LCODs but can fall to as low as $5/t$CO_2$ (gross) if large capacity shared infrastructure is used alongside low-cost storage locations.

Utilisation of air captured CO_2 to produce valuable commodities may complement DACCS deployment and help reduce costs in regions where geologic storage is not available or not desired. CO_2 utilisation options may result in permanent CO_2 storage (e.g. construction materials) or displacement of fossil based products (e.g. synthetic fuels), which can be sold at higher prices than their conventional counterparts. Deploying further DAC plants for utilisation can ultimately reduce the costs of DACCS with dedicated geologic storage through supporting early deployment and economies of scale, especially for smaller scale plants. However, estimated future costs of air captured CO_2 are several times more than the costs of CO_2 produced conventionally.

Access to low-cost energy is the most prominent factor determining the economic viability of DACCS. In the long-term solar PV is likely to be the lowest cost electricity source globally, typically in equatorial regions. Other countries usually have access to some combination of low-cost wind energy, new hydropower dams, nuclear waste heat or geothermal energy. Electricity prices are found to be more influential on liquid plants, compared to solids, due to their higher power demand. Therefore, liquid DACCS are likely to be focussed on in regions with lowest-cost low-carbon electricity prices. Furthermore, for most efficient operation, hybrid solid DACCS plants need to be co-located with a source of waste heat, potentially restricting its deployment to vicinities of existing industrial sites, nuclear or geothermal plants. Fossil fuel energy sources are not expected to result in economically viable DACCS costs unless almost all associated emissions are captured as may be done in hybrid liquid DACCS alternatives.

Inclusion of DACCS in IAMs

To date DACCS representation in IAMs has been relatively simplistic. IAMs are one of the most influential quantitative tools with respect to global climate change mitigation analyses. Despite seemingly large DACCS deployment potential in existing IAM-based studies, most have focused on liquid DACCS and only one has considered solid technologies in their portfolios. Models necessarily rely on relatively sparse and divergent literature for estimates of DACCS cost. Indeed, the literature presents wide cost ranges from \$30-\$1,000/tCO_2, with estimates from sources close to industry ranging from \$100-\$300/tCO_2.

Technical parameters compiled and developed throughout this study can be used for representation of DACCS technologies in future IAM studies. A summary table of key techno economic DACCS parameters emerging from this study is presented on page 48 of the report, which includes two values for most parameters to represent typically more ambitious commercial data and more conservative literature/academic data. IAM practitioners should consider differentiating between DACCS technologies and considering multiple plant configurations, including those running on electricity only and a mix of heat and electricity. Practitioners should also take care to ensure consistent treatment of financing costs for all technologies across their models. Furthermore, operating and labour costs are likely to be region dependent and IAMs can use reference tables to estimate how these costs would differ between countries.

DACCS uptake in a range of models, including IAMs, is very high and not significantly limited by uptake constraints investigated to date. Non-IAM analyses often report DACCS capacities in the range of 10-15 $GtCO_2$/year by the late 21st century. In contrast, IAM-based studies often produce scenarios with even greater potentials of up to 30-40 $GtCO_2$/year by 2100. The availability of CO_2 storage, renewables, water, and land are key global siting factors which should be investigated further in IAMs with regional granularity to determine the locations with high DACCS viability and ultimately provide a more nuanced view of overall DACCS potential.

Current and Future DACCS Policy Support Mechanisms

Most current DACCS policy support consist of RD&D funding and financial support aimed at wider NETs or CCS technologies. The US, the UK, the EU, Canada and Australia are key regions with relatively developed CCS regulations and R&D and demonstration programmes targeting carbon removal or general CCS projects. The 45Q tax credits in the US (priced at \$50/tCO_2 removed and currently under revision for a potential increase) and California's Low Carbon Fuel Standard (LCFS) are the only financial mechanisms in the world available for large-scale DACCS projects at the time of writing this report.

The following actions could help to deploy DACCS at scale (these are merely suggestions and food for thought, and not meant to be seen as prescriptive and/or complete):

- Governments have in the past invested in R&D and demonstration funding towards CCS projects. R&D and demonstration (R,D&D) funding towards DACCS could be expected to also encourage R,D&D. (Specific areas could include, e.g., capture chemicals, scaling up systems, supporting front end engineering and design (FEED) studies and knowledge sharing networks).
- Financial support to reduce the burden of high Capex. This has demonstrated benefits in encouraging other technology demonstrations. (Specific instruments could include, e.g., tradable tax credits, low interest loans or loan guarantees, private activity bonds, accelerated depreciation, and direct equity investment.)
- Financial mechanisms to provide revenues for CO_2 removal. (E.g., establishing a negative emissions trading scheme, clean energy standards, tradable tax credits, direct procurement, or contract for differences.)
- Supporting and accelerating permitting for DACCS projects and infrastructure could help with reducing development timeframes and costs.
- Developing comprehensive regulatory frameworks for CO_2 accounting, including measurement, monitoring, and verification (MRV) standards. Also, having strong governance and international cooperation especially for developing CO_2 MRV standards and cross-border CO_2 T&S infrastructure.
- Continued support and data sharing on CO_2 storage site appraisal.
- Incentivising CO_2 utilisation with DAC by developing markets for CO_2-based products (e.g. through procurement programmes and development/maintenance of public product databases) might help establish early commercial opportunities. Care needs to be taken regarding the permanence of the desired CO_2 utilisation pathways.
- Considering, whether separating national targets for CO_2 mitigation and removal is practicable.
- Prioritising public engagement and social considerations to improve DACCS perception and knowledge among many stakeholders.

Expert Review Comments

7 reviewers from industry, academia and other organisations took part in the expert review process of this study. The majority of the comments were minor, requiring simple responses, clarifications and/or additions. The more substantive comments included:

- Emissions from CO_2 transport and storage should be included in the analysis. → Literature research early in the project revealed a significant lack of data in this area, thus it could not be included. This was made clearer in the methodology section and was added to the recommendations for further work.
- Several reviewers suggested to add costs for CCS, BECCS, and hard to abate sector mitigation technologies to enable a comparison with the DACCS costs. → BECCS costs were already given in the main body of the report. A representative range (min/max values) of

costs for CCS was added for informative purposes, however, a direct comparison of CCS and DACCS costs is not very helpful, as (fossil) CCS does not provide negative emissions.

- Adding further sensitivities to the tornado graphs, including plant lifetime and scaling factors → Plant lifetime sensitivity was added. Scaling factor sensitivity was not added, as this is not an inherent property of the technology and both investigated DACCS technologies (solid and liquid) use different scaling methods. This justification was added to the report.
- There were multiple comments around water consumption, asking for further detail regarding: mechanism of water generation and the relationship between time, temperature and humidity. → Ranges quoted in the literature on water use were already present in the report. The contractor did not feel able to provide additional comments or conclusions, as there is a significant lack of data on water use and mechanism for DACCS plants. In general, it is thought that compared to the counterfactual, water use in DACCS plants will likely not be a major limitation. The lack of data in this area was added to the recommendations for further work.
- The choice of naming 2050 costs as NOAK was perceived as problematic → NOAK costs presented in the study are meant to represent 5-7 doublings of capacity and do not mean that they can only be reached at a certain point in time, i.e. 2050. Thus, explicit references to 2050 were removed and it is now stated that NOAK might be reached as early as 2035 if conditions are favourable.
- The assumed solid DACCS plant lifetime increase from 10 to 25 years might be too optimistic. → Added some discussion around the uncertainties in solid DACCS lifetime, also (as mentioned under the third bullet point) sensitivity analysis now includes plant lifetime.

Conclusions

This study improves the current DACCS cost-performance evidence base by synthesising data from the recent literature and technology developers to explore the economic feasibility of different DACCS technologies across timescales, capacities, configurations, and numerous global siting factors. It shows that although DACCS is more expensive than many carbon mitigation and removal options, careful plant siting and rapid learnings can achieve significantly more competitive DACCS costs.

Compared to other NETs, DACCS has some advantages due to its smaller land footprint and water consumption, as well as potential for easy scalability. NETs relying on biomass and ecosystems, such as afforestation, soil carbon storage and BECCS, require significant water and arable land. Other chemical NETs, such as enhanced weathering, risk changing the chemistry of oceans and rivers. DACCS avoids many of these limitations as it has a comparatively small land footprint, but does require a sustainable energy source, geological CO_2 storage to operate, and is relatively immature technology with as-yet unproven deployment potential.

The technoeconomic modelling of base case DACCS configurations showed that the lifecycle emissions associated with DACCS range from 7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants if low carbon energy is used. These are mostly associated with energy carbon intensities, underlining the importance of access to low-carbon energy. Early DACCS projects in the 2020s are likely to range from ~\$400-\$700/net-tCO_2 stored when global average solar PV costs are used, which drop to ~\$350-\$550/net-tCO_2 with low-cost renewables. LCODs for NOAK plants in the 2050s fall to ~\$194-\$230/net-tCO_2 due to reduced electricity prices, financing costs and upfront capital investment. For liquid systems, large-scale plants are significantly more cost-effective due to economies of scale. Solid DACCS costs scale more linearly with size and are likely to be the more cost-effective option for smaller plants (<100ktCO_2/year), with significant potential for cost reduction through innovation. Capex, electricity prices and solid adsorbent costs are found to be the most influential parameters on costs.

An exploration of key global siting factors on DACCS costs and viability reveals that access to CO_2 storage, land and water requirements are not expected to limit global DACCS potential but may determine where plants are built. CO_2 transport and storage costs are found to be ~6-15% of total LCODs which may be reduced by \$20-\$25/tCO_2 if plants use shared infrastructure. Energy costs are found to be as much as 50% of long-term liquid DACCS costs. DACCS costs in the range of ~\$150-\$200/net-tCO_2 may be achieved in the long-term if very low-cost solar energy is used. However, long-term costs are likely to be significantly higher than the industry target of \$100/tCO_2 captured, except under the most ambitious cost-performance assumptions and favourable conditions. The best regions for DACCS will have access to excess low-cost and low-carbon power and heat. These regions also have CO_2 storage resources, have strong commitments to reducing their emissions and have regulatory/policy support for DACCS, CCS and NETs. In the short-medium term, some ideal locations for DACCS may be parts of North America, Western Europe (North Sea), Australia, Middle East and Eastern China, and Japan (although Japan does not have plentiful low carbon electricity sources, some potential for low carbon geothermal heat was identified).

To date DACCS representation in IAMs has been relatively simplistic. Despite seemingly large DACCS deployment potential in existing IAM-based studies, most have focused only on liquid DACCS. Models necessarily rely on relatively sparse and divergent literature for estimates of DACCS cost. Technical parameters compiled and developed throughout this study can be used for representation of DACCS technologies in future IAM studies. IAM practitioners should consider differentiating between DACCS technologies and considering multiple plant configurations, including those running on electricity only and a mix of heat and electricity. Practitioners should also take care to ensure consistent treatment of financing costs for all technologies across their models. Furthermore, operating and labour costs are likely to be region dependent and IAMs can use reference tables to estimate how these costs would differ between countries. The availability of CO_2 storage, renewables, water, and land are key global siting factors which should be investigated further in IAM parameterisation with regional granularity to determine the locations with high DACCS viability and ultimately provide a more nuanced view of overall DACCS potential. Lastly, IAM studies may want to better integrate emerging climate policies, such as separate targets for emissions reduction and negative emissions, by developing alternative scenario designs placing constraints on the ability of NETs to accommodate short term GHG overshoots.

Most current DACCS policy support consists of generic RD&D funding, and financial support aimed at wider NETs or CCS technologies. The US, UK, EU, Canada and Australia are key regions with relatively developed CCS regulations and R&D and demonstration programmes targeting carbon removal or general CCS projects. The 45Q tax credits in the US and California's LCFS are the only financial mechanisms available for large-scale DACCS projects. The key policy priorities of governments wishing to accelerate DACCS deployment in the future should be providing further dedicated R,D&D funding, developing financial incentives which represent fair value of achieving negative emissions, and establishing regulatory frameworks to enable large-scale roll-out DACCS and supporting technologies.

Recommendations

This study shows that current DACCS costs are higher than almost all other point source CCS applications and some sustainable aviation fuels. However, future learning potential, careful siting of large-scale plants, and continued and improved policy support can significantly reduce DACCS costs. To further assess the role and potential of DACCS as part of a portfolio of decarbonisation strategies, the following future work is recommended:

- Further independent engineering analysis of DACCS performance and costs to verify and support commercial data, especially as the technology matures.
- Expansion of the LCA study to include the impact of non-carbon by-products of solvent/sorbent manufacture and energy requirements for mass production of capture chemicals.
- Demonstrations of a range of DACCS technologies and configurations at scale to provide real-world data.
- Detailed review of geographical locations and differences, including costs of external factors as well as siting influence on technical requirements (e.g., water consumption), combined with further research on overall spatial mapping of DACCS potential, cognisant of access to renewables, CO_2 storage, and water and land requirements (especially indirect land footprint from renewables) to refine potential uptake estimates in IAMs.
- R&D on solid sorbents and electric calciners to improve performance and drive down costs.
- Continued R&D on novel DACCS concepts currently at low maturity levels.
- Exploration of value and technical feasibility of flexible DACCS systems, including pilots and wider energy system analysis.
- Better estimates of the potential for roll-out rates of DACCS systems, considering limitations around construction, chemical production, CO_2 storage site development and renewables deployment rates.
- Knowledge sharing and collaboration between academia, technology developers and third-party assessors to make information accessible and accelerate progress.

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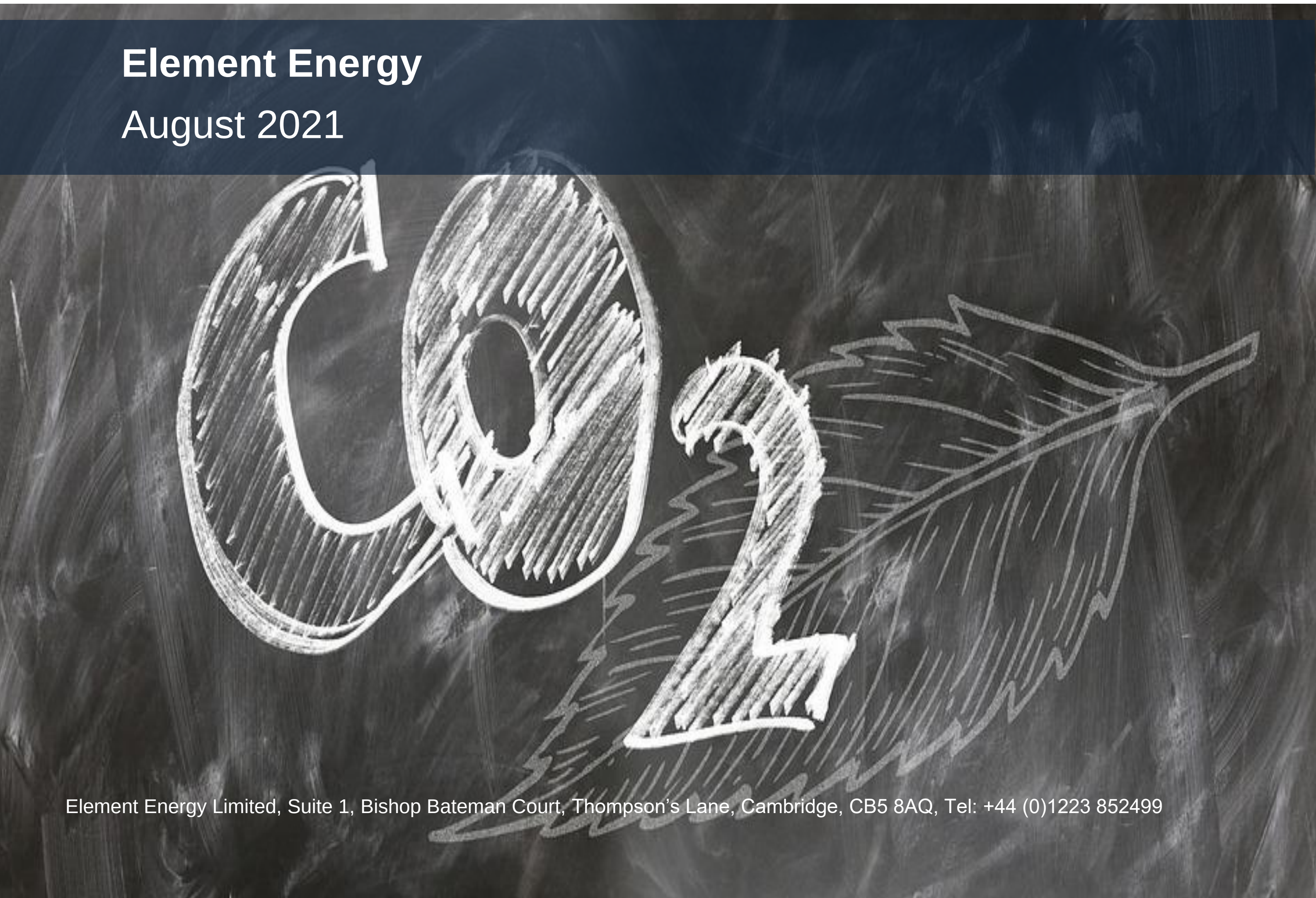
Global Assessment of Direct Air Capture Costs

For IEAGHG



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Element Energy is a strategic energy consultancy, specialising in the intelligent analysis of low carbon energy. The team of over 80 specialists provides consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport. Element Energy provides insights on both technical and strategic issues, believing that the technical and engineering understanding of the real-world challenges support the strategic work.

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Executive Summary

Background and project objectives

Negative emissions technologies (NETs) are essential for limiting atmospheric greenhouse gas concentrations and achieving global temperature targets. NETs, including direct air carbon capture and storage (DACCS), can be used to offset emissions from industries that are very difficult to abate, such as aviation, thereby decoupling decarbonisations efforts from the source of emissions. Analyses by Integrated Assessment Models (IAMs) presented in IPCC reports show that 87% of all IAM scenarios consistent with limiting global temperature rise to 2ºC and 100% of IAM scenarios limiting temperature rise to 1.5ºC require large-scale NETs (1.3 to 29 $GtCO_2$/year) to be deployed in the second half of this century[1].

DACCS has some advantages over other NETs due to its smaller land and water footprint, as well as potential for easy scalability. NETs interacting with biomass, such as afforestation, soil carbon storage and bioenergy with carbon capture and storage (BECCS), require significant water and arable land[2]. Other chemical NETs, such as enhanced weathering, risk changing the chemistry of oceans and rivers[3]. DACCS avoids many of these limitations as it has a comparatively small land footprint, but does require a sustainable energy source, geological CO_2 storage to operate and is relatively immature technology with as-yet unproven deployment potential. Furthermore, the varying levels of modularity of DACCS systems imply potential for easy scaling up and rapid deployment.

Current information on DACCS costs, performance, and impact of plant siting have several data gaps and significant uncertainties. Despite the climate relevance of DACCS technologies, current capture capacities are only at $ktCO_2$/year levels. Therefore, literature on DACCS is limited to few desk-based models and high-level data shared by technology developers with commercial interests. Consequently, most IAMs either omit DACCS or include it without granularity on specific configurations.

This study aims to collate and improve current evidence on the costs of DACCS systems and provide recommendations for the IAM community and policymakers to inform next steps. The study consists of the following objectives:

- **Develop a high-level techno-economic model** to investigate the costs of DACCS technologies across plant scales and timeframes, as well as identifying significant uncertainties and gaps in the literature.
- **Assess key global siting factors** influencing DACCS deployment, such as energy prices and emissions, CO_2 storage and transport availability, regulatory support, land, and water availability.
- **Derive recommendations for the IAM community** on integration of DACCS into IAMs.
- **Discuss the required policy incentives** in the context of current challenges and progress.

Please note that although it is possible to combine DAC with CO2 utilisation to produce low-carbon or net-negative products, this study primarily focusses on combination of DAC with permanent storage so as to provide a common reference point for costs of negative emissions.

Short and long term DACCS costs

To better investigate the current and future DACCS costs under different settings and conditions, a high-level techno-economic model was developed, which calculates the levelised cost of DACCS (LCOD)[4] of each plant configuration, assuming a base plant capacity of 1 $MtCO_2$/year captured. Both liquid solvent and solid sorbent technologies[5] are investigated as first-of-a-kind (FOAK) plants commissioning in mid-2020s

[1] IPCC, 2018- Link
[2] Smith, P., et al., 2016- Link
[3] Kohler, P., et al., 2010- Link
[4] LCOD, expressed in $/t$CO_2$, is calculated by dividing the lifetime costs of a DACCS plant to the total amount of CO_2 it removes over its lifetime, discounted to present day. It is a common metric used to compare projects of different sizes, lifetimes, technologies, etc. Full methodology and assumptions are provided in section 0 and the appendix.
[5] In general, liquid technologies use relatively mature and centralised chemical processes requiring reaching very high temperatures (~900ºC). Solids use more novel processes with more modular designs capable of utilising waste heat at lower temperatures (80ºC -120ºC).

and long-term N^th^-of-a-kind (NOAK) plants, assumed to be in the 2050s. A further distinction is made between plants using pure electricity and hybrid plants requiring both electricity and heat inputs. Lastly, gross LCODs (\$/tCO_2 captured) calculated in the model are converted to net LCODs (\$/tCO_2 net removed) by accounting for some of the lifecycle emissions made throughout the DACCS supply chain.

This study uses 2050 as the base year for NOAK calculations, however, this does not imply that NOAK stage is likely to be reached only by 2050. Reaching NOAK status depends on deployment rates of individual technologies and this study does not make an assumption regarding future DACCS deployment. Here, NOAK roughly coincides to 5-7 doublings of initial large-scale production capacity and depending on future support for DACCS, NOAK stage may be reached by as early as 2035.

Below are the key findings from the techno-economic analysis, which can also be seen in Figure 1:

Current Performance

- Early DACCS projects in the 2020s are likely to range from **~\$400-\$700/net-tCO_2 stored** (when global average solar PV costs are used) depending primarily on scale and type of technology.
- Costs drop to **~\$350-\$550/net-tCO_2** stored[6] with low-cost renewables, therefore early plants are likely to be situated where renewable electricity is most affordable. Liquid DACCS plants get significantly more cost-effective with increasing size due to economies of scale. Solid DACCS costs scale more linearly with size and are likely to be the more cost-effective option for smaller plants (<100ktCO_2/year).

Key Cost Influences

- **Liquid DACCS costs are most sensitive to upfront capital investment (Capex) and electricity prices**. Due to the relatively balanced distribution of costs, most parameters are influential on LCODs, except for consumable prices including capture chemicals.
- **Solid DACCS prices are most sensitive to adsorbent costs** and future adsorbent performance improvements are the single most important factor which will determine cost-effectiveness of solid DACCS. Solid DACCS costs are also more sensitive to plant lifetime and may significantly suffer if lifetime is reduced.

Cost Reduction

- Significant cost reduction can be achieved in the future, with DACCS reaching **~\$194-\$230/net-tCO_2** for 1 MtCO_2/year NOAK plants (~2050), driven by reduced electricity prices, cost of capital and upfront capital investment. Costs are likely to be higher for smaller plants and further cost reduction potential exists for more ambitious renewables and adsorbent cost reduction, with solid technologies having more room for innovation learning as they utilise more novel chemical processes.
- Liquid DACCS further benefits from overall improvements in lifecycle emissions. Solid DACCS technologies experience further cost reduction through increases in plant lifetimes (from 10 to 25 years) and cost-performance improvements of adsorbents.
- CO_2 transport and storage costs are found to be ~6-15% of total LCODs and **costs may be reduced by \$20-\$25/tCO_2 if plants use shared infrastructure.**
- Energy costs are as much as 50% of long-term liquid DACCS costs. **DACCS costs in the range of ~\$150-\$200/net-tCO_2** may be achieved in the long-term if very low-cost solar energy is used.
- Long-term costs are found to be significantly higher than the industry target of \$100/tCO_2 captured, except under ambitious cost-performance assumptions and favourable conditions. These favourable conditions may come to exist, but commenting on the size of the opportunity is difficult.

[6] 1PointFive and Occidental are developing a 1 MtCO_2/year plant using Carbon Engineering's technology. It is expected to be financed by revenues from the 45Q tax credits+ California's Low Carbon Fuel Standards + CO_2 sales, totalling ~\$250-\$300/tCO_2. Carbon Engineering suggest that this model is replicable in the region- Link

Lifecycle Emissions	• Emissions are primarily associated with the energy inputs (electricity and heat) and upstream methane emissions if natural gas is used in the process. Therefore, reducing the carbon intensity of energy sources is of paramount importance. • The lifecycle emissions associated with DACCS range from **7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants** (if low carbon energy is used).
Uncertainties	• Since no large-scale plant is built to date, **inherent uncertainties on most parameters are high**. The largest uncertainties requiring major assumptions are on capital costs, plant scaling factors, future cost reductions through learning, and solid adsorbent cost-performance dynamic.

Global siting factors for DACCS deployment

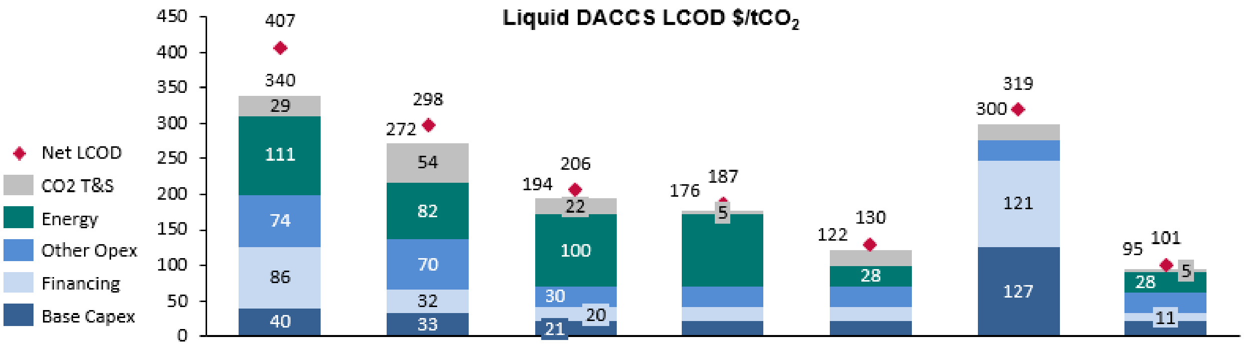
Initially it may appear as if DACCS technologies can be deployed anywhere, with key factors being access to low carbon energy and CO_2 storage resources. This study did not identify many other constraints on overall DACCS potential. However, many other factors such as environmental footprint, downstream CO_2 processing, and legal and policy environments will likely influence specific siting decisions. This study investigated these global siting factors qualitatively and, in some cases, quantitatively.

Dedicated geologic storage space is not likely to restrict global DACCS potential but will influence where DACCS can be deployed cost effectively. Sedimentary basins capable of storing CO_2 over very long periods of time are relatively well distributed around the world and all major CO_2 emitting countries are believed to have access to such storage spaces. Modest estimates calculate global storage potential to be over three times the total greenhouse gas emissions since the beginning of the Industrial Revolution.

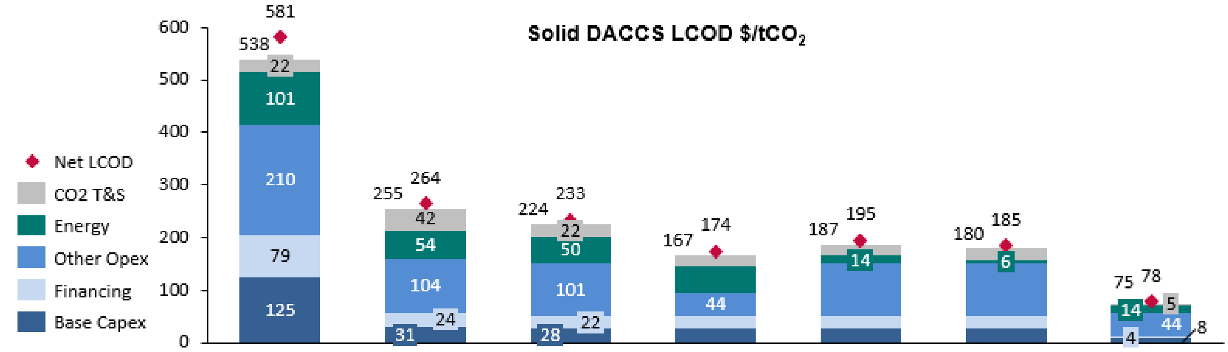
CO_2 transport and storage costs can be significantly reduced by using shared infrastructure. CO_2 transport and storage costs for stand-alone plants are found to be 6-15% of total LCODs but can fall to as low as $5/t$CO_2$ (gross) if large capacity shared infrastructure is used alongside low-cost storage locations.

Utilisation of air captured CO_2 to produce valuable commodities may complement DACCS deployment and help reduce costs in regions where geologic storage is not available or not desired. CO_2 utilisation options may result in permanent CO_2 storage (e.g. construction materials) or displacement of fossil based products (e.g. synthetic fuels), which can be sold at higher prices than their conventional counterparts. Deploying further DAC plants for utilisation can ultimately reduce the costs of DACCS with dedicated geologic storage through supporting early deployment and economies of scale, especially for smaller scale plants. However, estimated future costs of air captured CO_2 are several times more than the costs of CO_2 produced conventionally.

Access to low-cost energy is the most prominent factor determining the economic viability of DACCS. In the long-term solar PV is likely to be the lowest cost electricity source globally, typically in equatorial regions. Other countries usually have access to some combination of low-cost wind energy, new hydropower dams, nuclear waste heat or geothermal energy. Electricity prices are found to be more influential on liquid plants, compared to solids, due to their higher power demand. Therefore, liquid DACCS are likely to be focussed on in regions with lowest-cost low-carbon electricity prices. Furthermore, for most efficient operation, hybrid solid DACCS plants need to be co-located with a source of waste heat, potentially restricting its deployment to vicinities of existing industrial sites, nuclear or geothermal plants. Fossil fuel energy sources are not expected to result in economically viable DACCS costs unless almost all associated emissions are captured as may be done in hybrid liquid DACCS alternatives.



Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low T&S Cost	5- Low-Cost Solar	6- Flexible Operation	7- Very Ambitious
Maturity	FOAK	NOAK	NOAK	NOAK	NOAK	NOAK	NOAK
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Electric	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Base Case	Base Case	15% Plant Utilisation	Base Case
Electricity Source	Solar PV – Base Case ($68/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Low ($14/MWh)	Free Solar PV	Solar PV – Low ($14/MWh)
CO_2 T&S	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	In Cluster ($5/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	In Cluster ($5/tCO$_2$)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%



Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low-Cost Adsorbent	5- Low-Cost Electricity	6- Low-Cost Energy Hybrid	7- Very Ambitious
Timeline	FOAK 2020s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Hybrid	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Low Sorbent Cost	Base Case	Base Case	Low Sorbent Cost & High Learning Rate
Electricity Source	Solar PV – Base Case ($68/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Low ($50/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)
Heat Source	Nuclear ($19/MWh)	Nuclear ($19/MWh)	-	-	-	Free Waste Heat	-
CO_2 T&S	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	Base Case ($22/tCO$_2$)	In Cluster ($5/tCO$_2$)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%

Figure 1: Charts and tables showing technical parameters describing key liquid and solid DACCS cases and breakdown of associated gross and net costs. Base cases showing long-term electric plant parameters are highlighted. Parameters which are same as the base case are faded. Please see page 32 for more information on definition of these cases.

DACCS plants operating flexibly to follow renewable generation may access lower-cost electricity, but overall LCODs are expected to be higher than continuous operation. Solar and wind are intermittent energy sources, therefore operating DACCS plants with renewables will either require energy storage, purchasing a portfolio of low-carbon power or operating plants flexibly to match renewable generation. Reducing the operating hours of plants is likely to be technically feasible but would increase the impact of capital costs on LCODs. Operating plants at a 15% load factor, as opposed to 90%, would increase long-term levelised costs of DACCS in 2050s by up to 50%, even if electricity is assumed to be free of charge.

Land and water requirements for DACCS, which depend on the source of energy and regional climate, are not expected to be restrictive in most areas. Land occupied by DACCS plants is relatively inconsequential, estimated to be 2,000 km^2 for a total capacity of 1 $GtCO_2$/year including space for solar PV[7]. This footprint is estimated to be orders of magnitude smaller than area required to remove the same amount of CO_2 by afforestation and BECCS, and may even reduce further if other power sources, such as nuclear, are used. Similarly, water requirements are not likely to be limiting for most regions, though they will likely influence siting choices. A total DACCS capacity of 1 $GtCO_2$/year is calculated to consume only 0.16% of agricultural water used globally. In the worst case, supplying water through desalination is estimated to increase LCODs by less than 5%. Moreover, some regions with poor water supplies, such as deserts, may save costs on solar PV generation.

Public acceptance, policy, and regulatory support for DACCS and relevant enabling technologies are often overlooked factors influencing practical feasibility of rapid scaleup. The US, Canada, the UK, Norway, China, Japan, and Australia are countries with some of the most favourable policies supporting carbon capture and storage (CCS). Furthermore, CCS regulatory provisions are most developed in North America, Australia, and the European Union. Considering the close link between CCS and DACCS technologies, these regions may be the most suitable for early deployment.

Carbon capture clusters with access to shared CO_2 infrastructure and low-carbon renewables/gas are ideal sites for future DACCS plants which can reduce LCODs significantly. Electricity price is found to be the most influential parameter for liquid DACCS costs; the most ideal settings with lower cost of capital, lower electricity price and shared CO_2 infrastructure resulted in costs ~\$100/net-tCO_2. For solid DACCS plants adsorbent price is the most important parameter, and ambitious performance improvements may cut LCODs by 25%. Under similarly ambitious assumptions, including additional capital cost reduction through high learning rates, solid DACCS may reach LCODs as low as \$80/net-tCO_2.

Inclusion of DACCS in IAMs

To date DACCS representation in IAMs has been relatively simplistic. IAMs are one of the most influential quantitative tools with respect to global climate change mitigation analyses. Despite seemingly large DACCS deployment potential in existing IAM-based studies, most have focused on liquid DACCS and only one has considered solid technologies in their portfolios[8]. Models necessarily rely on relatively sparse and divergent literature for estimates of DACCS cost. Indeed, the literature presents wide cost ranges from \$30-\$1000/tCO_2, with estimates from sources close to industry ranging from \$100-\$300/tCO_2.

Technical parameters compiled and developed throughout this study can be used for representation of DACCS technologies in future IAM studies. A summary table of key techno economic DACCS parameters emerging from this study is presented on page 44, which includes two values for most parameters to represent typically more ambitious commercial data and more conservative literature/academic data. IAM practitioners should consider differentiating between DACCS technologies and considering multiple plant configurations, including those running on electricity only and a mix of heat and electricity. Practitioners should also take care to ensure consistent treatment of financing costs for all

[7] The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. C. Beuttler, et al., 2019.
[8] An inter-model assessment of the role of direct air capture in deep mitigation pathways. Realmonte, G., et al., 2019.

technologies across their models. Furthermore, operating and labour costs are likely to be region dependent and IAMs can use reference tables to estimate how these costs would differ between countries.

DACCS uptake in a range of models, including IAMs, is very high and and not significantly limited by uptake constraints investigated to date. Non-IAM analyses often report DACCS capacities in the range of 10-15 $GtCO_2$/year by the late century. In contrast, IAM-based studies often produce scenarios with even greater potentials of up to 30-40 $GtCO_2$/year by 2100. The availability of CO_2 storage, renewables, water, and land are key global siting factors which should be investigated further in IAMs with regional granularity to determine the locations with high DACCS viability and ultimately provide a more nuanced view of overall DACCS potential.

Current and future DACCS policy support mechanisms

Most current DACCS policy support consist of RD&D funding and financial support aimed at wider NETs or carbon capture and storage (CCS) technologies. The US, the UK, the EU, and Australia are key regions with relatively developed CCS regulations and R&D and demonstration programmes targeting carbon removal or general CCS projects. The 45Q tax credits in the US (priced at \$50/tCO_2 removed and currently under revision for a potential increase) and California's Low Carbon Fuel Standards are the only financial mechanisms in the world available for large-scale DACCS projects at the time of writing this report. Additional supporting policies include consideration of DACCS in national decarbonisation roadmaps (e.g. the UK), ongoing development of robust negative emissions accounting frameworks in the EU and establishment of a Carbon Removal Program and a Carbon Dioxide Removal Taskforce in the US.

Governments may implement a range of different policies and actions if they aim to deploy DACCS at scale:

- **Increasing R&D and demonstration funding** earmarked for DACCS technologies and related value chain components, with particular emphasis on improving capture chemicals, scaling up systems, supporting FEED studies and knowledge sharing networks.
- **Financial support to reduce the burden of high Capex**, such as tradable tax credits, low interest loans or loan guarantees, private activity bonds, accelerated depreciation, and direct equity investment.
- **Financial mechanisms to provide revenues for CO_2 removal,** including establishing a negative emissions trading scheme, clean energy standards, tradable tax credits, direct procurement, or contract for differences.
- **Supporting and accelerating permitting** for DACCS projects and infrastructure (including CO_2 storage, renewable generation, and electricity infrastructure) to reduce development timeframes and costs.
- **Developing comprehensive regulatory frameworks** for CO_2 accounting, including measurement, monitoring, and verification standards.
- **Incentivising CO_2 utilisation with DAC** by developing markets for CO_2-based products through procurement programmes and development/maintenance of public product databases.
- **Separating national targets for CO_2 mitigation and removal.**
- **Continued support and data sharing on CO_2 storage site appraisal**.
- **Prioritising public engagement and social considerations** to improve DACCS perception and knowledge among many stakeholders.
- **Having strong governance and international cooperation** especially for developing CO_2 measurement, monitoring and verification standards and cross-border CO_2 T&S infrastructure.

Recommendations for further work

This study shows that current DACCS costs are higher than almost all other point source CCS applications (ranging from $50/t$CO_2$ for capture from steel plants to $180/t$CO_2$ for aluminium plants[9]) and some sustainable aviation fuels (virtually all options costing[10] higher than $300/t$CO_2$). However, future learning potential, careful siting of large-scale plants, and continued and improved policy support can significantly reduce DACCS costs.

To further assess the role and potential of DACCS as part of a portfolio of decarbonisation strategies, the following future work is recommended:

- Further **independent engineering analysis** of DACCS performance and costs to verify and support commercial data, especially as the technology matures.
- **Expansion of the LCA study** to include potential leakage from CO2 T&S infrastructure, the impact of non-carbon by-products of solvent/sorbent manufacture and energy requirements for mass production of capture chemicals.
- **Demonstrations of a range of DACCS technologies** and configurations at scale to provide real-world data.
- **Detailed review of geographical locations and differences**, including costs of external factors as well as siting influence on technical requirements (e.g., water consumption), combined with **further research on overall spatial mapping of DACCS potential**, cognisant of access to renewables, CO_2 storage, and water and land requirements to refine potential uptake estimates in IAMs.
- **R&D on solid sorbents and electric calciners** to improve performance and drive down costs.
- **Continued R&D on novel DACCS concepts** currently at low maturity levels.
- **Exploration of value and technical feasibility of flexible DACCS systems**, including pilots and wider energy system analysis.
- **Better estimates of the potential for roll-out rates of DACCS systems**, considering limitations around construction, chemical production, CO_2 storage site development and renewables deployment rates.
- **Knowledge sharing and collaboration** between academia, technology developers and third-party assessors to make information accessible and accelerate progress.

[9] Technology readiness and costs of CCS. GCCSI, 2021.
[10] Levelised cost of carbon abatement: an improved cost-assessment methodology for a net-zero emissions world. Friedmann J., et al., 2020.

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Contents

Acronyms

BECCS	Bioenergy with carbon capture and storage
Capex	Capital expenditure
CC(U)S	Carbon capture (utilisation and) storage
CDR	Carbon dioxide removal
CE	Carbon Engineering
CfD	Contract for difference
CH4	Methane
CO_2	Carbon dioxide
CRF	Capital recovery factor
CSP	Concentrated solar power
DAC(CS)	Direct air (carbon) capture (and storage)
EOR	Enhanced oil recovery
ETS	Emissions trading scheme
EU	European Union
FEED	Front End Engineering Design
FEL	Front end loading
FOAK	First-of-a-kind
GCCSI	Global CCS Institute
GGR	Greenhouse gas removal
HHV	Higher heating value
IAM	Integrated assessment model
IEA	International Energy Agency
LCA	Lifecycle analysis/assessment
LCFS	Low Carbon Fuel Standard
LCOD	Levelised cost of DACCS
LCOE	Levelised cost of electricity
LF	Load factor
LHV	Lower heating value
MMV	Measurement, monitoring and verification
$MtCO_2e$/year	Mega tonnes of CO_2 equivalent per year
NETs	Negative emissions technologies
NG	Natural gas
NOAK	Nth-of-a-kind
Opex	Operational expenditure
RAB	Regulated asset base
R&D	Research and development
R&I	Research and innovation
TEA	Techno-economic analysis/assessment
T&S	Transport and storage
TRL	Technology readiness level
US DOE	United States Department of Energy
VALCOE	Value-added LCOE
WACC	Weighted average cost of capital

1. Introduction

1.1 Background

Negative emissions technologies (NETs) are essential for limiting atmospheric greenhouse gas concentrations and achieving global temperature targets. NETs can be used to offset emissions from industries that are very difficult to abate, such as aviation, thereby decoupling decarbonisations efforts from the source of emissions. Analysis by Integrated Assessment Models (IAMs) presented in IPCC reports show that 87% of all IAM scenarios consistent with limiting global temperature rise to 2ºC and 100% of IAM scenarios limiting temperature rise to 1.5ºC require large-scale NETs to be deployed in the second half of this century[11].

The total capacities of NETs deployed in climate models show considerable variation. For example, extensive review of published IAM studies reveal that scenarios consistent with the 1.5ºC target have NETs capacities in the range of 1.3 to 29 $GtCO_2$/year, most falling between 5 and 15 $GtCO_2$/year[12] in the second half of the century. These models usually calculate economically feasible capacities where alternative emissions mitigation methods would be more expensive. A recent study[13] adopts a bottom-up approach to estimate the hard-to-abate emissions based on environmental justice and technical restrictions (as opposed to economic considerations), arriving at carbon removal requirements of 1.5 to 3.1 $GtCO_2$/year by 2100. Lastly, as shown in Figure 2 below, the International Energy Agency's (IEA) Net Zero scenario[14] estimates a ramp up carbon removal to 1.9 $GtCO_2$/year in 2050 to offset all remaining emissions.

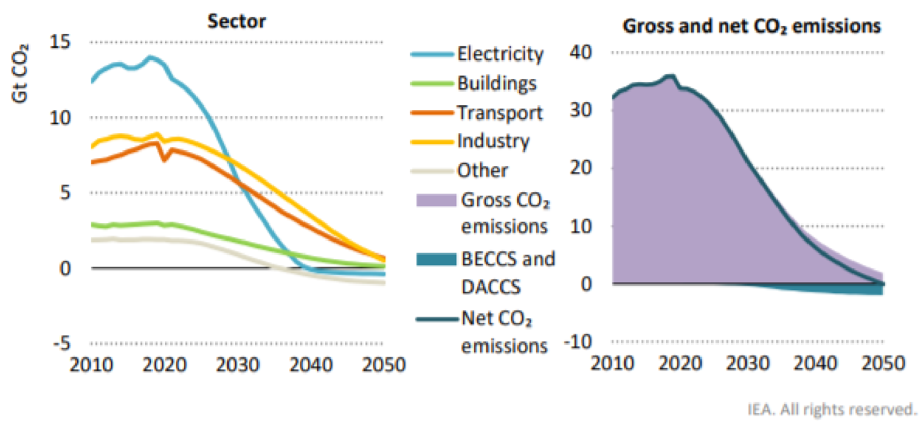


Figure 2: Global sectoral net CO_2 emissions and negative emissions required to reach net-zero in IEA's Net Zero Emissions Scenario (IEA Net Zero by 2050, 2021)[14]

Direct air capture (DAC) refers to technologies which separate and isolate CO_2 from dilute sources, such as the atmosphere. DAC can be coupled with carbon utilisation to produce low carbon products or can permanently store the captured CO_2 in underground geological formations (called direct air carbon capture and storage- DACCS) to generate negative emissions. DACCS is mostly perceived to have less restrictions for global siting and deployment than other NETs, as it may not compete for agricultural land and scarce bioresources. This has led some climate scenarios to include very high levels of DACCS deployment, whereas some other studies approach DACCS with caution. Fuss et al. (2018) estimates[12] a DACCS deployment potential of 0.5-5 $GtCO_2$/year by 2050. On the other hand, the IEA's Net Zero Emissions Scenario includes 985 $MtCO_2$/year of DAC in 2050, 630 $MtCO_2$/year of which is DACCS specifically.

[11] IPCC Special Report Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. 2018.
[12] Negative emissions—Part 2: Costs, potentials and side effects. Fuss et al., 2018.
[13] CDR Primer. J. Wilcox, B. Kolosz, & J. Freeman, 2021.
[14] Net zero by 2050: a roadmap for the global energy sector. IEA, 2021.

Integrated assessment models (IAMs) are one of the most influential quantitative tools with respect to global climate change mitigation analyses, however DACCS representation in IAMs has been limited so far. For a long time, afforestation and BECCS were seen as the only available NETs, therefore many studies are restricted by the type of NETs they allow in their technology mix. Over the past decade studies have started to incorporate DACCS and other options, as more information has become available. It is very unlikely that the required levels of negative emissions can be realistically delivered by one or two types of NETs, so there is value in better understanding and representing DACCS as part of a portfolio of solutions in future modelling studies.

Current information on DACCS costs, performance, and the impact of plant siting contains several data gaps and significant uncertainties. Despite the climate relevance of DACCS technologies, current capture capacities are only at ktCO_2/year levels. Therefore, literature on DACCS is limited to few desk-based models and high-level data shared by technology developers with commercial interests, making it difficult to accurately understand and represent the technoeconomic potential of DACCS.

1.2 Study aims, objectives and report structure

In light of the above discussion, it is clear that although DACCS appears to be a valuable technology option for long-term global decarbonisation strategies, current data presents significant uncertainties and DACCS representation in IAMs is very limited.

This study aims to collate and improve current evidence on costs of DACCS systems and provide recommendations for the IAM community and policymakers to inform next steps. Specific objectives include:

- Developing a high-level techno-economic model to investigate the costs of DACCS technologies across plant scales and timeframes, identifying significant uncertainties and gaps in the literature.
- Assessing key global siting factors influencing DACCS deployment, such as energy prices and emissions, CO_2 storage and transport availability, regulatory support, land, and water availability.
- Deriving recommendations for the IAM community on integration of DACCS into IAMs.
- Reviewing current DACCS policy support and identifying future policy recommendations in the context of current DACCS challenges and progress.

Throughout the study external stakeholder engagement was conducted to extract input and feedback around methodology, data gathering and project outputs from the DACCS, modelling and wider NETs community.

The rest of this report is structured into the following sections:

Section 2 provides an overview of the main DACCS technologies, including their status, current capacities, deployment plans in the near future.

Section 3 presents a high-level techno-economic model and summarises emissions and costs of DACCS technologies in the short and longer terms. It also explores the sensitivities and uncertainties of main parameters.

Section 4 discusses the major global siting factors which influence the technical feasibility and economic viability of DACCS deployment in different regions and suggests low hanging fruits for early projects.

Section 5 reviews current DACCS representation in IAMs and synthesises the results of the previous sections to provide an updated set of parameters suitable for future use in IAM studies.

Section 6 summarises existing DACCS related policies/actions and presents policy recommendations to incentivise rapid DACCS deployment.

Section 7 summarises the key conclusions and recommendations for further work.

Section 8 lists the references to the literature in alphabetical order.

Section 9 contains the appendix showing detailed assumptions, results and data acquired for this project.

2. Current status of DACCS and comparison to other NETs

This section provides a brief overview of the most common DACCS technologies, current DACCS development levels, current deployment and future plans and cost trajectories in the literature. After summarising the features of DACCS systems, comparisons are made with other NETs to better understand its strengths and weaknesses as well as its environmental impact in relation to alternative options.

2.1 DAC technology overview

All DAC technologies broadly operate at two stages: first CO_2 is captured by some type of chemical after coming into contact with air, then CO_2 is released from this chemical and collected for processing. There are two broad types of DAC technologies, usually called liquid absorbents and solid adsorbents (liquid and solid DAC for short), named after the type of chemical, used to capture the CO_2. Carbon Engineering, one of the 3 main DAC technology developers, uses a liquid process, whereas Climeworks and Global Thermostat employ solid adsorbents.

Figure 3 below illustrates the chemical processes of Carbon Engineering's current DAC system using a hybrid energy configuration [15]. In general, liquid technologies use hydroxide solutions in air contactors to capture CO_2, which is later passed on to calcium containing chemicals and released when $CaCO_3$ pellets are heated with natural gas in an oxy-fired calciner. Loops regenerate chemicals and all the CO_2 generated from natural gas combustion is co-captured inherently in the process. The CO_2 release process requires heat at high temperatures (~900 ºC). Future optimization and evolution of this process as described section 3.2 results in the all-electric driven configurations depicted in Carbon Engineering's longer-term models.

Most process equipment used by liquid DAC systems are well established chemical process equipment. The front-end capture process has modular design meaning air contactors are made up of smaller repeating units allowing for mass production. The CO_2 release processes are more central and rely on economies of scale where higher capacity plants experience significant cost reduction.

The process requires some make-up of capture chemicals (hydroxide solution and $CaCO_3$), on-site oxygen production and water.

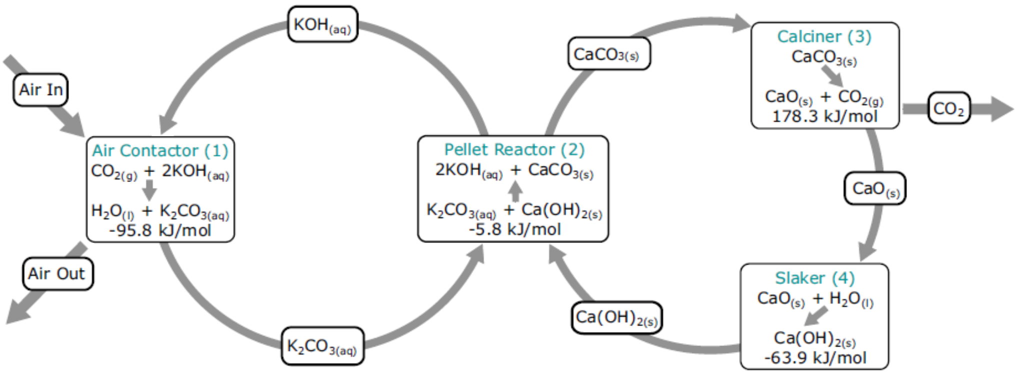


Figure 3: Summary of Carbon Engineering's DAC process using recirculating liquid absorbent with thermal calcination[15]

There are more technology developers working on solid DAC systems, leading to a range of technology designs. This section summarises the key general features of solid technologies along with an illustration of Climeworks' unit design[16] in Figure 4. In solid systems, CO_2 is captured when it binds to functionalised chemicals on solid filters in the air contactor. Each air contactor module operates cyclically, where CO_2 is captured in phase 1 and released in phase 2. Therefore, modules alternate between adsorption and

[15] A process for capturing CO_2 from the atmosphere. Keith et al., 2018.
[16] The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. C. Beuttler, et al., 2019.

desorption modes. CO_2 release is achieved via temperature-vacuum swing, where adsorbents are heated, and a vacuum is applied to force desorption.

Contrary to the liquid DAC, solids use heat at lower temperatures (80-120 ºC), possibly allowing waste heat from large industrial facilities or power plants to be used. The designs of solid systems are usually more modular than liquids, where both phases happen in a single unit which could be mass produced. Plants of desired capacities can be built by stacking the necessary amount of such units, which suggests that costs are expected to scale mostly linearly with plant size, except for common ancillary units. Depending on regional humidity, water may be another consumable or may be co-produced with CO_2.

Solid systems use more novel processes compared to liquids; therefore, they may have more room for cost reduction. However, the process currently requires frequent replacement of adsorbents, increasing costs.

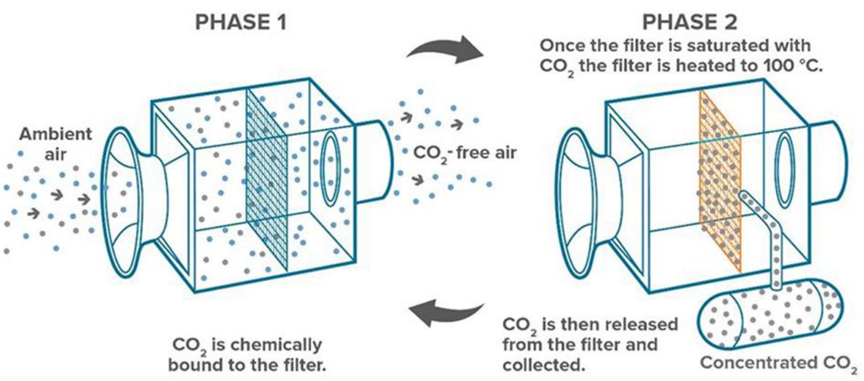


Figure 4: Schematic illustration of Climeworks DAC air contactor units using solid adsorbents and a temperature-vacuum-swing process (Beuttler et al., 2019)[16]

2.2 DACCS technical maturity and current capacities

A useful metric to classify maturity of technologies are technology readiness levels (TRLs), which indicate the stage a technology is at on its way to large-scale commercialisation. Typically, lower values are associated with technologies at concept or early laboratory experiments stages and higher values are associated with at scale demonstration and deployment. Figure 5 below shows the TRL ranges of various components of a DACCS value chain, according to the IEA's Energy Technology Perspectives[17].

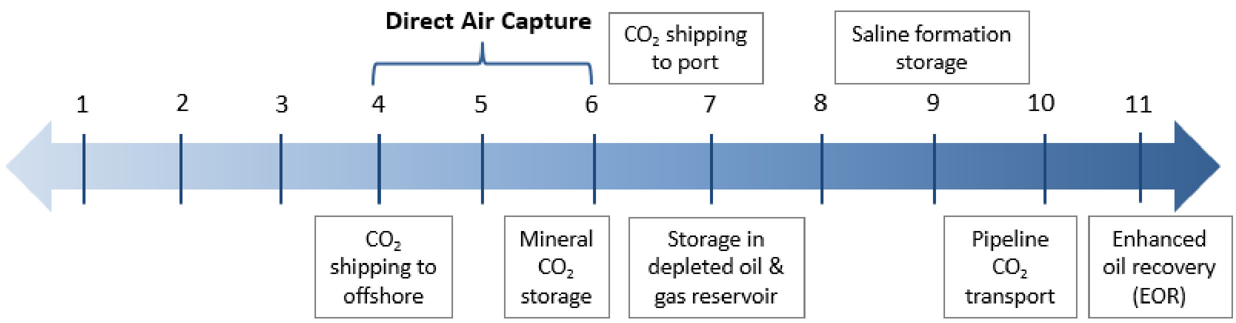


Figure 5: Technology readiness levels of DACCS value chain technologies[17,18,19]

Currently DAC is believed to be at TRL 4-6 where higher TRLs are represent the progress of the major technology developers and lower TRLs correspond to several other emerging technologies which are at

[17] Energy technology perspectives 2020. IEA, 2020- Link

[18] Mineral CO_2 storage refers to permanent storage in basalt rock formations. Its TRL is based on Element Energy's judgement.

[19] DAC TRL refers to large-scale system and is based on Element Energy's judgement (IEA has DAC at TRL 6).

various stages of demonstrating their technologies at small scales. In general, CO_2 transportation through pipelines is a well-established practice, however, shipping CO_2 to other ports or directly to offshore storage sites are still at medium TRLs, needing further demonstration. Using CO_2 for enhanced oil recovery (EOR) or storage in saline formations are the two more mature storage options. In summary, the CO_2 transport and storage (T&S) components of the DACCS value chain are relatively well understood and not likely to pose any technological limitations. On the other hand, the capture component still needs demonstrating as large scale.

This study focusses on the most mature DACCS technologies which are the solid and liquid options developed by the main technology developers discussed above. Lower maturity DACCS concepts are an active area of R&D and could be very promising in the future, but they are excluded from this study due to lack of data.

Currently there are 15 operational DAC plants in the world[20] with a total capacity of 11.3 $ktCO_2$/year. Larger plants either store the CO_2 in geologic formations or use it in the beverages industry, however, demonstrator plants have wider applications including greenhouse fertilisation and production of chemicals and fuels.

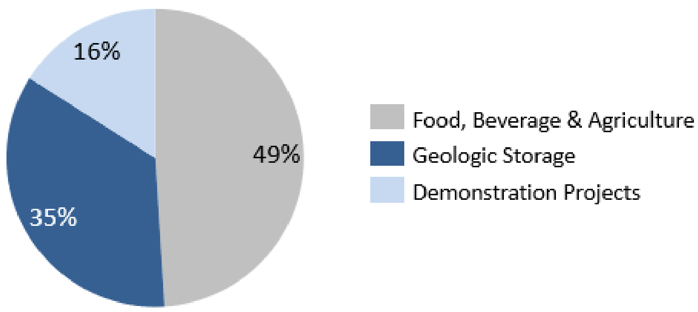


Figure 6: Breakdown of the current DAC capacity[20]

Some notable DAC projects under development are:

- **Carbon Engineering:** 1 $MtCO_2$/year plant in Texas is planned for 2024 in partnership with Oxy Low Carbon Ventures for EOR application.
- **Climeworks:** A 4 $ktCO_2$/year plant for dedicated storage in Iceland will be operational by mid-2021. Credits will be sold to clients including Microsoft, Stripe, Audi, and Shopify.
- **Global Thermostat:** Two plants are under construction, each with 2 $ktCO_2$/year capacity, to explore industrial use of CO_2. They are expected to be operational by late 2021.

2.3 DACCS literature and cost projections

A review of recent DACCS literature reveals that there are only a limited number of studies (<20) with detailed analysis of DACCS costs. A high portion of these studies provide only secondary or tertiary data which build on previous assumptions and outputs. At times, the separation between academic work and commercial data is blurred since some researchers are part of DACCS companies and some studies partially use data from these companies.

Direct comparison of DACCS costs between studies are also challenging due to the high impact of assumptions on external parameters. Energy prices, cost of capital and lifecycle emissions are relatively influential on final costs and can vary considerably between studies. Furthermore, almost none of the studies include CO_2 transport and storage costs, hence reported outputs are technically not fully representative of delivering negative emissions.

[20] The DAC MAPP by Carbon 180 [accessed 29 April 2021]- Link

Representative techno-economic parameters on solid and liquid DACCS technologies are provided in Table 19 in Appendix 5, using a few of the more recent studies in the literature. These data are provided for background information and are not all used in the current study.

Below are some of the short and long term DACCS costs estimates from the literature:

- **Current costs:** After reviewing available DAC literature in 2018, Fuss et al. estimated[12] first of a kind (FOAK) DAC costs to be \$600-\$1000/tCO_2, whereas IEA Energy Technologies Perspectives[21] (2020) reports overall DAC costs as \$130-\$340/tCO_2. US National Academies of Sciences[22] (2019) calculates medium net removal cost ranges for liquid DAC as \$156-\$506/tCO_2 and solid DAC as \$89-\$877/tCO_2 based on various fuel assumptions. Rhodium Group[23] has slightly more optimistic estimates of \$124-\$325/tCO_2 across different technologies and assumptions.

- **Cost projections:** Cost reduction potential of DAC in the literature is mostly speculative, based on applying learning rates observed in other sectors or adopting targets declared by tech developers. Fuss et al. (2018) expects[12] Nth of a kind (NOAK) cost to reduce to \$100-\$300/tCO_2. Fasihi et al. (2019) estimate[24] that DAC capital costs may reduce by up to 75% if ~0.5 GtCO_2/year cumulative capacity is reached. Rhodium Group[23] is also very optimistic with long term DAC costs of \$46-\$164/tCO_2 in a 2050 timeframe. Most technology developers quote a future target of reaching \$100/tCO_2 if capacities can be sufficiently expanded[25].

2.4 DACCS in comparison to other NETs

DACCS is only one of the technologies capable of delivering negative emissions, therefore comparing its attributes to other NETs is useful to understand its strengths and weaknesses as well as conditions where it can be a more competitive option. Table 1 below summarises the main characteristics of major NETs based on Fuss et al. (2018)[12] and the UK Royal Society Greenhouse Gas Removal Report (2018)[26] which base their analysis on literature reviews and authors' judgements.

Some nature-based NETs- such as afforestation/reforestation, soil carbon sequestration and ecosystem restorations- are techniques practiced for long periods of time, hence have the highest TRLs. BECCS and DACCS are engineered or hybrid options where underlying operating processes are well understood, but they need to be optimised and demonstrated in more commercial settings. Biochar is more suitable for smaller applications with uncertainty around its exact impact on agricultural soils. Lastly, enhanced weathering and ocean-based removal are simple concepts but lag in terms of real-world data and demonstrations.

All NETs display relatively high-cost variability, but both the literature and the current study implies that DACCS is likely to be one of the most expensive carbon removal options, especially compared to mature natural solutions. Furthermore, DACCS has almost no co-benefits besides CO_2 removal, whereas other options generally result in useful co-products and/or improve the quality of the environment.

DACCS, BECCS and potentially enhanced weathering positively separate from the other NETs in their ability to provide permanent geologic storage. Natural solutions generally depend on storing CO_2 in the form of biomass or biomass derived products, which needs to be managed and/or monitored and is under constant risk of re-emissions.

DACCS also has fewer negative impacts and siting restrictions than most other NETs. As long as it has access to low-carbon energy and CO_2 storage resources, DACCS can be deployed in most regions (albeit

[21] IEA ETP 2020 special report on CCUS, 2020.
[22] Negative emissions technologies and reliable sequestration: a research agenda. National Academy of Sciences, Engineering, and Medicine, 2019.
[23] Capturing leadership: policies for the US to advance direct air capture technology. Rhodium Group, 2019.
[24] Techno-economic assessment of CO2 direct air capture plants. Fasihi et al., 2019.
[25] News article- Link
[26] Greenhouse gas removal. UK Royal Society, 2018.

with differing costs). NETs relying on ecosystems or biomass compete for scarce agricultural land and other scarce bioresources (even if waste residues are used). Furthermore, they usually have very large land footprints, since they rely on plant growth or spreading certain chemicals/solids over large areas. Although biochar may have positive agricultural benefits, these are currently not well understood or quantified. DACCS does require mass production of capture chemicals, but these are mostly recycled in the process and are generally believed to not restrict large-scale deployment.

Lastly, a factor which is often overlooked in technology comparisons is public perception or social acceptability. Literature on public attitudes on negative emissions is extremely sparse but some early surveying suggests that the public may be more in favour of mature nature-based solutions as opposed to engineered technologies[27]. Further discussion of social acceptance is provided in Box 4 in section 6.1.

[27] The path to net zero. Climate Assembly UK, 2020.

Table 1: Comparison of different NETs attributes, adapted from Fuss et al. (2018)[12] and UK Royal Society (2018)[26]

NETs	Potential[28] $GtCO_2$/year	Costs[28] $/t$CO_2$	Positive Impacts	Negative Impacts	CO_2 Permanence	TRLs	Siting Constraints
DAC[29]	0.5 - 5	100 – 300	Some applications can improve indoor air quality	Some land requirement, potential impact of materials/chemicals consumption, high current costs and energy requirements	High permanence with adequate geological storage	4 – 6	Requires CO_2 storage options nearby with preference for CCS clusters to reduce CO_2 T&S costs. Low cost and low-carbon electricity as well as waste heat availability important.
BECCS	0.5 - 5	100 – 200	Electricity, heat or biofuels as co-products, energy independence, economic diversification	Competition with agricultural land, deforestation, biodiversity losses, albedo change, land use change emissions	High permanence with adequate geological storage	Bioenergy: 7 – 9 BECCS: 4 – 7	Requires CO_2 storage options nearby with preference for CCS clusters. Constrained by biomass availability. Locations with high forest activity and land not tied for agriculture have higher potentials.
Afforestation/ Reforestation	0.5 – 3.6	5 – 50	Improved soil, carbon, nutrient, and water cycle; potential biodiversity improvement; local livelihood; environmental services (flood protection)	Competition with agricultural land, potential for biodiversity loss, albedo change, land use change	Vulnerable to disturbance, requires maintenance, sink saturation may limit capacity	8 – 9	Main limitation is land requirements. Forests should not compete with agricultural land or areas designated for social use. Countries with most potential[30] are Russia and Canada (boreal), US, Australia, Brazil (tropical), and China.
Enhanced Weathering	2 – 4	50 – 200	Increase crop yield, improved soil fertility, nutrient, moisture, increased soil pH	Mineral extraction/transport impacts, risk of heavy metal release, change in soil hydraulic properties	Months to geological scales	1 – 5	Needs to be applied to croplands or beaches. USA, China, India and Brazil have high potentials[31]. Silicate mining may be needed, requiring additional energy, for larger volumes, but resources are well distributed globally.
Ocean Fertilisation	[0.5 – 44][32]	[0 – 460][32]	Enhanced biological production, potential increase in fish catches	Nutrient balance change. Potential impact on marine biology unknown.	Fragile, from months to millennia	1 – 5	Will require energy, raw materials and smaller amounts of land and water for iron fertilisation. Using nitrate/phosphate may require more resources than iron. Transport infrastructure for minerals and proximity to oceans needed.
Biochar	0.5 – 2	30 – 120	Reduced CH_4 and N_2O emissions, increased crop yield, reduced drought, improved water, nutrient cycling	Competition for biomass sources, plant vulnerability may increase if plant defence is downregulated	Decades to centuries depending on soil type, management, and conditions	3 – 6	Biochar projects are likely to be relatively small scale. Proximity to biomass sources (such as forests) and agricultural land to spread the biochar are main considerations.
Soil Carbon Sequestration	2 – 5	0 – 100	Pollution reduction, increased soil quality, improved soil resilience, agricultural production, water/air quality	Possible increased N_2O emissions, faster depletion of N and P	Reversable if practices are discontinued	8 – 9	Can be applied to all managed land at low cost. Main barriers are lack of knowledge or incentive. Countries with large managed lands should have high potential.

28 Reported potentials and costs are authors' best estimates based on the ranges presented in the literature.
29 Does not include CO_2 transport and storage. Will need to add a T&S price in the range of $8-$35/tCO_2 for full DACCS costs.
30 The global tree restoration potential. Bastin et al., 2019.
31 Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Beerling et al., 2020.
32 Fuss et al. (2018) see limited potential for ocean fertilisation. Reported numbers are min-max in the literature.

3. Techno-economic analysis

This section presents the methodology used to develop a high level technoeconomic DACCS model and investigates short and long-term costs of carbon removal. It also explores the key parameters which are most impactful on DACCS costs to understand potential for improvements. Finally, a quick discussion on data quality and uncertainties is provided.

3.1 Methodology for TEA

In this study the short- and long-term costs of DACCS technologies are calculated through a high-level technoeconomic analysis (TEA). Figure 7 below summarises the key input and output parameters of the model. Parameters such as CO_2 transport and storage (T&S) costs, energy prices and energy carbon intensities are more regionally dependent, whereas capital expenditure (Capex), scaling factors[33], cost of capital operation and maintenance costs are technology dependent in the model. In practice, some of these factors would show regional variation as well, for instance the cost of capital changes according to the risk premium of countries, but this global TEA does not take these regional influences into consideration.

The source of the data used in this TEA and key uncertainties are discussed at the end of this sub-section and in section 3.4.

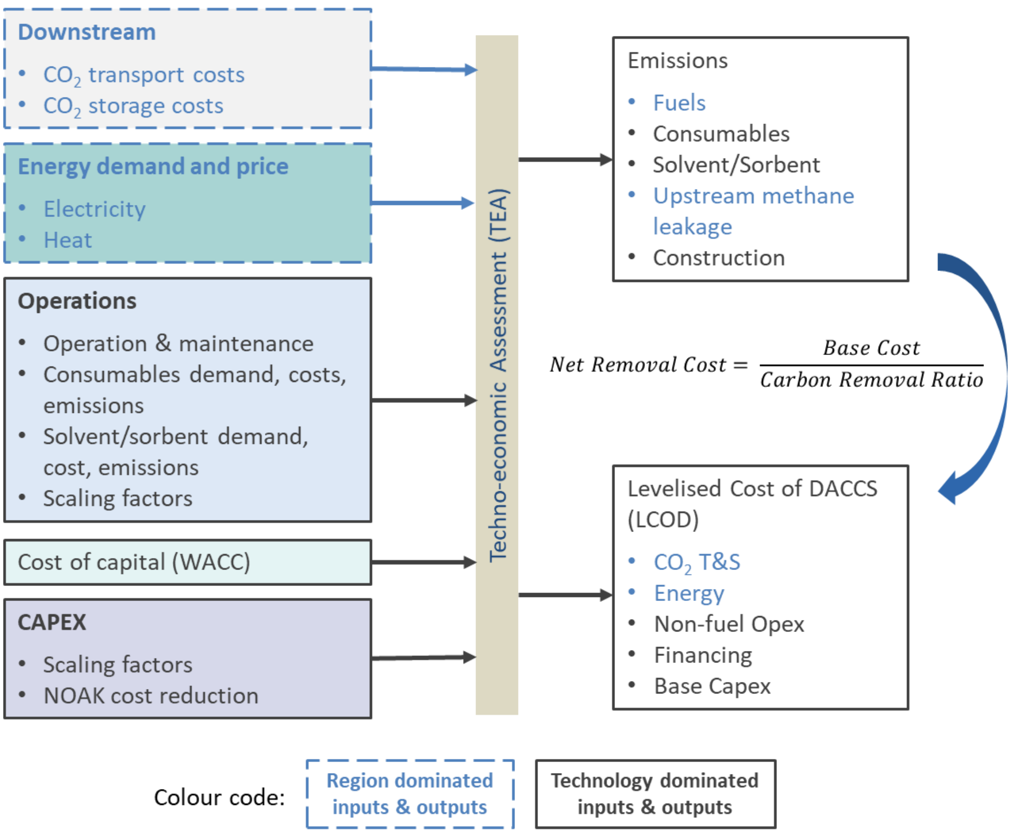


Figure 7: Schematic overview of techno-economic input and output parameters[,34]

The TEA is used to calculate the levelised cost of DACCS (LCOD) of individual plants. LCOD is simply the total levelised cost (discounted) a plant incurs over its lifetime, divided by the total mass of CO_2 it will remove from the atmosphere[35]. LCOD is a convenient measure allowing comparison of technologies with

[33] Scaling factors allow scaling key costs between plants of different sizes (capacities).
[34] Consumables refer to water, oxygen, and other chemicals such as $CaCO_3$.
[35] This is implicitly discounted to reflect the real-world discounting of any incentives received by the plant.

different lifetimes, cost of capitals, capacities, etc. Equation 1 is a simplified expression showing how LCODs are calculated in this TEA:

$$LCOD = \frac{Capex * CRF + annual\ fixed\ Opex + variable\ Opex * annual\ CO_2\ capture}{annual\ CO_2\ capture} \quad (1)$$

The calculation is simplified by considering annual costs and CO_2 capture, which is straightforward for variable and fixed operational costs. Capex is assumed to be paid back over the lifetime of the plant along with the cost of capital. Annual Capex payments are calculated by multiplying total Capex with the capital recovery factor (CRF), which represents the portion of the initial Capex that needs to be paid every year. CRF is based on the cost of capital (i) and plant lifetime (n) as shown below:

$$CRF = \frac{i * (1+i)^n}{(1+i)^n - 1} \quad (2)$$

The simple LCOD calculated this way represents gross carbon removal costs or the cost of capturing and processing one tonne of CO_2 from the atmosphere. However, DACCS plants also directly or indirectly emit CO_2 or other greenhouse gasses throughout their value chains. This study estimates the total lifecycle assessment (LCA) emissions associated with constructing and operating a plant to find the net cost of carbon removal:

$$Net\ LCOD = \frac{Gross\ LCOD}{Carbon\ Removal\ Ratio} \quad (3)$$

In this context, the carbon removal ratio is defined as:

$$Carbon\ Removal\ Ratio = 1 - \frac{total\ LCA\ emissions}{total\ CO_2\ captured\ from\ air} \quad (4)$$

Therefore, a system which emits 100 $kgCO_2/tCO_2$ captured has a carbon removal ratio of 90% and its net LCOD is 11% more than its gross LCOD, showing the importance of minimising LCA emissions. The net LCOD reported in this study following the above methodology is different than the metrics typically reported in other studies, which often focus on the cost of capture (without CO_2 T&S) and without accounting for all lifecycle emissions.

As described in the introduction section, this study investigates two main DACCS technologies: liquid absorbent and solid sorbent systems. The TEA calculates LCODs for both first-of-a-kind (FOAK) plants, assumed to be deployed in mid-2020s, and Nth-of-a-kind (NOAK) plants which are assumed to be deployed in the long term around 2050. Intermediate steps with costs in between FOAK and NOAK stages are not considered in this study.

This study uses 2050 as the base year for NOAK calculations, however, this does not imply that NOAK stage is likely to be reached only by 2050. Reaching NOAK status depends on deployment rates of individual technologies and this study does not make an assumption regarding future DACCS deployment. Here, NOAK roughly coincides to 5-7 doublings of initial large-scale production capacity and depending on future support for DACCS, NOAK stage may be reached by as early as 2035.

A further distinction is made between plants using both heat and electricity (referred to as hybrid plants) and electricity only plants. This separation is relatively more straightforward for solid DACCS, since the heating requirements at low temperatures can be provided by heat pumps, but electric-only liquid DACCS is still at lower TRLs and needs further R&D to develop. Therefore, electric liquid DACCS is only considered at the NOAK stage.

This study focuses on large-scale DACCS technologies, represented by 1 $MtCO_2$/year plants, however, smaller scale (100 $ktCO_2$/year) plants are also considered as a case study to understand the impact of size on different DACCS technologies and configurations. Scaling factors for Capex, operational expenses and material/energy demand are used to estimate the costs for different plant sizes.

Furthermore, this TEA assumes a flat 90% plant capacity factor (availability) across all the cases and excludes emissions from transport and storage of CO_2, since literature around this was lacking and it is generally considered to be very small. A plant lifetime of 30 years was used for liquid technologies and for solids the lifetime was 10 years for FOAK and 25 years for NOAK plants.

Please see Appendix 1 for the technology related parameters used in this TEA. Our data is based on the most recent DACCS literature as well as information provided directly by the technology developers. Since solid DACCS technologies are pursued by more companies, most solid DACCS data used in this study came from the literature. On the other hand, Carbon Engineering is the largest developer specialising in liquid DACCS technologies, so a substantial amount of technical data used in this study for liquid DACCS was provided by them. While we cannot share all of the specific data Carbon Engineering provided to us due to commercial sensitivity, a public version of this data is made available in the appendix. It should be noted that Carbon Engineering's data is not far off some of the parameters provided in the literature, albeit more ambitious on capex and lifetime. A discussion around major uncertainties and quality of data used in this study is provided at the end of this section.

Apart from the technology specific data described above, common literature sources were used to investigate energy prices, energy carbon intensities and CO_2 T&S costs. Low, medium, and high values used for different energy sources and CO_2 T&S modes are provided in Appendix 2 and

Appendix 3. These ranges are used to study sensitivities and global siting factors in section 4.

DACCS costs are highly site dependant, because factors such as electricity prices and emissions are highly influential. So developing global base case DACCS costs is difficult, and results would not be representative of all regions. Therefore, in this study, a set of base case parameters were chosen as the most representative of global DACCS costs. The set of assumptions used for base case calculations are briefly summarised in Table 2 below and are explained further in Appendix 4. It is important to note that these base case costs are not the minimum achievable costs and unique settings can significantly reduce LCODs.

Please note that nuclear waste heat is picked for the base case of hybrid solid DACCS plants only as a representative source in terms of its cost and associated emissions. It is not suggested that nuclear energy is expected to be the best or the most common heat source for these plants. Future capacities of solid DACCS technologies would not be limited by availability of nuclear plants.

Table 2: Parameters used for base case DACCS LCOD calculations

Parameter	FOAK Liquids	NOAK Liquids[36]	FOAK Solids	NOAK Solids
Electricity Price and Emissions	Solar PV $68/MWh 51 kg$CO_2$/MWh	Solar PV $50/MWh 25 kg$CO_2$/MWh	Solar PV $68/MWh 51 kg$CO_2$/MWh	Solar PV $50/MWh 25 kg$CO_2$/MWh
Heat Price and Emissions	Natural Gas $19/MWh 49 kg$CO_2$/MWh	Natural Gas $8/MWh 22 kg$CO_2$/MWh	Nuclear Waste Heat $19/MWh 4 kg$CO_2$/MWh	Nuclear Waste Heat $19/MWh 4 kg$CO_2$/MWh
Cost of Capital	10%	5%	10%	5%
CO_2 Transport	1Mt plant: Offshore Pipe $8/t$CO_2$ 100 kt plant: Trucking $13/t$CO_2$	1Mt plant: Offshore Pipe $8/t$CO_2$ 100 kt plant: Trucking $13/t$CO_2$	1Mt plant: Offshore Pipe $8/t$CO_2$ 100 kt plant: Trucking $13/t$CO_2$	1Mt plant: Offshore Pipe $8/t$CO_2$ 100 kt plant: Trucking $13/t$CO_2$
CO_2 Storage	Offshore Pipeline $14/t$CO_2$	Offshore Pipeline $14/t$CO_2$	Offshore Pipeline $14/t$CO_2$	Offshore Pipeline $14/t$CO_2$

3.2 Short and long term DACCS costs and LCA emissions

DACCS life-cycle emissions

Since LCA (life-cycle assessment) emissions have a direct influence on net carbon removal costs, it is useful to first understand the sources and scale of such emissions. The key emissions sources investigated in this study are **plant construction emissions, indirect emissions from production of capture chemicals and other consumables ($CaCO_3$), energy related (heat and electricity) emissions and upstream methane leakage** when natural gas is used. Figure 8 below, summarises these emissions for FOAK and NOAK 1 MtCO_2/year liquid and solid plants for the base case.

Note that this study does not perform a full cradle to grave LCA analysis and relies on publicly available sources for estimating emissions. Any potential CO_2 leakage from the T&S infrastructure is also not included.

[36] The solar PV cost of $50/MWh used for NOAK plants is the average value added levelised cost of electricity (VALCOE) of solar PV in 2040 according to the World Energy Outlook 2020 by IEA. This value represents an energy price which is modified to better account for the intermittent nature of solar generation. So, it accounts for additional grid balancing or power storage required to reliably use solar energy. More information is provided in Appendix 4.

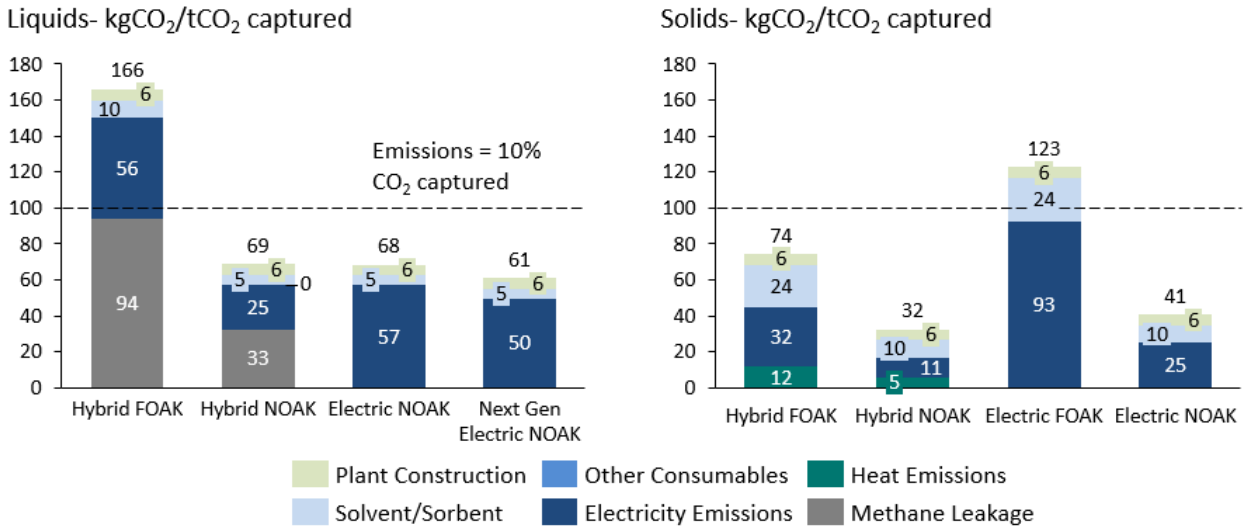


Figure 8: LCA emissions of liquid and solid 1 $MtCO_2$/year plants[37]

Emissions from plant construction and production of other consumables (e.g. $CaCO_3$ for liquids) are expected to be very low and inconsequential at wider scales according to our estimations. LCA emissions from capture chemicals (KOH or solid adsorbents) are relatively more significant for solid systems where adsorbent lifetimes are usually lower and the complex nature of the adsorbents result in higher carbon intensities.

Heating emissions from solid plants are also expected to be low since the base case uses nuclear waste heat with marginal carbon intensity. Shifting to electric only configurations would likely increase these emissions slightly even if low carbon power is used. On the other hand, having access to clean heat sources is essential for solid DACCS plants. For instance, if heat was provided by natural gas combustion without any carbon capture, LCA emissions of NOAK hybrid solid systems would be 43% of total atmospheric CO_2 captured.

Perhaps the most important contributor to LCA emissions is the source of electricity. For the base case calculations, we assume that electricity is provided by solar PV, which still results in some emissions due to panel production. Solar PV carbon intensity is assumed to be halved between the FOAK and NOAK stages (see the Appendix 2 for specific values), reducing overall NOAK DACCS emissions. Higher electricity demands of electricity-only plants compared to hybrid plants and of liquid plants compared to solids explains the relative LCA emissions shown above.

Lastly, upstream methane leakage is a significant factor for hybrid liquid plants, which use natural gas as a heat source. The climate impact of methane is 32 times more than that of CO_2 in a 100-year timeframe, meaning these leakages from extraction, processing, and transport of natural gas (which are external to the DACCS plant) can reduce carbon removal efficiencies significantly. We assume that average upstream methane emissions will reduce by 57%[38] between FOAK and NOAK stages, which results in significant improvements for NOAK hybrid liquid plants. Although we used global averages in our TEA, these emissions vary regionally and locating DACCS plants in countries with low leakage would improve plant economics.

Overall LCA emissions of NOAK plants are expected to be 3-4% for solid plants and 6-7% for liquids, which are relatively low, with marginal impact on net LCODs. Still, FOAK hybrid liquids and FOAK electric solids have emissions well above 10% due to upstream methane leakage and high electricity demand, respectively. It should be noted that these emissions are provided for base case assumptions using low

[37] For liquid NOAK plants "electric" refers to the first generation of liquid electric plants which may be available in late 2020s, whereas "Next Gen" electric refers to a future configuration in research stages with lower costs and energy demand.
[38] Assumption based on the OGCI countries' target of 2.7% annual leakage reduction, quoted in: Potential ways the gas industry can contribute to the reduction of methane emissions. Gie and Macrogaz, 2019.

carbon energy sources, so resorting to fossil energy sources would significantly increase emissions. For example, FOAK hybrid liquid systems using 2020 average global grid electricity (237 kgCO2/MWh[39]) would emit 39.4% of the CO_2 captured.

DACCS short-term costs

Figure 9 below shows the gross LCOD breakdown of FOAK DACCS plants commissioning in mid-2020s (costs given as 2020 US dollars), where the red diamonds show net carbon removal costs once LCA emissions, are considered. Base Capex represents the cost of repaying initial capital investment if there was no cost of finance, and financing cost represents additional payments needed for cost of capital.

As discussed earlier, only hybrid plants are included for liquid DACCS system analysis because electricity only options are not expected to be available until late 2020s. The TEA also includes several cases with smaller 100 $ktCO_2$/year plants, although Carbon Engineering does not expect to build such small facilities in the future. Indeed, scaling up DACCS to climate-relevant levels is likely to be easier with larger plants, however, smaller applications may be valuable in specific regional settings, such as in areas with low-carbon waste heat available.

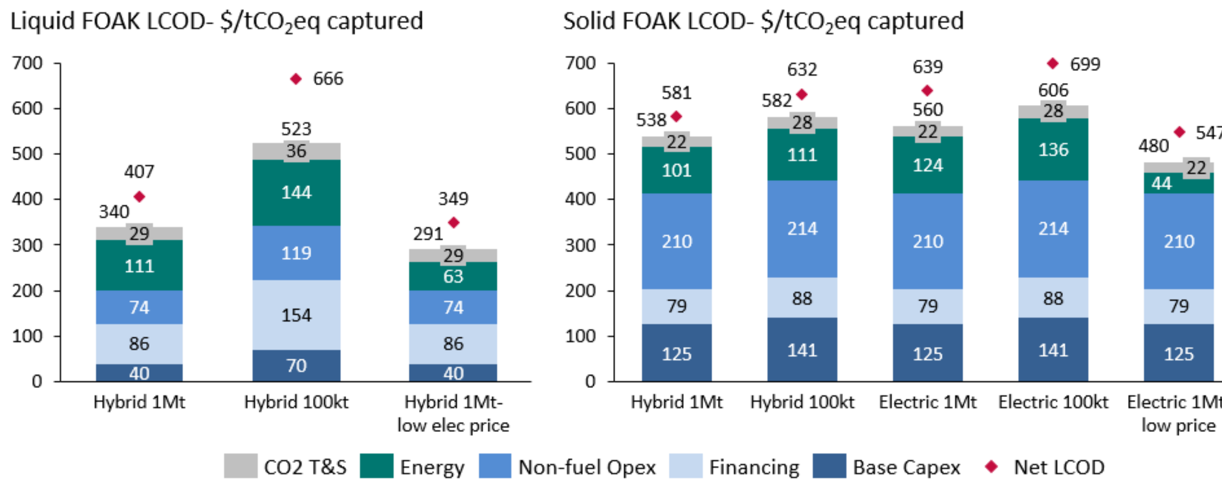


Figure 9: Gross and net costs[40] of different FOAK liquid and solid DACCS configurations[41]

Lastly, the columns named "low-cost electricity" represent a case study of using a solar PV cost of $24/MWh, as opposed to $68/MWh in the base case. These costs are already achievable in certain locations currently[41] and provide valuable insight to how much DACCS costs can fall if there is access to low-carbon renewable energy.

FOAK costs calculated in this study broadly fall within the wide range of costs quoted in the literature, however they are closer to the higher end estimates (see section 5.1 for more detail on literature values). The main differences with the literature were due to higher energy price and adsorbent consumption/cost assumptions and inclusion of LCA emissions and CO_2 T&S costs.

The breakdown of liquid DACCS costs is relatively even, with more prominent components being energy, finance and Opex costs. Finance costs are calculated to be up to twice as much as base Capex, showing the impact of cost of capital on overall LCOD.

Solid DACCS costs are dominated by non-fuel Opex, primarily due to very high costs for replenishing expensive adsorbents, assumed to be $180/$tCO_2$ for FOAK plants[42]. Base Capex is also relatively higher

[39] World Energy Outlook 2020, IEA.
[40] The bars show gross costs and red diamonds show total net LCOD after accounting for LCA emissions.
[41] A case with low-cost solar at $24/MWh based on recent average USA power purchase agreements- LINK
[42] Cost based on literature review and discussions with Climeworks.

for solid plants because investment must be recovered over its 10-year lifetime, as opposed to 30 years for liquids.

CO_2 T&S costs form a smaller proportion of total costs for both technologies. Liquids have higher T&S costs than solids because the liquid DACCS system co-captures and processes additional CO_2 (30% of CO_2 captured from air) from natural gas combustion.

Liquid DACCS costs for large scale plants were found to be significantly less than solid costs. However, liquid plants scaled down much less favourably to 100 ktCO_2/year capacity, showing the importance of economies of scale for liquid technologies, which utilise traditional chemical process equipment. On the other hand, solid DACCS costs were found to scale much more linearly due to their more modular design and less dependence on centralised process equipment. Therefore, liquid DACCS options are likely to be more economically viable for larger applications, whereas solids may be more suitable for smaller scales in the short term.

As shown by the rightmost bars in the above graphs, access to low-cost renewable electricity can reduce net LCODs by ~$60-$90, so initial DACCS projects would significantly benefit from being situated in locations with the most favourable energy sources. A more detailed discussion on the impact of energy prices on LCODs is provided in section 4.3.

Box 1: A note on CO_2 accounting for policy purposes

This study reports net DACCS costs by estimating full chain emissions to represent the total impact of the technology. These include scope 1 (direct plant emissions), scope 2 (emissions from electricity sources) and scope 3 (indirect emissions from consumables, construction, etc.). However, most national carbon accounting frameworks only consider direct scope 1 emissions within each sector; scope 2 and 3 emissions under these frameworks sit within their respective sectors.

Recently there is interest to align carbon pricing policies with national accounting frameworks. This implies that only direct emissions from DACCS plants would be accounted for when payments or incentives are calculated. Emissions from electricity production would reside within the power sector and result in increased low-carbon energy prices. If DACCS policies/incentives only consider scope 1 emissions, the LCODs will be slightly lower than the net costs reported in this study. Any interpretation of the TEA model outputs should be viewed with this consideration.

DACCS longer-term costs

Figure 10 below shows gross and net DACCS costs of NOAK plants commissioning in the long-term (e.g., 2050). In addition to the cases discussed above, future cost analysis now includes two types of electricity-only liquid plants: one labelled “Electric” which represents an earlier design, estimated to become available in late 2020s, and one labelled “Next Gen”, which represents an improved design likely to be developed in the longer term according to Carbon Engineering.

Similar to the FOAK costs analysis, the “low price” case investigates cost reduction opportunities of having cheaper solar PV access ($24/MWh as opposed to $50/MWh). Finally, the solid DACCS graph includes an additional case with even lower solid adsorbent prices[43] in line with expectations of Climeworks.

[43] In this study adsorbent costs are assumed to reduce from $180/t$CO_2$ (FOAK) to $72/t$CO_2$ (NOAK). The low adsorbent cost case presented here assumes further reduction to $31.5/t$CO_2$ which is Climeworks’ long-term expectation.

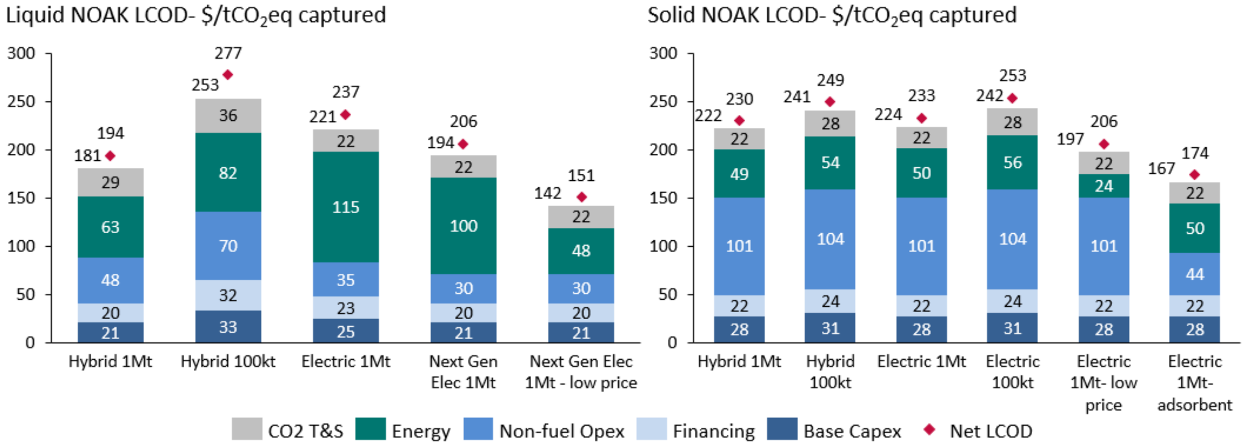


Figure 10: Gross and net costs[40] of different NOAK liquid and solid DACCS configurations[41]

Both technologies achieve significant cost savings from FOAK to NOAK, with NOAK costs ranging from \$151-\$277/tCO_2 and the distribution of costs mostly staying the same. For liquids, the main savings are from a lower cost of capital, reduced Capex, lower cost electricity and reduced upstream methane emissions. For solids, the main cost savings are due to reduced adsorbent costs (improvement of price-lifetime balance), plant lifetime improvement, Capex reduction and access to lower cost electricity. Improvements in adsorbent prices are expected in the future due to increased efficiencies and improved economies of scale as these novel chemicals are started to be mass produced.

Energy prices were found to be more dominant for NOAK liquid electric plants because they have higher power demand than solid options. On the other hand, non-fuel Opex, specifically solid adsorbent cost, is clearly the most dominant cost component for solid DACCS.

The overall relationship between costs of smaller and larger scale plants are similar to that of the FOAK stage. Hybrid and next generation liquids are found to achieve slightly lower LCODs than solids for 1 MtCO_2/year plants, presumably due to favourable economies of scale, although regular electric plants had broadly the same LCOD as solid options. On the other hand, solids seem to stay more cost effective for smaller applications.

The base case costs were found to be in the range of \$200-\$250/net tCO_2 for long-term NOAK plants, which is double the frequently quoted long-term industry target of \$100/tCO_2 (which excludes CO_2 T&S costs). The main barriers for achieving this lower target are energy prices and solid adsorbent costs, as demonstrated by the TEA. Potential for further cost reduction, including an assessment of lowest likely DACCS costs, will be explored at a greater extent in the rest of this section and under the global siting factors discussion.

3.3 Sensitivity analysis

In order to understand the importance and impact of key parameters on overall DACCS costs, a sensitivity study is performed by varying the values of selected parameters by certain amounts and calculating resulting LCODs. Figure 11 and Figure 12 below summarise the outputs of the sensitivity analysis performed on NOAK 1 MtCO_2/year capacity liquid and solid hybrid plants, respectively. The columns on the right indicate how much the parameters were changed, and the bars show the percentage shift on total net LCOD. Hybrid plants were used as opposed to electric-only configurations to be able to assess impact of heating costs. Plant scaling factors are not included in this analysis since they are not an inherent property of the technologies and different scaling methods were used for solid and liquid DACCS.

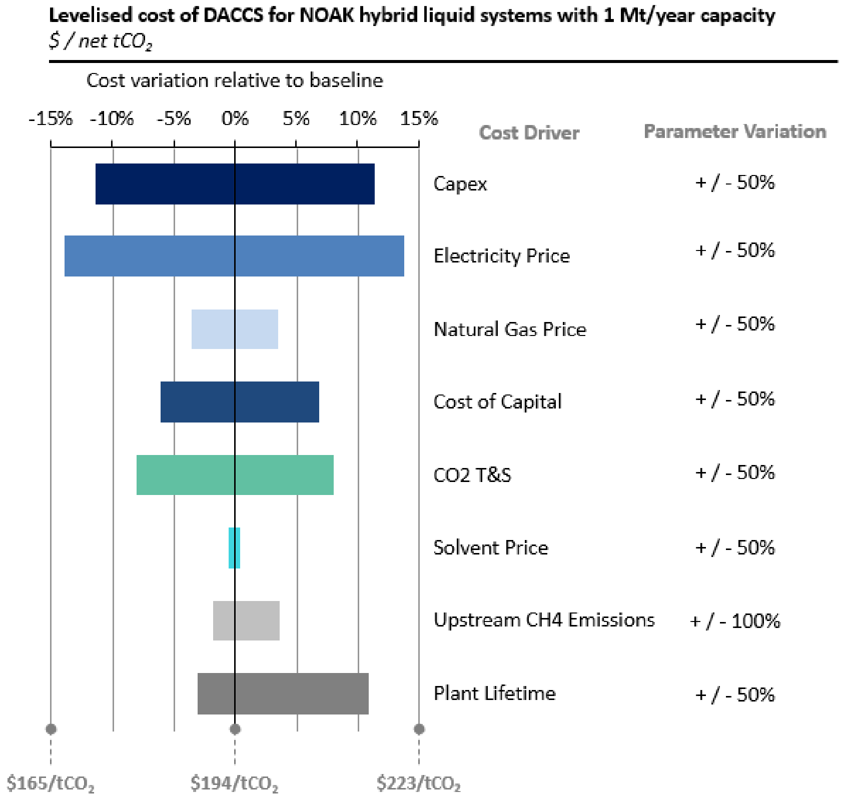


Figure 11: Sensitivity of 1 $MtCO_2$/year capacity NOAK hybrid liquid DACCS costs ($/$tCO_2$ net)

Capex and electricity prices were the most influential parameters on overall liquid DACCS costs, demonstrating the importance of access to low-cost renewables once again. Cost of capital was found to have moderate impact, therefore securing affordable finance can be a useful enabler for future DACCS deployment. CO_2 T&S costs were another moderately influential component, especially because liquid systems transport and store more CO_2 than originally captured from air. As discussed in more detail in the next section, locating a DACCS plant in a CCS cluster can significantly reduce T&S costs if infrastructure is shared. Natural gas prices and upstream methane leakage have the potential to impact costs, but variation of these parameters is likely to be limited. Lastly, liquids LCODs are not sensitive to solvent and other consumable prices since these are common chemicals with already relatively low costs.

Compared to liquids, the most significant difference of solid DACCS sensitivity is the very high impact of adsorbent prices. Adsorbent cost is a product of adsorbent performance and unit costs. There is usually a trade-off between better performing/longer lasting adsorbents and unit adsorbent costs. Still, further R&D and economies of scale can improve adsorbent economics, which can increase cost-effectiveness of solid DACCS.

Solid DACCS costs display less sensitivity to electricity and CO_2 T&S prices compared to liquids due to lower power demands and volumes of CO_2 processed. Heat prices are found to have moderate impact on solid DACCS costs. Some studies in the literature assume waste heat to be free of charge, but our analysis shows that heat can be a considerable cost component if it is not free.

Lastly, sensitivity of costs to plant lifetimes is noteworthy for both solid and liquid plants. Higher lifetimes do not reduce costs significantly due to discounting of future expenditure. However, halving of NOAK plant lifetimes is found to increase LCODs significantly, especially for solid DACCS plants, which have lower overall lifetimes than liquids.

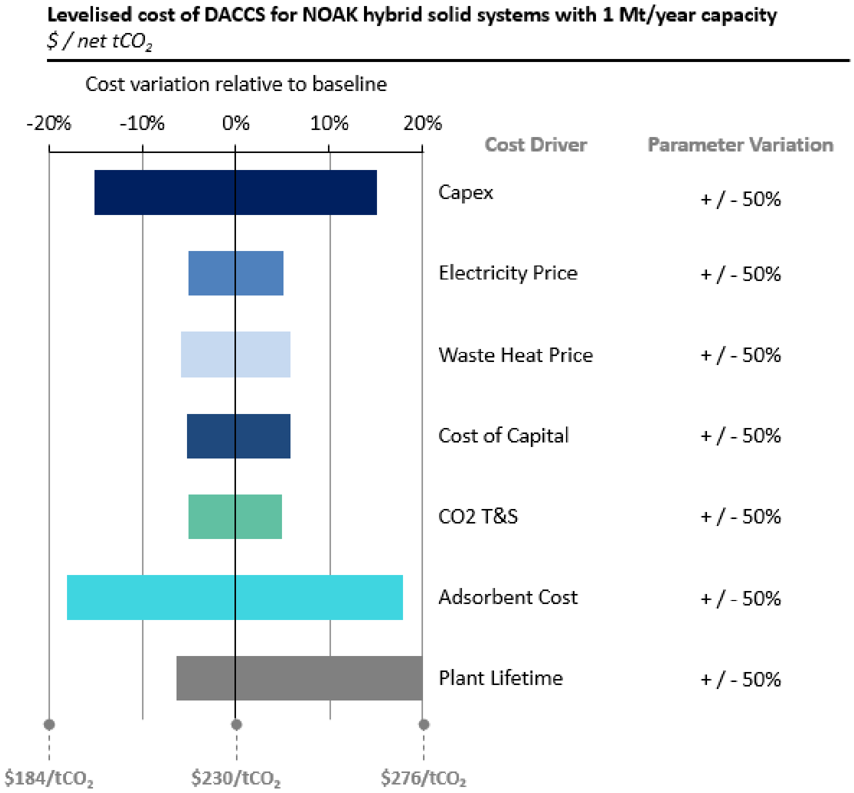


Figure 12: Sensitivity of 1 $MtCO_2$/year capacity NOAK hybrid solid DACCS costs ($/$tCO_2$ net)

The above discussion is provided for hybrid NOAK plants, however, sensitivities for other configurations are expected to differ slightly. For example, electricity-only plants would have no sensitivity to heating costs or methane leakage, whereas electricity prices would be much more influential. This implies that full electric plants would be well-suited regions with the cheapest low-cost power, whereas hybrid plants would be better suited regions with natural gas abundance and limited renewable access.

Since upfront capital investment and financing costs are higher for FOAK plants, early stage DACCS costs will show much higher sensitivity to Capex and cost of capital. Methane leakage and adsorbent prices are also expected to be more influential for FOAK plants because our model assumes significant reduction in both parameters in the future. On the other hand, heating and CO_2 T&S prices are expected to have much less impact on FOAK costs because they are external to capture plants and are not assumed to improve substantially over the next 30 years.

Box 2: Impact of learning rates and deployment levels on DACCS costs

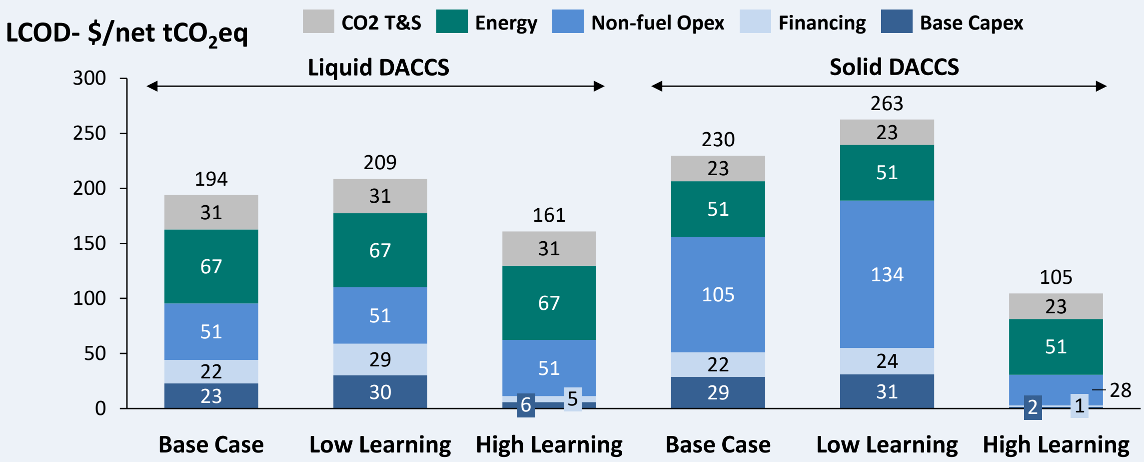
A common method to estimate future cost reduction potential of energy or chemical process technologies is using learning rates. Learning rates indicate how much the cost of a specific technology falls for each doubling of its installed capacity. Using this method successfully requires making assumptions about future deployment rates and choosing a learning rate suitable for the given technology. Since making assumptions about future DACCS deployment is difficult, NOAK DACCS costs in this study were calculated by using literature figures and technology developer estimates.

However, it is useful to investigate the implications of different learning rates and future DACCS capacities on LCODs considering some technologies such as solar PV historically achieved very significant cost reduction by maintaining a high learning rate. The International Energy Agency (IEA) assumes[39] the learning rates of relatively mature technologies- like bioenergy, geothermal, and onshore wind- to be 5%, whereas onshore wind and solar PV had higher rates at 15% and 20%, respectively.

Figure 13 below summarises the results of a sensitivity analysis where lower and higher DACCS costs are achieved depending on assumed learning rates and future deployment levels. Starting DACCS capacities are assumed to be 1 $MtCO_2$/year for liquids (the first large scale plant) and 100 $ktCO_2$/year for solids (based on sizes used in the literature). Future DACCS capacities are selected to represent medium and high-level deployment. Learning rates were picked in accordance with the above IEA ranges. Liquid technologies were given a lower 'high learning rate' of 15% because these systems consist of relatively mature chemical processes compared to solids. Lastly, cost reduction is only applied to Capex and solid adsorbent costs since the other components are either external to capture plants or not likely to benefit from learning.

Note that the capacities and learning rates provided for the base cases of both liquid and solid technologies are not directly used in this study but are provided to illustrate an example scenario of DACCS deployment and learning rates for reaching the NOAK costs presented.

The results indicate that our base case assumptions fall in between low and high learning rate variants and potentially DACCS can achieve significantly more cost reduction if high learning rates can be maintained. Solids appear to benefit more from learning rates, since they have substantial room for improvement in their adsorbent costs. It should be noted once again that currently there are no large-scale DACCS plants and initial cost reduction should be demonstrated in the future before learning rates can be used confidently.



	Base Case	Low Learning	High Learning	Base Case	Low Learning	High Learning
Initial Capacity	2 Mt	1 Mt	1 Mt	2 Mt	0.1 Mt	0.1 Mt
Final Capacity	113 Mt	100 Mt	5000 Mt	113 Mt	100 Mt	5000 Mt
Learning Rate	10%	5%	15%	~12%	5%	20%

Figure 13: Liquid and solid DACCS costs under various learning rates assumptions

3.4 Data availability and uncertainties

Below is an overview and discussion around the sources of data used to model liquid and solid DACCS technologies and inherent uncertainties related to these technologies.

Liquid DACCS data uncertainties:

- Carbon Engineering's 1 $MtCO_2$/year hybrid DACCS plant Capex estimate is based on a FEL-2 (front end loading) level of analysis[44] where all major equipment costs are based on technically and commercially evaluated budgetary quotes from multiple vendors at the plant scale. This level of estimate is more detailed than most other kinds of costs estimates in the DACCS literature. Still, a large-scale plant is not built to date, so there are inherent uncertainties in all costs compared to more established technologies.
- The Capex of the liquid plant with 100 $ktCO_2$/year capacity is scaled from this estimate, thus has a lower level of accuracy. Costs for electric plants, especially the next generation electric plant, and the cost reduction of NOAK plants are also estimates with much higher uncertainties.

Solid DACCS data uncertainties:

- Publicly available cost data on solid DACCS technologies are typically based on pure academic work and carry higher inherent uncertainties compared to liquids.
- Some data on energy consumption and LCA emissions from technology developers are available, but are based on smaller scale plants, so estimates for >10 $ktCO_2$/year plants require using scaling factors.
- Adsorbent cost (driven by consumption/lifetime and price) is the most influential parameter on LCOD, but information is commercially sensitive. There is significant room for reductions in future adsorbent costs due to efficiency improvements and mass production of novel chemicals; however, new sorbents need demonstrating, so somewhat conservative cost reductions are assumed in most cases in this study.
- The literature is particularly lacking in terms of future cost improvements, as estimates are only based on learning rates from other industries.

Common DACCS data uncertainties and availability:

- Some other parameters, such as operations, maintenance, and consumable prices have higher uncertainties, but are not as influential on final LCODs.
- CO_2 transport and storage costs are almost always excluded from DACCS analysis in the literature. These are relatively well-established processes with reasonable certainty, however, costs are highly site dependent, so should be considered separately unless shared infrastructure is used.
- Scaling down liquid plant sizes to 100 $ktCO_2$/year and scaling up solid plant sizes to 1 $MtCO_2$/year require using generic scaling factors and significant assumptions, presenting uncertainties.
- Long term cost reductions are inherently difficult to predict since total DACCS capacity to date is extremely limited. This uncertainty is unlikely to resolve until capacities reach at least several mega tonnes and some learning rates are demonstrated, which may take until the 2030s.
- Land and water requirements can show wide ranges in the literature. Although not very influential on costs, these parameters may be better understood once several facilities are built and interactions between closely sited DACCS plants are studied.

[44] More information on FEL- Link

3.5 Summary of key messages

This section has presented a techno-economic model and a set of base case plant configurations to explore DACCS costs and lifecycle emissions in the short and long terms. A sensitivity analysis is conducted to determine the relative impact of different cost components. Below are the key messages emerging from the model analysis.

Current Performance

- Early DACCS plants in the 2020s are likely to range from **~\$350-\$700/net-tCO_2 stored** (when medium cost renewables are used), depending primarily on scale and energy costs. Early plants are likely to be situated with low-cost renewable electricity.
- For liquid systems, large-scale plants are significantly more cost-effective due to economies of scale. Solid DACCS costs scale more linearly with size and are likely to be the more cost-effective option for smaller plants (<100ktCO_2/year).
- The early DACCS costs calculated here are higher than almost all other CCS applications (ranging from \$50/tCO_2 for capture from steel plants to \$180/tCO_2 for aluminium plants[9]) and some sustainable aviation fuels (virtually all options costing[10] higher than \$300/tCO_2).

Key Cost Influences

- **Liquid DACCS costs are most sensitive to Capex and electricity prices**. Due to the relatively balanced distribution of costs, most parameters are influential.
- **Solid DACCS prices are most sensitive to adsorbent costs** and future adsorbent performance improvements are the single most important factor which will determine cost-effectiveness of solid DACCS. Solid DACCS costs are also more sensitive to plant lifetime and may significantly suffer if lifetime is reduced.

Cost Reduction

- Significant cost reduction can be achieved in the future, with DACCS reaching **~\$194-\$230/net-tCO_2 stored** for 1 Mt/year NOAK plants (~2050), driven by reduced electricity prices, cost of capital and upfront capital investment. However, costs are likely to be higher for smaller plants and further cost reduction potential exists for more ambitious renewables and adsorbent cost reduction (discussed in more detail in section 4.6).
- Liquid DACCS further benefits from overall improvements in upstream methane leakage (57% reduction) in the gas industry. Solid DACCS technologies experience further cost reduction through increases in plant lifetimes (from 10 to 25 years) and cost-performance improvements of adsorbents.

Lifecycle Emissions

- The lifecycle emissions associated with DACCS range from **3-7% of the CO_2 captured for NOAK plants** (if low carbon energy is used) and are primarily associated with the energy inputs (electricity and heat) and upstream methane emissions if natural gas is used in the process. Therefore, reducing the carbon intensity of energy sources are of paramount importance.

Uncertainties

- Since no large-scale plant is built to date, **inherent uncertainties on most parameters are high**. The largest uncertainties requiring major assumptions are on plant scaling factors, future cost reductions through learning and solid adsorbent cost-performance dynamic.

4. Global DACCS siting considerations

4.1 Overview

On the surface it may appear as if DACCS technologies can be deployed anywhere with access to low carbon energy and CO_2 storage resources. Although this is mostly technically correct, DACCS costs and viability can be influenced by many other factors, some of which are summarised in Figure 14 below. In this section we will discuss most of the key global siting factors influencing the best locations or conditions for DACCS deployment. Specifically, the section will cover:

- CO_2 transport and storage infrastructure and availability.
- The option to utilise CO_2 to produce valuable commodities
- Availability of low carbon electricity and heat sources.
- Flexible operation of DACCS plants following renewables generation patterns.
- Water and land requirements.
- Regional policy and regulatory suitability.

Lastly, this section will pull from the above topics and the TEA presented in section 3 to explore several "low-hanging" fruit cases which would present ideal opportunities for DACCS deployment. We will also investigate how low DACCS costs can fall if many favourable conditions are achieved simultaneously.

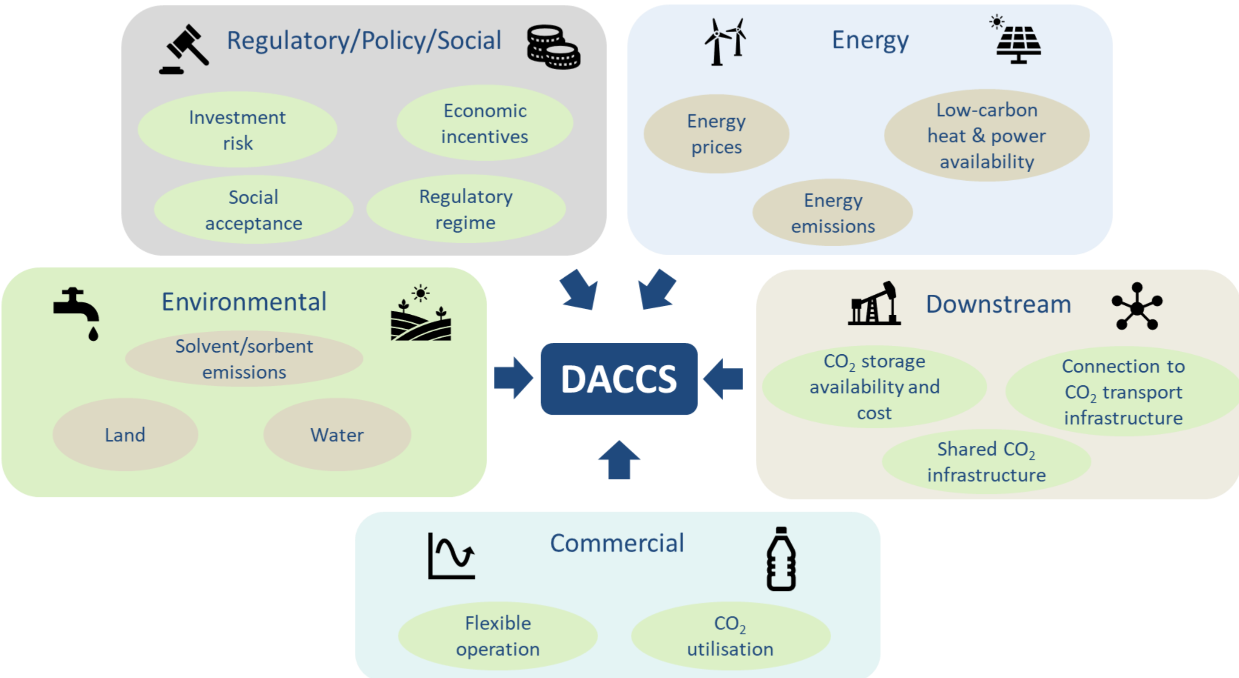


Figure 14: A schematic representation of key global DACCS siting factors

4.2 CO_2 transport and storage

Perhaps the most significant physical limitation for DACCS is having access to a geologic formation for permanent CO_2 storage. Currently the two main approaches to geographic CO_2 storage are injection of supercritical CO_2 in deep sedimentary formations and CO_2 mineralization into carbonate rocks by interaction with alkaline material. Storage in sedimentary formations have higher TRLs and a longer practice history, which have put this technique to the forefront of most studies and projects.

Recently, a study called CDR Primer[13] reviewed the literature on prospective sedimentary basins and compiled the existing data to map regions with favourable storage resources (as shown in Figure 15). It is noted that countries which emit the most greenhouse gasses (GHG) have relatively well-developed storage capacities. Lower estimates of the total global storage capacity are around 7,000 $GtCO_2$ which is over three times the total GHG emissions since the beginning of the Industrial Revolution. The US hosts the most current Enhanced Oil Recovery (EOR) projects and CO_2 injection activities. Europe, East Asia, and Australia represent the majority of future storage projects. Although global storage resources are not likely to be a limitation for DACCS deployment, detailed regional appraisal projects are needed to develop a more comprehensive understanding of which national or sub-national regions would be the best locations, especially considering that onshore storage in densely populated regions (e.g., Europe) is not likely.

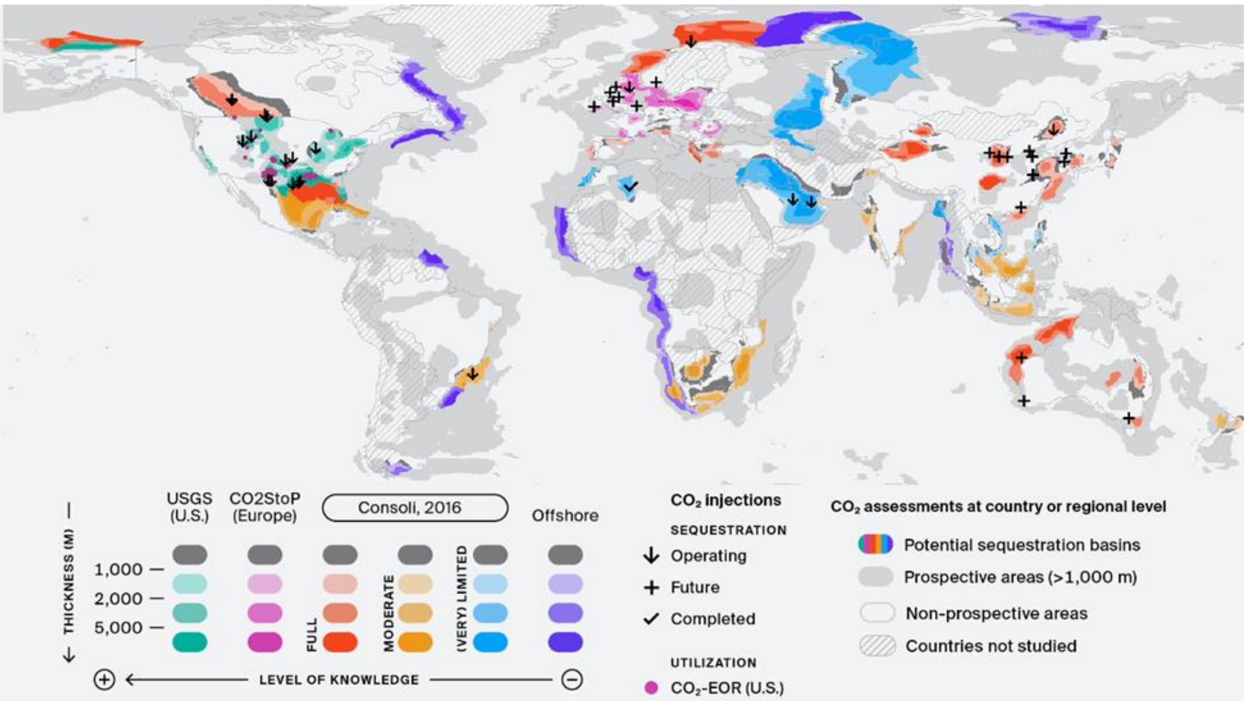


Figure 15: Prospective sedimentary basins for CO_2 sequestration. Colours represent the level and source of knowledge. Grey areas correspond to regions without local studies but with a sedimentary thickness of >1000m. Image taken from CDR Primer (2021)[13].

The Global CCS Institute (GCCSI) tracks the development of CO_2 storage resources in 80 countries by assessing factors such as total storage capacity, site appraisal programmes and experience with CO_2 storage projects. It ranks countries based on their global CCS storage indicator[45] (as shown in Figure 16 below) which is made up of these factors. By 2018, 12 countries had mature or near-mature storage resources: Norway, Canada, United States, China, Australia, Brazil, United Arab Emirates, Saudi Arabia, the UK, Netherlands, Germany, and Japan. GCCSI identifies moderately scoring European countries- such as Poland, Spain, France, Denmark, and Hungary- as high opportunity nations which should focus on having more detailed appraisal projects to develop commercially viable storage resources. Another group of high opportunity countries consist of Russia, Indonesia and India, which have poorly developed storage resources but high inherent interests in CCS since they heavily depend on fossil fuels.

[45] CCS storage indicator. GCCSI, 2018.

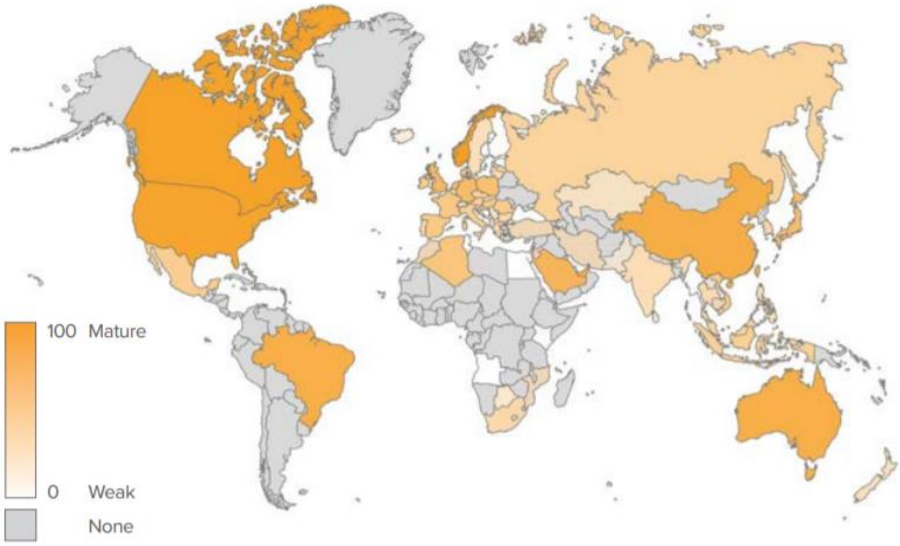


Figure 16: GCCSI's global CCS storage indicator heat map[45]

To better understand the impact of access to CO_2 T&S infrastructure, we investigated the different T&S costs a DACCS facility would face depending on various configurations. This study considers three types of CO_2 transport modes, which are:

- **Trucking:** ideal for smaller capacity plants and over short distances.
- **Shipping:** ideal for offshore storage over long distances or for smaller plants.
- **Onshore/offshore pipelines:** ideal for larger capacity plants over short/medium distances.

The current TEA considers low, medium, and high transportation costs[46] for the four modes listed above, based on travel distances for a 1 $MtCO_2$/year capacity plant. Additionally, low/medium/high estimates for onshore and offshore CO_2 storage are taken from the literature[47]. Please see

[46] Element Energy's internal analysis based on (A) Element Energy's CCUS at Dispersed Sites study for BEIS (2020) and (B) Element Energy's CO_2 Shipping model for BEIS (2018).
[47] The costs of CO_2 storage: post-demonstration CCS in the EU. Zero Emissions Platform, 2010.

Appendix 3 for more detail.

The base case LCOD calculations discussed so far used medium offshore transport and storage costs for 1 $MtCO_2$/year plants, which are \$8.18/tCO_2 and \$14.18/tCO_2 gross, respectively. Figure 17 below shows how these CO_2 T&S costs would change under different assumptions. These are gross costs per tonne of CO_2 processed in the plant - net costs per tonne of net CO_2 removed would be slightly higher once LCA emissions are taken into account. Also, hybrid liquid plants would have 30% higher T&S costs in their LCODs because these plants capture and process 0.3 tonnes of additional CO_2 from natural gas combustion for each tonne captured from the atmosphere[48].

Results indicate that costs increase with transport distance, as expected, but utilisation of ships can keep the long-distance transport costs to relatively acceptable levels. Onshore storage is expected to be lower cost than offshore operations, where T&S costs of a medium distance onshore storage project is found to be half the cost of an offshore option.

Significant cost savings can be achieved if shared T&S infrastructure is used. The "best case" option displayed is based on low onshore storage costs and short distance pipeline transport costs for a 10 $MtCO_2$/year project, which is representative of a wider CCS cluster. CO_2 T&S prices in these favourable conditions may be as low as \$5/tCO_2. Offshore versions of these clusters can be achieved around the North Sea and shores of Australia, China, and North America[49]. On the other hand, a worst-case scenario would be a much smaller facility (~100 $ktCO_2$/year) shipping CO_2 over long distances for offshore storage. Costs can easily exceed \$60/tCO_2 and become very prohibitive for DACCS projects under such conditions. In short, average CO_2 T&S costs are likely to be in the range of ~6-15% of total LCOD in our base case calculations and significant savings can be achieved by sharing the infrastructure with other projects.

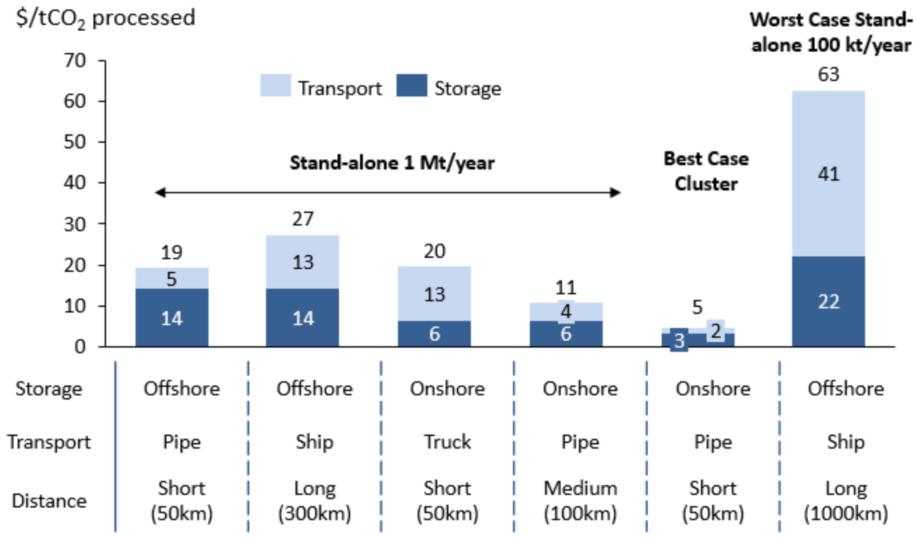


Figure 17: Gross CO_2 T&S costs per tonne of CO_2 processed for different configurations

CO_2 utilisation

DACCS plants discussed so far use CO_2 transport and storage to achieve net negative emissions, however, DAC can also be combined with various CO_2 utilisation routes to produce useful products. CO_2 utilisation with DAC may generate net negative emissions in some unique circumstances, but the majority of utilisation options only result in emissions mitigation by reducing embedded emissions in otherwise high carbon products. CO_2 utilisation can be used in regions without geological CO_2 storage resources, where infrastructure is not yet developed or where storage is not politically desirable or very expensive (such as

[48] This is accounted for in the LCOD in this study TEA
[49] Enabling the deployment of industrial CCS clusters. By Element Energy for IEAGHG, 2018.

small plants in remote locations). CO_2 utilisation can also increase total DAC deployment, thereby accelerate cost reduction through economies of scale, even if it does not produce negative emissions.

Accelerated mineralization and catalytic conversion (summarised in Figure 18 below) are two key CO_2 conversion pathways pursued by a high number of developers[50] and have applications which have reached TRL 9. These top pathways differ in the types of non-CO_2 feedstock they require, the final products and permanence of CO_2 storage. Other conversion pathways include fermentation and photosynthetic routes which have fewer developers and applications that are up to TRL 7. On the other hand, electrochemical and photocatalytic routes have higher numbers of developers but applications which are mostly TRL 4-5.

Lastly, CO_2 can be used in Enhanced Oil Recovery (EOR) to increase productivity of depleted oil wells. EOR is a very well-established technology (TRL 9). CO_2 can be permanently stored if it is continuously separated from the oil and re-injected to the well. Still, the overall process is close to net-zero emissions considering downstream emissions from of oil use[51].

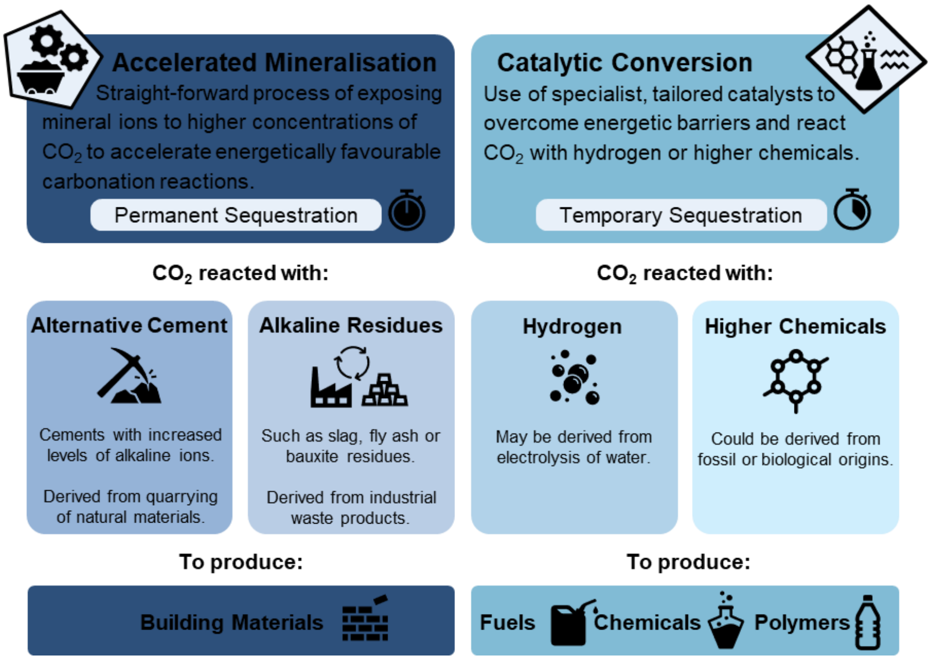


Figure 18: Summary of the two key mature CO_2 utilisation routes[50]

To investigate the impact of CO_2 utilisation on DAC costs, a set of different cases are considered, as shown in Figure 19 below. A 1 $MtCO_2$/year capacity hybrid liquid DAC plant is chosen as a base case. Costs are reported as gross, without accounting for LCA emissions, because CO_2 utilisation routes do not necessarily result in negative emissions, so presenting costs for net CO_2 removal is not possible.

Apart from the base case, the other scenarios considered in this analysis are:

- **No T&S case** has zero CO_2 T&S cost, representing a scenario where CO_2 is given to a nearby customer for free or where T&S costs cancel out any sales revenue.
- **CO_2 revenue case** where CO_2 sales generate $20/t$CO_2$ revenue[52], which is chosen as a representative CO_2 sales price without any special incentives.

[50] Element Energy CCU study- to be published
[51] Is EOR a dead end for carbon capture and storage? Thomas Overton, Power Magazine, 2016- Link
[52] The value of $20/t$CO_2$ is illustrative and will depend on CO_2 accounting; this value assumes that the DAC plant does not? receive any negative emissions incentive, but if the end-user receives the benefit, then this CO_2 value is likely to be considerably higher.

- **Lower costs case** where the same \$20/tCO_2 sales revenue is maintained and DAC costs are lower because the CO_2 does not need to be pressurised since transport or underground injection are not needed[53].
- Lastly a bar labelled **"California LCFS"** to represent the average value of a 1 tCO_2 credit in California's Low Carbon Fuel Standard mechanism[54] in which DAC or DACCS plants can participate. This represents one of the highest values a tonne of CO_2 can receive in the world.

Analysis shows that CO_2 utilisation can slightly reduce carbon capture costs if CO_2 T&S costs can be saved. Net costs after revenues can get closer to the \$100/tonne mark if CO_2 can be sold for a revenue and sub-\$100 net costs are likely to be achieved if CO_2 can be sold to nearby facilities at atmospheric pressure. Even in this best-case scenario, carbon sales alone cannot incentivise DAC deployment unless there is a significant premium placed on CO_2 captured from air (such as a carbon price of >\$81/tCO_2 even after a small revenue). Some existing policies, such as the LCFS can close this gap and future CO_2 utilisation policies may achieve similar effects. Please see section 6.2.5 for more information on existing and potential future policies to incentivise DAC and carbon utilisation.

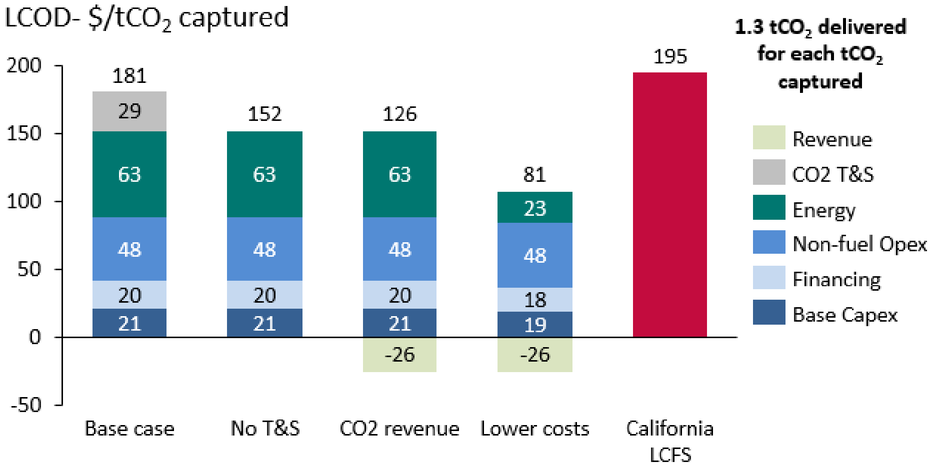


Figure 19: Exploratory gross LCODs of different CO_2 use scenarios for a NOAK 1 MtCO_2/year hybrid liquid DAC plant.

4.3 Energy prices and availability

The TEA discussion provided in section 3.2 briefly touched upon the significant DACCS cost reduction potential if low-cost renewables can be used. This section will provide an overview of global clean energy availability and investigate the impact of a wide range of energy prices on LCODs.

Figure 20 below maps the global potential for concentrated solar power (CSP), solar PV, onshore/offshore wind energy based on different literature sources[13]. Key favourable locations for low-carbon energy are:

Low carbon electricity:

- **Solar energy** is strongest in regions close to the equator and highest latitudes for feasible deployment is ~60 degrees. The regions with highest cost-effective potentials are Africa, the Middle East, Australia, Southern US, and South America.
- On the other hand, **wind power** tends to be stronger at higher latitudes and in offshore setting compared to onshore settings. The best locations are southern South America, New Zealand, the South Coast of Australia, and Northern Europe.
- New **hydropower** developments also present opportunities for DACCS. Most dam projects are in the Himalayas, South America and around Turkey.

[53] A process for capturing CO_2 from the atmosphere. Keith et al., 2018. Capex and electricity reduction ratios calculated from variants C and D.
[54] California LCFS traded at \$193-\$199/tCO_2 in the last quarter of 2020- Link

Low carbon heat:

- **Concentrated solar power** (CSP) is limited to latitudes of <45 degrees in the same general regions feasible for solar PV.
- **Nuclear** power is relatively abundant in densely populated areas of developed countries such as Europe, North America, and east coast of Asia. Nuclear can provide both low-carbon electricity and waste heat.
- **Geothermal** energy can be used for both heat and power with high availability. Some regions with high potential are the western US, Japan, the Philippines, Papua New Guinea, Turkey, Iceland, and New Zealand.

It is important to note that although hybrid plants require both sustainable heat and power sources, electric only configurations only need to secure low-carbon electricity. Solid DACCS plants operate at low temperatures (80-120 ºC) so they can utilise most sources of heat, including geothermal and nuclear waste heat described above. Hybrid liquid DACCS require heat at high temperatures (~900 ºC), hence only CSP would be a viable option of low-carbon heat, besides Carbon Engineering's current design of combusting natural gas with 100% co-capture of resulting CO_2.

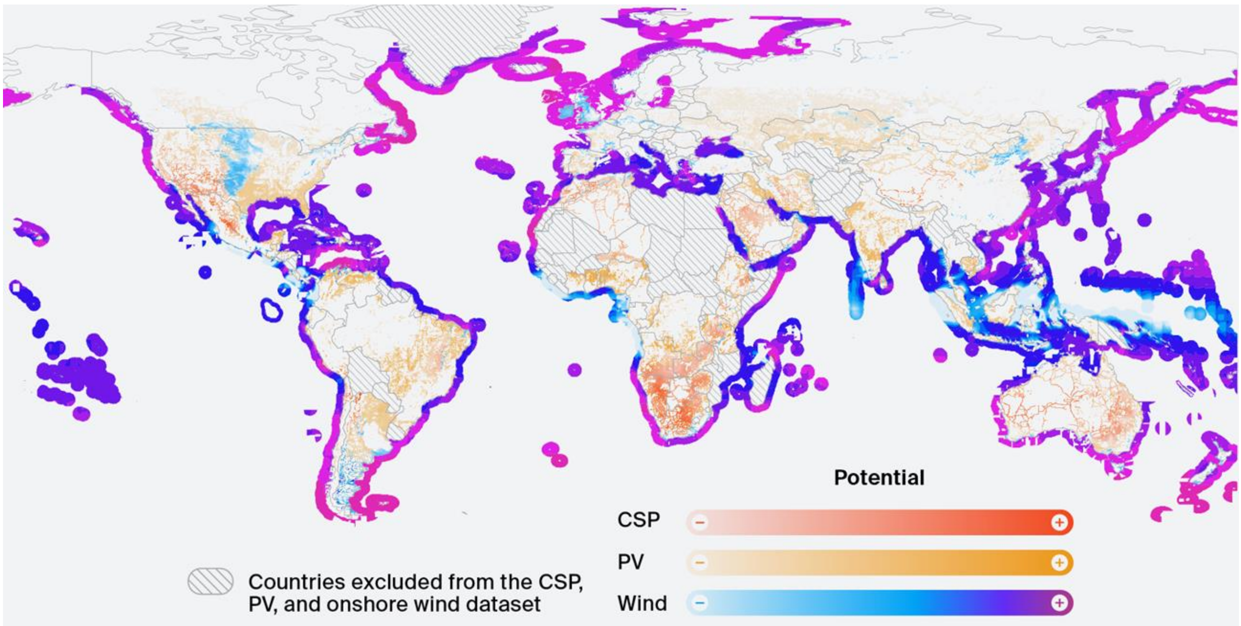


Figure 20: Heat and electricity production opportunities from CSP, solar PV and wind[13]

To better understand the impact of chosen electricity and heat sources on DACCS costs, a comprehensive sensitivity study is performed. Figure 21 and Figure 22 below present the changes in LCODs of 1 $MtCO_2$/year capacity NOAK liquid and solid DACCS plants respectively, when different energy sources are used. In both graphs, the x-axis shows the cost of electricity and the y-axis displays net LCODs, which consider total LCA emissions. LCODs for both hybrid and electric-only plants are provided for low/medium/high costs of solar PV, wind, natural gas CCS and average global grid[55]. Further information on power and heat price assumptions can be found in Appendix 2. Although nuclear power is not included on the charts, it has a similar carbon intensity to wind power, therefore wind energy data points can be extrapolated to the desired electricity prices to estimate nuclear powered DACCS costs. Lastly, Table 3 provides representative solar PV and offshore wind levelised cost of electricity (LCOE) for different regions. These may provide useful context for interpreting the sensitivity charts, but it should be noted that LCOEs only represent power generation costs, not purchase prices.

[55] The grid represents an average global grid in 2050. Costs and carbon intensity are based on IEA World Energy Outlook 2019 and IEA Future of Hydrogen.

Table 3: Representative renewables 2040 LCOEs for different regions[39,56]

Region	Solar PV ($/MWh)	Offshore Wind ($/MWh)
India	15	55
USA	25	50
Europe	30	35
China	20	40

LCOD of liquid DACCS varies between $130-$498/tCO_2 depending on the electricity price and emissions assumed. For cost effective DACCS deployment it is important to site the plants near a source of low-cost low carbon power. As expected, LCODs of electric-only plants show greater variation with the cost and source of electricity, which implies that hybrid systems using natural gas for heat (capturing CO_2) may be better suited to regions with high electricity prices, whereas electric DACCS may be more cost effective in areas with low-cost renewable electricity. Power from unabated natural gas or coal are not expected to be used for DACCS, since LCA emissions, thus costs, would be too high, going beyond the ranges shown here.

[56] The costs presented here are generation costs, therefore DACCS plants are likely to experience higher prices due to grid balancing.

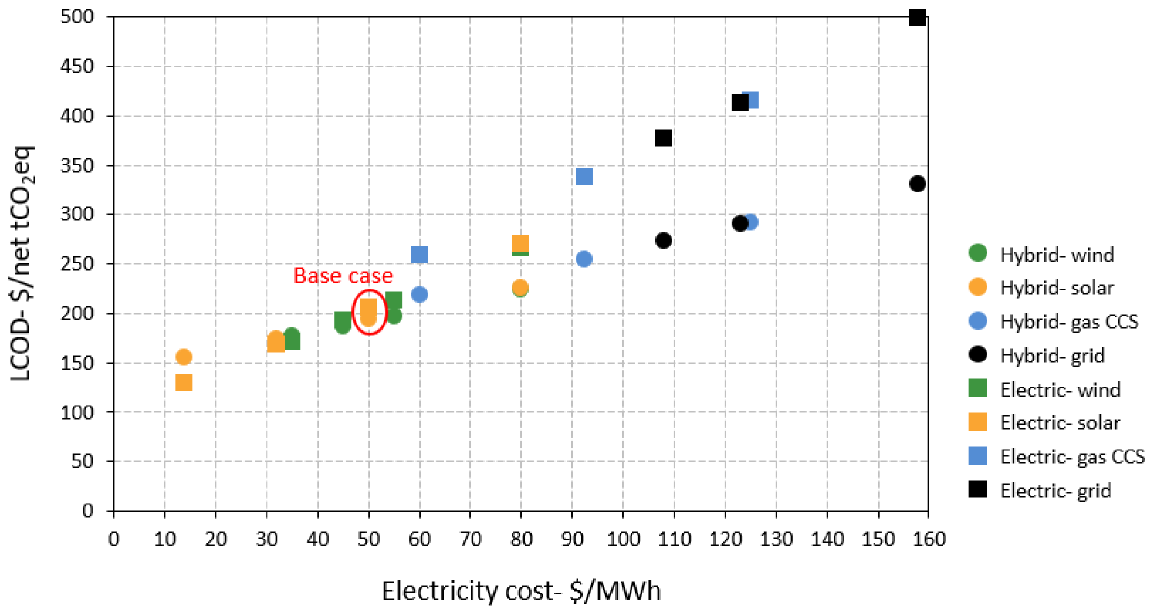


Figure 21: Sensitivity of NOAK 1MtCO_2/year liquid DACCS costs to different electricity sources

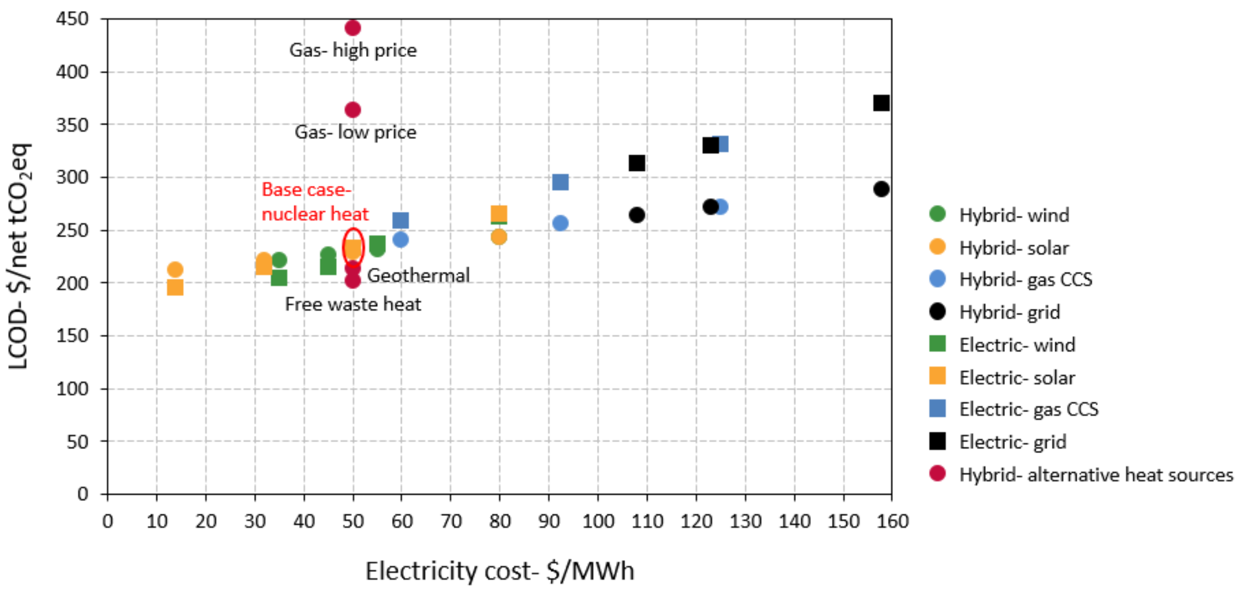


Figure 22: Sensitivity of NOAK 1MtCO_2/year solid DACCS costs to different energy sources[57]

Solid DACCS sensitivity follows a similar pattern to liquids, except costs are slightly less influenced by power prices, since solids have lower electricity demands. LCODs around the $200/t$CO_2$ mark are achievable when different types of low-cost waste heat sources are used, however, using unabated gas for heating can significantly increase DACCS costs by increasing LCA emissions. In reality, unabated gas is not expected to be used as a heat source for DACCS but is included here to make a comparison.

[57] Natural gas low ($7.98/MWhth LHV) and high ($35.9/MWhth LHV) refer to different prices. Free waste heat represents an idealised case of zero cost zero emissions heat availability. See Appendix 2 for more information.

Box 3: Flexible DACCS operation matching renewables generation patterns

Using intermittent renewables to power DACCS can introduce challenges since solar and wind are not available all the time (have low load factors). DACCS plants may circumvent this issue by storing electricity (which would increase costs), making low-carbon power purchase agreements (may not always be available) or operating plants flexibly.

Currently technology developers have no plans of operating DACCS flexibly, but they believe that this is technically feasible. Solid plants can operate flexibly rather easily, but frequent shutdowns would be a challenge for liquid DACCS which needs to operate desorption process at 900ºC. Still, it is possible to operate the CO_2 capture process flexibly, store the $CaCO_3$ pellets onsite and run the desorption process continuously.

To explore the potential impact of flexible DACCS operation on costs, several indicative cases are developed for a NOAK 1 $MtCO_2$/year electric liquid plant as shown in Figure 23 below. It is assumed that the total Capex does not change from the base case. As plant load factors decrease from 90% (base case) to 30% and 15%, the base Capex and financing components of LCODs increase to 3 and 6 times the original, respectively. This is due to assets getting utilised less, where each tonne of CO_2 removed now needs to recover more of the Capex.

The objective of flexible operation is to reduce electricity prices. This is explored through the low and zero electricity price cases. CO_2 T&S and non-fuel Opex are assumed to stay constant across cases.

It is found that a 30% load factor coupled with more affordable electricity is likely to cost slightly more than the base case. On the other hand, having free electricity can reduce LCODs below the base levels. Still, securing free electricity with a load factor as high as 30% would not be very likely. Lower load factors around 15% are expected to be much more expensive than continuous operation.

Please note that this is only a high-level "what-if" exploration with several simplistic assumptions. Further dedicated work is needed to better understand the potential benefits of flexible DACCS operation. As power grids are decarbonised in the future, the value of grid balancing and flexibility may increase to levels where flexible DACCS can be economically more viable.

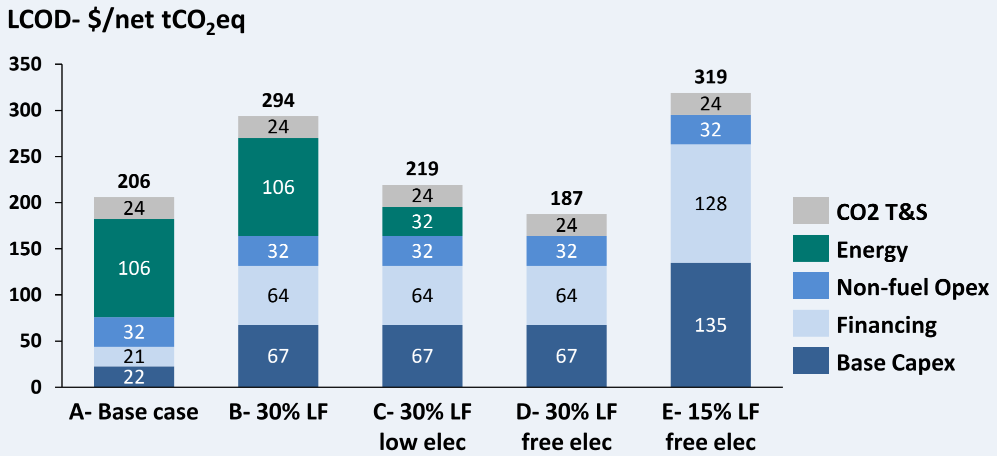


Figure 23: Costs of flexible operation of a 1 $MtCO_2$/year NOAK liquid electric plant. Load factor (LF) is the proportion of time the plant is running. Base elec: \$50/MWh; low elec: \$15/MWh.

4.4 Water and land requirements

The environmental impact and potential restrictions of DACCS technologies were briefly discussed in comparison to other NETs in section 2.4. Land and water requirements of climate change mitigation options are usually considered to be key siting factors, so this section will provide further discussion on these requirements and their implications for siting DACCS plants.

Climeworks estimates that 1 $GtCO_2$/year DACCS capacity would use 64 km^2 for the base plant, going up to 2000 km^2 including solar PV installations[16] to supply energy to the plant. This estimation uses higher solar irradiation observed in the US and a heat pump coefficient of performance of 3.5. Still, as can be seen in Figure 24 below[58], DACCS would take up less space than some other NETs even if land use is tripled. Hybrid DACCS systems using waste heat or natural gas would take even less space since power demand would be reduced. Furthermore, DACCS does not require arable land, allowing it to be situated on lower quality land as long as it has access to infrastructure and energy sources. Regions with land restrictions may consider hybrid DACCS options or offshore power generation options.

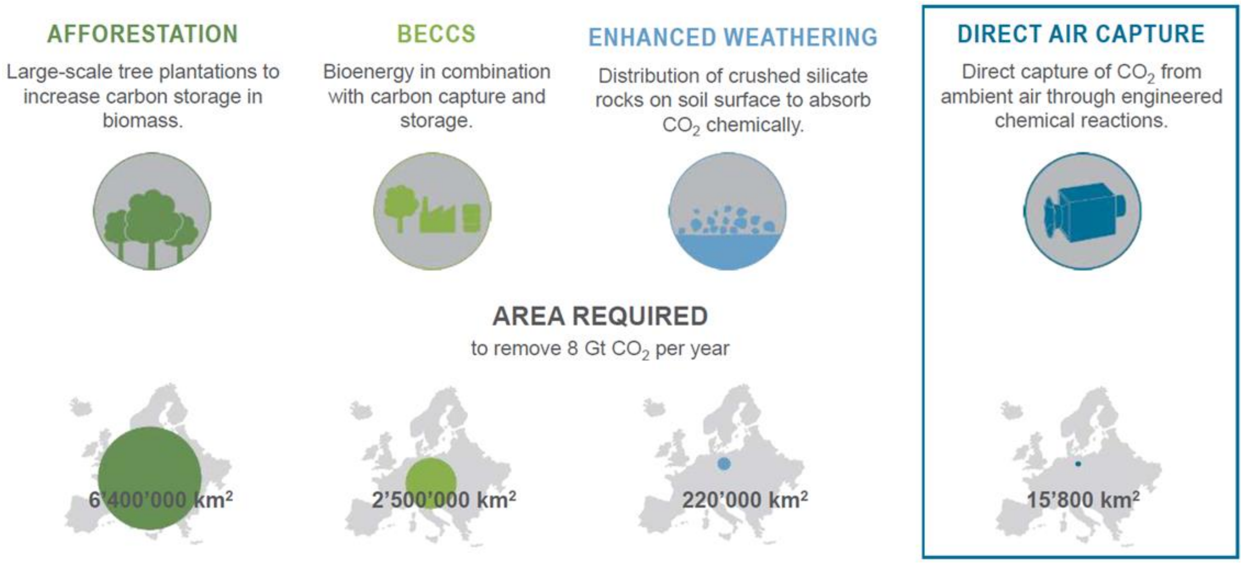


Figure 24: Comparison of land area required by different carbon removal options[58]

DACCS water consumption depends on the relative humidity and temperature of a given location. In general water losses are lower for humid and colder environments. A wide range of water demand estimates are provided in the literature. For liquid systems estimates[22,53] are in the range of 2-8 $kgH_2O/kgCO_2$. For solids, a range[22,59] of 1.6-12 $kgH_2O/kgCO_2$ is quoted. Depending on the selected solid technology and the environment, water may even be generated.

In order to maintain a DACCS capacity of 8 $GtCO_2$/year, a maximum of 96 Gt water would be needed every year when the upper estimate is used. This corresponds to about 1.26% of global agricultural water use. This requirement compares favourably with BECCS and Afforestation, which require 220 $kgH_2O/kgCO_2$ and 319 $kgH_2O/kgCO_2$ respectively[59].

Overall water demand is not expected to be a large restriction in most regions, except for very dry and hot settings such as deserts. Desalination of water may cost 2.5 times as much as regular freshwater in the US[60]. Increasing water price by 2.5 times increases LCODs of both liquid and solid electric NOAK plants by <3%, implying that resorting to desalination, although not ideal, may be viable for DACCS.

[58] Presented by Climeworks in Clean Energy Ministerial CCUS Initiative Webinar- Direct Air Capture of CO_2: Helping to Achieve Net-Zero Emissions. 21 April 2020.
[59] Biophysical and economic limits to negative CO_2 emissions. Smith et al., 2015.
[60] News article- Link

Note that the water demand discussion provided here is for the capture process only and full DACCS supply chain operation would require higher water use. For example, Climeworks' DACCS plant in Iceland which stores CO_2 in basalt formations requires ~20 kgH_2O/kgCO_2 brackish water.

In short, despite wide variation in estimated water demand of DACCS technologies, this is not expected to be a major limitation for the technology in most settings, especially compared to alternative NETs.

4.5 Regulatory, policy and social factors

A group of key global DACCS siting factors which are often overlooked in more technical studies are regulatory, policy and social considerations. These factors can act as barriers to deployment or enablers for rapid uptake of new technologies depending on unique circumstances. Most of these factors are external to the physical technology itself and can be influenced by governments or other actors relatively quickly. A discussion on current and potential future policies or actions to incentivise DACCS is provided in section 6. A brief overview of some of these factors and a list of countries which have more advanced CCS policies are given below.

- **Public perception:** Social preferences regarding NETs vs emissions reduction options and DACCS vs nature-based carbon removal can be very influential on viable regional decarbonisation strategies. Furthermore, public perception on onshore and offshore CO_2 storage may limit future DACCS options. A more detailed discussion on DACCS public perception is provided in Box 4 in section 6.1.
- **Climate ambition:** Regions with strong climate commitments are likely to be ideal locations for siting initial DACCS projects. The climate ambition of countries or regions may be evidenced by clear net-zero targets, inclusion of emerging technologies in decarbonisation roadmaps, an active carbon tax or other carbon pricing mechanisms and willingness to be climate change leaders. Europe and North America, especially regions with a carbon tax, are prime examples of areas with high climate ambitions.
- **Policies:** Since the only product of DACCS is CO_2 removal from the air, financial incentives should be placed on carbon removal to enable DACCS businesses. Current financial support for DACCS is extremely limited, but some countries have recently shown interest in expanding financial support for DACCS demonstration and R&D. Enabling DACCS, will also require a host of supportive policies such as dedicated carbon removal targets, creation of international negative emissions credits markets, skilled workforce training, and support for CO_2 storage site appraisal.
- **Regulations:** As discussed in section 6.2.4 in more detail, currently regulations surrounding DACCS are only limited to some general CCS related provisions in a small number of countries. North America, Europe and Australia are some of the regions further ahead in terms of having a developed CCS regulatory regime. Fast deployment of DACCS plants in the medium to long term requires establishment of clear and comprehensive regulations and efficient permitting processes for capture plants, CO_2 T&S businesses, renewable power projects and electricity infrastructure upgrades, which are essential components of DACCS value chains. Moreover, resolving legal issues surrounding differences between surface land and underground pore space ownership rights in the US and other countries[61] is essential to enable scaling up DACCS.

GCCSI tracks the CCS policy support in different countries and calculates representative policy indicators[62] for each region. Some of the key factors tracked are policy leadership, fiscal incentives, market mechanisms, public finance, and regulations. As shown in Figure 25 below, six countries are clearly ahead of the rest in terms of policy support: The US, Canada, the UK, Norway, China, and Japan. All these countries have experience with large or smaller pilot scale CCS facilities. Although UK has no operational

[61] News article- Link
[62] CCS policy indicator. GCCSI, 2018.

CCS facility to date, its strong institutional frameworks granted it a high score. According to GCCSI, the second band of countries with strong, albeit not very comprehensive, set of CCS policies are the Netherlands, Denmark, Australia, and South Korea. These countries are likely to be ideal locations for early DACCS plants since CCS support can be an indicator of willingness to support engineered carbon removals. Still, governments must adopt significant DACCS and NETs specific policies to present attractive investment opportunities.

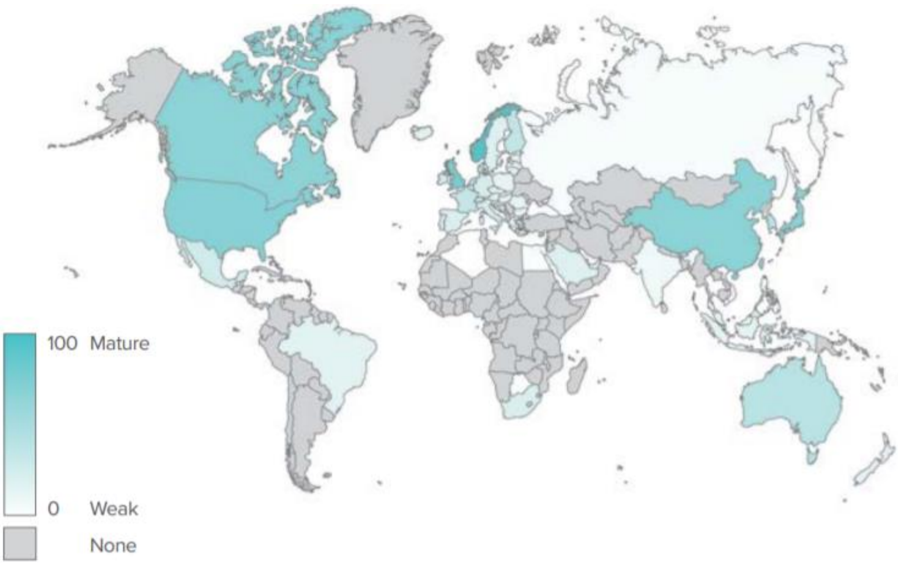


Figure 25: GCCSI's global CCS policy indicator heat map[62]

4.6 Low hanging fruits and favourable DACCS cases

The above sub-sections discussed the key global DACCS siting factors and in some cases explored their impact on costs. This section aims to combine some of these factors to present different cases for both liquid and solid DACCS plants which may be low hanging fruits or ambitious cost targets.

Table 4 and Table 5 below summarise the different parameters used to define these low hanging fruit cases for long term NOAK liquid and solid DACCS technologies, respectively. Figure 26 and Figure 27 then provide the net LCODs associated with these cases. The parameters provided in the tables follow from general literature values gathered for the TEA and the analysis carried out in this section. In general, the cases differ in the specific DACCS technology and capex, source and price of energy, CO_2 T&S setup, and cost of finance.

For liquid DACCS technologies, siting a plant in an industrial CCS cluster can achieve moderate cost reduction, especially considering large volumes of CO_2 processed. A more effective option for improving plant economics is using low-cost solar power (cases 3 and 4) which can achieve 24%-33% lower LCODs depending on the type of electric liquid technology used. Combining low-cost solar, shared CO_2 T&S infrastructure and an ambitious 3% cost of capital may reach LCODs as low as the long-term industry target of $100/t$CO_2$.

Although renewable generation is likely to be achieved at these low costs in some regions in the future, the cost of energy storage or grid balancing may keep electricity purchase prices higher than the ambitious assumptions in these scenarios. CCS clusters with access to shared CO_2 infrastructure and low-carbon renewables/gas in regions with low project risks are ideal low hanging fruits for future liquid DACCS plants.

Table 4: Main parameters used for long-term NOAK liquid plant costs calculation under favourable conditions. Blue boxes show parameters that have changed from the base case.

Sensitivity	1 - Base Case	2 - Cluster	3 - Low-Cost Solar	4- Low Capex	5 – Very Ambitious
Technology	Hybrid Liquid	Hybrid Liquid	Electric Liquid	Next Generation Electric	Next Generation Electric
Capex, Fixed Opex, Solvent, Consumables	Base Case	Base Case	Base Case	Base Case[63]	Base Case[63]
Electricity Source	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)
CO_2 T&S	Base Case ($22/t$CO_2$)	In Cluster ($5/t$CO_2$)	Base Case ($22/t$CO_2$)	Base Case ($22/t$CO_2$)	In Cluster ($5/t$CO_2$)
Cost of Capital	5%	5%	5%	5%	3%

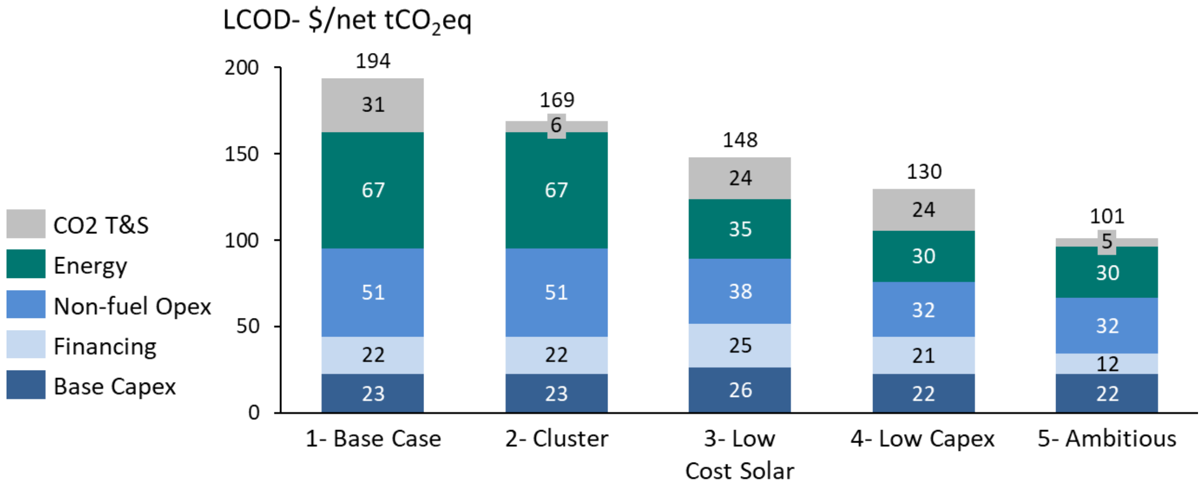


Figure 26: Liquid long-term NOAK 1 MtCO_2/year plant costs for various favourable conditions

The single most important cost reduction opportunity for solid DACCS plants is improving adsorbent cost-performance balance, which is illustrated with case 2 where LCOD may reduce by up to $60/t$CO_2$ when a more ambitious adsorbent assumption is made. As shown with case 3, reaching ~$170/t$CO_2$ without better adsorbents require solid hybrid plants to have simultaneous access to low-cost solar energy, shared CO_2 T&S infrastructure, and free waste heat.

Electric solid DACCS plants with access to low-cost solar are estimated to achieve 15% cost reduction, which is significantly less than the equivalent cost reduction observed with liquids. Lower power demand and higher overall base case LCOD of solids are the main reasons for this result.

Lastly, a very ambitious case combining improved adsorbents, low-cost solar, shared T&S infrastructure, lower cost of capital and more favourable learning rates[64] is found to be able to bring solid DACCS costs to relatively very low levels of ~$80/t$CO_2$.

[63] Next generation electric plants have lower Capex and power demand than earlier electric plant designs.
[64] Capex and financing costs for the very ambitious case presented here are calculated following the methodology described in Box 2, assuming a learning rate of 15%, initial DACCS capacity of 1 MtCO_2/year and a final 2050 capacity of 2 GtCO_2/year.

Low hanging fruit opportunities for deployment of solid DACCS are industrial CCS clusters with waste heat availability and access to low-cost renewables in regions with minimal project risks. However, ensuring reduction of adsorbent costs is likely to be as effective as situating plants in these most ideal locations.

Table 5: Main parameters used for long-term NOAK solid plant costs calculation under favourable conditions. Blue boxes show parameters that have changed from the base case.

Sensitivity	1- Base Case	2- Better Sorbent	3- Low-Cost Cluster	4- Low-Cost Solar	5- Very Ambitious
Technology	Hybrid Solid	Hybrid Solid	Hybrid Solid	Electric Solid	Electric Solid
Capex, Fixed Opex, Solvent, Consumables	Base Case	Low Adsorbent Cost[65]	Base Case	Base Case	Low Adsorbent Cost[65] & High Learning Rate[64]
Electricity Source	Solar PV – Base Case ($50/MWh)	Solar PV – Base Case ($50/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)	Solar PV – Low ($14/MWh)
Heat Source	Nuclear ($19/MWh)	Nuclear ($19/MWh)	Free Waste – no cost, no emissions	-	-
CO_2 T&S	Base Case ($22/tCO_2$)	Base Case ($22/tCO_2$)	In Cluster ($5/tCO_2$)	Base Case ($22/tCO_2$)	In Cluster ($5/tCO_2$)
Cost of Capital	5%	5%	5%	5%	3%

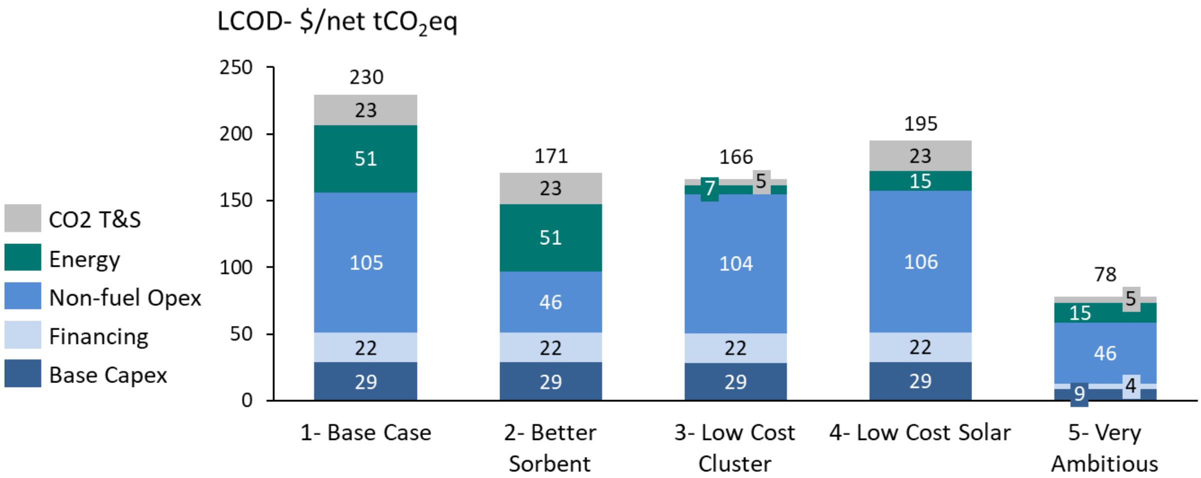


Figure 27: Solid long-term NOAK 1 $MtCO_2$/year plant costs for various favourable conditions

[65] This study assumes solid adsorbent costs of $180/tCO_2$ (FOAK) and $72/tCO_2$ (NOAK), however Climeworks has a long-term estimate of reaching $31.5/tCO_2$ captured from air, which is used for the ambitious cases here.

4.7 Summary of global siting factors

This section has explored the key global siting parameters quantitatively or qualitatively to understand their impact on economic feasibility of different DACCS technologies and to better understand regions most suitable for DACCS deployment. Below are the major messages on these siting factors:

Key Influential Factors

- Conditions change significantly between regions, requiring **site and project specific studies** in the future.
- Stakeholders and our analysis identified **access to low-cost renewable power, cost of capital and proximity to CO_2 transport and storage** as the most influential global siting factors. These resources are not evenly distributed globally but most of the current largest emitting countries are expected to have enough storage capacity and access to low-cost renewables.
- **Water and land requirements are not expected to be major barriers** in most regions/countries. Even if higher cost desalinated water is used, DACCS costs expected to rise by <3%.
- **Public acceptance, regulatory regimes, investment risks and policy support** can be major early challenges, but these can be resolved by governments and policy so are not barriers inherent to DACCS technology.
- If global trading of carbon removal develops on an international CO_2 accounting framework[66], then DACCS will likely only be situated in particularly favourable locations with low-cost renewables and CO_2 storage.

Favourable Regions

- The most favourable regions for DACCS will have access to excess low-cost & low-carbon power and heat, CO_2 storage resources (with no public resistance), have strong commitment to reducing their emissions and have regulatory/policy support for DACCS, CCS and NETs. **Under ambitious cost-performance assumptions and favourable conditions, DACCS costs could reach ~\$100/net-tCO_2 long term**. These favourable conditions may come to exist, but it is difficult to comment on the size of the opportunity.
- In the short-medium term, some ideal locations for DACCS may be parts of North America, Western Europe (North Sea), Australia, Middle East and Eastern China, and Japan.

Less favourable Regions

- Countries at higher latitudes are likely to have higher renewables costs in the longer term, particularly if they do not have offshore wind opportunities, meaning **DACCS is likely >\$200 /net-tCO_2**. Other barriers to DACCS are lack of national CO_2 storage, where the remaining options are DAC with carbon utilisation (limited in scale and needs permeant sequestration[67]) and export of CO_2.
- Although not modelled separately in this study, **using renewables to replace coal generation is shown to be more effective than removing CO_2 from air via DACCS to reduce net emissions**[13,68]. Countries with coal dependence such as China, India, Poland, can first focus on displacing those assets rather than allocating scarce renewables to power DACCS.

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[66] e.g. Article 6 of the Paris Agreement

[67] Most CO_2 utilisation options do not permanently store carbon, hence do not provide negative emissions. Some exceptions are net-negative cement/aggregate production.

[68] Natural gas vs. electricity for solvent-based direct air capture. McQueen et al., 2021.

5. Inclusion of DACCS in IAMs and recommendations for the modelling community

The term "Integrated Assessment Model" (IAM) defines a range of modelling approaches that represent interactions between global energy, industry, land-use, and earth systems with a view on exploring possible pathways to mitigate climate change. They typically consider long timeframes to at least 2100, with 5-year to 10-year timesteps, and some regional disaggregation of the world. Most IAMs explicitly capture possible scenarios of technology adoption, potentially including different forms of DACCS technology, often with exogenous (or in some cases endogenous) characterisation of technology learning over time.

IAMs are arguably the most influential quantitative tools with respect to global climate change mitigation analyses, largely due to their role within the Intergovernmental Panel on Climate Change (IPCC). For example, more than 1000 IAM scenarios from more than 30 models featured in the 5th Assessment Report[69] of the IPCC, and more than 500 scenarios from 19 models were presented in the more recent IPCC Special Report on 1.5°C[11]. Such models can provide decision-support to those setting global ambition on climate change mitigation, alongside providing the ability to investigate a myriad of policy, technology and other issues. For example, and of relevance to the present study, is that IAMs have been used to investigate differences between scenarios with and without CCS[70].

In the past decade, some IAMs have been applied to consider the prospects for DACCS technology. This began with Chen and Tavoni (2013)[71] who studied DACCS potential using the WITCH model, finding potential for a very substantial 37GtCO_2/year capacity, spurring further interest in the technology. This was followed by Fuss et al (2013), Marcucci et al (2017)[72], Strefler et al (2018)[73], Hilaire et al (2019)[74] and Realmonte et al (2019)[75], most of which also communicated a high potential for DACCS. These studies relied heavily on very few sources of DAC technoeconomic characterisation, usually stemming from APS (2011)[76] with subsequent updates and optimisations in Mazzotti et al (2013)[83] and Zeman (2014)[77].

Given the potential for DACCS found in recent IAM studies, it is important for the community have access to a high quality techno-economic characterisation that reflects the latest knowledge. One important reason why this is true is due to the potential impact of DACCS in shaving temperature overshoot in mitigation scenarios, and moreover producing a possible change in the risk profile of DACCS. The latter point is important because to date DACCS is often seen as relatively high risk due to the possibility that it might incentivise a slowdown of near-term mitigation on the assumption that DACCS will become available late this century, but this may not transpire.

This chapter sets out recent analyses in the literature with respect to the techno-economic characteristics of DACCS technology and presents a synthesis of the new work presented in this report as an updated representation for consideration in future IAM studies. The following sub-sections set out the techno-economic parameters for DACCS, followed by a short discussion of considerations and assumptions regarding uptake constraints and CO_2 storage and utilisation. A summary of areas worthy of investigation in future research is presented in section 7.2.

69 Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, 2014.
70 The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. E. Kriegler, et al., 2014.
71 Direct air capture of CO2 and climate stabilization: A model-based assessment. Chen, C., Tavoni, M., 2013.
72 The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. Marcucci, A., Kypreos, S. & Panos, E., 2017.
73 Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. Strefler J., et al., 2018.
74 Negative emissions and international climate goals—learning from and about mitigation scenarios. Hilaire, J., et al., 2019.
75 An inter-model assessment of the role of direct air capture in deep mitigation pathways. Realmonte, G., et al., 2019.
76 Direct air capture of CO2 with chemicals: a technology assessment for the APS panel on public affairs. APS, 2011.
77 Reducing the cost of Ca-based direct air capture of CO2. Zeman F., 2014.

5.1 Techno-economic parameters for DACCS

The literature contains a very wide range of estimates of the overall cost of DACCS technology, ranging from US$30-$1000/tCO_2 according to Sanz-Pérez et al (2016)[78]. Moreover, cost estimates are generally disputed in the literature, with Ishimoto (2017)[79] noting that estimates from those associated with industry tend to be lower than those from independent academic sources, but also recognising that either of these viewpoints could be correct.

On the high-cost side, examples such as Pritchard (2015)[80] and Ranjan and Herzog (2011)[81] produced sceptical analyses of DACCS usually above $500/t$CO_2$ based on thermodynamic arguments. Conversely, on the low-cost side the pace of technological development and optimised design are cited to justify costs as low as $30/t$CO_2$[82], though more often in the range of $100 - $300/t$CO_2$.

A key reference source for techno-economic data for liquid DACCS in recent IAM-based studies has been APS (2011)[76] which arrived at costs of approximately $600/t$CO_2$ including financing costs and energy costs. Mazzotti et al (2013)[83] subsequently optimised the APS (2011)[76] system, down to $520/t$CO_2$. This was then further optimised by Zeman (2014)[77] pushing cost down further to $310/t$CO_2$. An overall summary of techno-economic assumptions in selected recent IAM studies that included DACCS is presented in Table 6, with the APS (2011) study for reference.

According to Fuss (2018)[12] the primary cost drivers of DACCS relate to (1) capital cost, (2) energy costs for capture and regeneration, and (3) sorbent loss and maintenance. The following sub-sections deal with these areas and add some further considerations that are important for energy systems and integrated assessment modelling.

[78] Direct air capture of CO2 from ambient air. Sanz-Perez et al., *Chem. Rev*. 116, 19, 11840–11876, 2016.
[79] Putting costs of direct air capture in context. Ishimoto Y., et al., FCEA Working Paper Series: 002, 2017.
[80] Thermodynamics, economics and systems thinking: what role for air capture of CO2? Pritchard C., 2015.
[81] Feasibility of air capture. Manya Ranjan, Howard J. Herzog, 2011.
[82] Capture of carbon dioxide from ambient air. Lackner, K., 2009.
[83] Direct air capture of CO2 with chemicals: optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor. Mazzotti, M., Baciocchi, R., Desmond, M.J. et al., 2013.

Table 6: Summary of techno-economic representation of DACCS in selected published IAM studies to 2020

	APS (2011) Liquid DAC	Chen and Tavoni (2013) Liquid DAC	Fuss et al (2013) Liquid DAC	Marcucci et al (2017) Liquid DAC	Strefler et al (2018)	Realmonte et al (2019) Liquid DAC	Realmonte et al (2019) Solid DAC
Cost (CAPEX inc. financing costs plus OPEX exc. energy)	$469 / tCO2 realistic $349 / tCO2 optimistic	$470 / tCO2 realistic $350 / tCO2 optimistic from APS (2011)	-	-	-	High: $300 / tCO2 Low: $180 / tCO2 Floor: $100/ tCO2 6%pa/0.06 learning	High: $350 / tCO2 Low: $200 / tCO2 Floor: $50/ tCO2 6%pa/0.06 learning
Cost (CAPEX inc. financing costs plus OPEX inc. energy and CO2 T&S)	-	-	$550 / tCO2 from APS (2011)	$600 / tCO2 (ref Chen & Tavoni 2013) reducing to $200 / tCO2	$430-$570 / tCO2 (exact cost basis not stated)	-	-
Cost (CAPEX exc. financing costs)	$110 / tCO2 realistic $150 / tCO2 optimistic	-	-	-	-	-	-
Cost (CAPEX inc. financing costs)	$350 / tCO2 realistic $260 / tCO2 optimistic	$350 / tCO2 realistic $260 / tCO2 optimistic	-	-	-	-	-
Cost (OPEX exc. energy costs)	$119 / tCO2 realistic $89 / tCO2 optimistic	$120 / tCO2 realistic $90 / tCO2 optimistic	-	-	-	-	-
Energy consumption	6.1GJ / tCO2 assumed at 75% eff (8.1GJ / tCO2) thermal 1.8GJ / tCO2 electric	8.1GJ / tCO2 thermal 1.8GJ / tCO2 electric	-	8.1GJ - 5GJ / tCO2 thermal 1.8GJ / tCO2 electric	-	High: 8.1GJ/tCO2 thermal, 1.8GJ/tCO2 electric Low: 5.3GJ/tCO2 thermal, 1.3GJ/tCO2 electric	High: 7.2GJ/tCO2 thermal, 1.1GJ/tCO2 electric Low: 4.4GJ/tCO2 thermal, 0.6GJ/tCO2 electric
Lifetime	20 years depreciation	-	-	-	-	20 years	15 years
Storage capacity	-	1002 – 1825 GtCO2 from Hendriks (2004)	-	1660 GtCO2 from Hendriks (2004)	-	9,000 – 11,000 GtCO2	
Availability	88.9%	-	-	-	-	-	-
Start year	-	2050 – 2065 (in results)	-	2060 (input)	2030 (input)	~2050 (in results)	~2050 (in results)
Constraints	-	DAC maximum 70% of all CCS	-	-	-	20% annual growth rate, 30GtCO2/year NETs limit, NG use with 95% capture rate	20% annual growth rate, 30GtCO2/year NETs limit, NG use with 95% capture rate

*Reported figures are as per related publications, and therefore readers should consult that respective papers for details of assumptions related to each.

5.1.1 Capital cost

The IAM literature has largely focused on the liquid DACCS option to date, with only Realmonte et al (2019))[75] also considering solid DACCS systems. For liquid DACCS, the capital cost reported in the APS (2011)[76] study was $480m for a 1Mt$CO_2$/year plant. Following an established Chemical Engineering methodology for overall cost estimation, this was then multiplied by a factor of 4.5-6.0 to arrive at $2.2-$2.9b total installed cost, equating to $110-$150/tCO_2. Financing costs at 7%p.a. are then added to these figures to arrive at a range of $260-$350/tCO_2.

The optimisation of the APS design in Mazzotti et al (2013)[83] reduced the capital cost to $450m, thereby making installed cost $2.0-$2.7b, which equates to $100-$135/tCO_2, again net of financing costs. Zeman (2014)[77] also proposed an alternative design of the same technology, though using plastic packing material, and arrived at a substantially reduced capital cost of $305m, leading to installed cost of $1.37b-$1.83b ($68-$92/tCO_2) net of financing costs. In the case of Zeman (2014), financing costs bring total capital costs to $165/t$CO_2$, using the same charge rate as Mazzotti et al (2013).

It should be noted that DACCS costs used in most IAM studies have included financing costs, which is an assumption that should be reflected upon in light of IAM structure to ensure avoidance of any double counting of these financing costs, and to ensure comparability of costs within individual models (i.e. are financing costs included for all technologies across the model on an equitable basis, using an appropriate cost of capital?).

Table 7: DACCS capital costs stated during research for this study for a 1 MtCO_2/year plant

	FOAK Liquid	NOAK Liquid	FOAK Solid	NOAK Solid
Capital cost for 1 MtCO_2/year plant ($m)	1200	600-700[84]	1129	626
Capital cost ($/t$CO_2$ captured)	40	20-23	125	28
Capital cost inc. financing ($/t$CO_2$ captured) and associated cost of capital	126 (10%)	41-48 (5%)	204 (10%)	50 (5%)

Capital costs estimated in this study are presented in Table 7. This study has also noted that solid DACCS systems may entail lower overall cost for smaller scale systems than liquids. In this case, for a 100 ktCO_2/year plant, solid DACCS capital cost was estimated at $31-$141/tCO_2 (NOAK-FOAK). While these costs are relatively high due to lack of the economies of scale of the 1 MtCO_2/year systems, reduced further costs (e.g., energy, sorbent, etc) result in lower overall cost relative to equally small liquid DACCS systems.

Therefore, overall, DACCS capital costs in this study are generally significantly lower than those used in IAM studies in the literature, for example with NOAK capital costs for liquid systems at approximately half the value presented in Zeman (2014).

Furthermore, in many IAMs regional capital cost variations are taken into account. This is often done using regional cost multipliers to scale up or down overnight capital costs. For the case of DACCS no literature evidence on these factors has been located in this study, and indeed it has been shown that difference in technology costs by region varies between IAMs, with some showing lower capital cost in developing countries, and some showing higher[85]. As such, no regional variation of cost has been estimated in this study. Those concerned with regional variation in capital cost should note that 17.9% of total direct field costs is labour[15] for liquid DACCS plants, and variations in labour costs by country can be sourced from

[84] Representing 5-7 doubling of the total deployed capacity starting from initial large-scale plants. These costs may be achieved earlier than 2050 if DACCS deployment reaches very high levels.
[85] Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. Krey et al., 2019.

the International Labour Organisation statistics on wages database, in this case using the "Construction" economic activity category[86]. Likewise, where variation in financing costs are needed for a model, these may be sourced following the methodology outlined in Ondraczek et al (2015)[87], where results by country are listed in the supplementary material of that article. As an illustrative example, if one assumes a 50% reduction in wage costs where 17.9% of total direct field costs are labour, one would expect the capital cost to decrease to 91% of the values reported in this report. Conversely, if financing costs were to increase due to local factors, from the 5% (NOAK) assumed in this report to 28% representing a high case in Brazil, the impact on finance-inclusive capital cost would be an increase of more than 3-fold to $177/tCO_2$ for a 1 $MtCO_2$/year liquid DACCS plant.

5.1.2 Energy consumption

As most IAMs endogenously calculate energy prices, and take energy consumption as the exogenous input data, we focus on energy consumption here. As with capital costs, energy consumption has been estimated and re-estimated or optimised within the literature in several contributions in the past decade.

For liquid DAC, the APS (2011) and subsequent re-design studies have been used most prominently in IAM studies. The APS study found a thermal consumption of 6.1 GJ/tCO_2 (which they translated to 8.1 GJ/tCO_2 natural gas demand due to 75% conversion efficiency), and 1.8 GJ/tCO_2 electricity needs. Mazzotti et al (2013) presented optimised design that could up to halve the APS fan electricity consumption, and Zeman et al (2014) arrived at 6.7 GJ/tCO_2 thermal needs, similar to the APS study. Realmonte et al (2019) used the APS figures as a "high estimate" for liquid DAC energy, and also used a "low estimate" of 5.3 GJ/tCO_2 thermal needs and 1.3GJ/tCO_2 electricity needs based on Keith et al (2018)[15].

For solid DAC, the National Academy of Sciences (2019)[22] found a consumption of 3.4-4.8 GJ/tCO_2 thermal and 0.55-1.1 GJ/tCO_2 electricity (their "mid-range" estimates). This study also produced a useful graphic (Figure 5.5 in that document) comparing estimates in the literature, which were generally in the range of 0.5 - 2.0 GJ/tCO_2 for electricity, and generally in the range of 2.0 – 9.0 GJ/tCO_2 for thermal needs. In IAM analyses, only Realmonte et al (2019)[75] characterises solid DAC, and used a high estimate of energy needs at 1.1GJ/tCO_2 electrical and 7.2 GJ/tCO_2 thermal based on Gebald (2011)[88], and a low estimate of 0.6GJ/tCO_2 electrical and 4.4 GJ/tCO_2 thermal based on Ishimoto (2017)[79].

Table 8: Energy consumption estimates reported in research for this study for liquid and solid DACCS. Figures in brackets for solid DACCS are an electric-only configuration where heat is supplied to the process via a heat pump with COP of ~2.5. Thermal energy required for liquids and solids are at ~900ºC and ~100ºC, respectively.

	FOAK Liquid DACCS[89]	NOAK Liquid DACCS[89]	FOAK Solid DACCS	NOAK Solid DACCS
Thermal energy cons. (GJ/tCO_2)	6.8	0	10.8 (-)	4.9 (-)
Electrical energy cons. (GJ/tCO_2)	2.2 – 3.7	7.2 – 9	2.3 (6.6)	1.6 (3.6)

In research for the present study, energy consumptions were estimated to be as presented in Table 8. The reader should note that much of this data is sourced from companies developing DACCS systems. These are largely in line with those in the literature, with the slight exception of solid DACCS, where electricity consumption is at the higher end of the reported ranges in the literature, and the addition of the possibility of electricity-only solid DACCS systems.

[86] International Labour Organization, Statistic on wages [accessed 11.06.2021]- Link
[87] WACC the dog: the effect of financing costs on the levelized cost of solar PV power. Ondraczek J., et al., 2015.
[88] Amine-based nanofibrillated cellulose as adsorbent for CO2 capture from air. Gebald et al., 2011.
[89] Publicly available data not used in energy cost modelling in other parts of this report.

5.1.3 Operating and maintenance costs

For liquid DACCS systems chemical costs do not significantly impact the economics, with approx. 1% of Calcium purged each cycle[15] (3.5 kg/tCO_2[22]) and approx. 0.4 kg/tCO_2[22]of potassium hydroxide. In this study $CaCO_3$ was assumed to cost \$250/t and KOH \$700/t based on recently observed market prices. In addition to materials costs, liquid DACCS O&M cost (i.e. labour and parts) reported during research for this study were \$50-\$60/tCO_2 for FOAK and \$25-\$30/tCO_2 for NOAK[15], which for FOAK is slightly higher than those previously reported in the literature of \$42/tCO_2.

For solid DACCS, adsorbent costs form a much more significant part of the overall cost. Adsorbent consumption is also significant, where according to Deutz and Bardow (2021)[90] it is approximately 7.5kg/kgCO_2 in the case of FOAK, dropping to 3kg/kgCO_2 in the case of NOAK. Adsorbent cost from National Academy of Sciences is approximately \$50/kgCO_2[22], though it is recognised that there is substantial room for innovation with respect to solid sorbents, and as such costs may reduce in future. After discussions with Climeworks during stakeholder engagement, \$180/tCO_2 captured was assumed to represent adsorbent costs of FOAK plants. A 60% reduction to \$72/tCO_2 is then assumed for the NOAK stage in 2050s. Furthermore, an ambitious case of \$31.50/tCO_2 has been proposed by Climeworks as the long-term goal. Finally, for solid DACCS systems, regular labour (i.e. operation) is estimated at \$7/tCO_2, whereas regular maintenance is estimated at 3% of capital cost.

As for the labour component of capital cost discussed above, labour costs vary by region. Variation in labour costs by region can be estimated using the International Labour Organisation statistics on wages database, using an appropriate economic activity category[86] such as manufacturing.

5.1.4 Lifetime, availability, and cost of capital

Very few IAM studies discuss system lifetime or cost of capital for financing for DACCS technology. The original APS (2011) study assumed 20-year depreciation and a 7% cost of capital for calculation of financing costs. Mazzotti et al (2013) assumed recovery of fully built-up capital cost of 5% per year depreciation (i.e. 20 year economic lifetime) plus 7% per year return on investment, and Zeman (2014) followed the same charge rate as Mazzotti. Realmonte et al (2019) assumed 20-year lifetime for liquid DAC, and 15-year lifetime for solid DACCS.

Likewise, very few IAM studies stated availability assumptions, but APS (2011) quoted 89%, which has largely been adopted. During the course of this study consultation with Carbon Engineering suggested that Liquid DACCS FOAK availability of 89%, and NOAK availability of 92-95%. Solid DACCS in this study has availability of 90%.

Table 9: Lifetimes, plant availability, and costs of capital used in this study

	FOAK Liquid DACCS	NOAK Liquid DACCS	FOAK Solid DACCS	NOAK Solid DACCS
Lifetime (years)	30	30	10	25
Plant availability	90%	90%	90%	90%
Cost of capital	10%	5%	10%	5%

Table 9 shows the technology lifetime assumed in this study, which are substantially above those previously assumed in the literature, with both liquid and solid DACCS remaining operational for 10 further years, specifically 30 years for liquid DACCS and 25 years for solid DACCS, which were suggested by Carbon Engineering and Climeworks, respectively. Table 9 also shows cost of capital assumed here for calculation of financing costs presented above, and the reader should bear in mind the regional variation in financing costs described above in the Capital Cost section.

[90] Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Deutz, S., Bardow, A., 2021.

5.1.5 Water and land use

Water consumption and land use requirement are often cited with respect to DAC systems, and may be important for IAM studies that consider land use explicitly and/or consider water nexus issues in climate change mitigation scenarios.

For liquid DAC water use is 4.7 t/tCO_2 at 20ºC and 64% relative humidity[15], and for solid DAC this reduces to 1.6 t/tCO_2[75]. There is high uncertainty as to water requirements for solid DAC, which depends on the specific selection of technology. In some cases, studies have noted that water may even be generated depending on the regional temperature and relative humidity.

Land use also differs between the DACCS technologies, though is widely recognised to be orders of magnitude lower than other NETs options such as afforestation and BECCS, which require large land area for related vegetation. The land area required for liquid DACCS at 1 MtCO_2/year capacity is reported to be 6 acres for direct use, increasing to 1730 acres to include spacing between the units[22], which is a figure challenged by some stakeholders. In this study Carbon Engineering's estimates for a 1 MtCO_2/year plant of ~100 acres (FOAK) and ~60 acres (NOAK) are used. Solid DACCS is assumed to require 64.6 acres for the DAC unit at 1Mt/year capacity for FOAK, reducing to 19.4 acres for NOAK, both based on Deutz and Bardow (2021)[90].

5.2 Estimates of DAC potential and uptake constraints

Non-IAM studies that estimated the potential of DACCS generally envisage that it is significant, potentially with no meaningful technical constraints, given low and non-arable land requirements, and potential to co-locate with low-cost energy and/or CCS infrastructure and storage sites. Most such studies put the potential in the range of 10-15 GtCO_2/year. For example, Smith et al (2016)[59] estimated 13.2GtCO_2/year in 2100, Fuss (2017)[91] up to 12.1GtCO_2/year in 2100, while McLaren (2012)[92] estimates 10 GtCO_2/year as soon as 2030-2050. The counterpoint to these are studies such as Pritchard (2015)[80] which is doubtful of any meaningful potential at all, largely based on thermodynamic arguments.

Despite potentials generally being seen as significant, many IAM studies to date have estimated even greater potential and uptake. For example, the IAM modelling in Marcucci et al (2017)[72] allowed DAC uptake beginning from 2060, and the technology was strongly adopted, ultimately reaching approximately 40 GtCO_2/year by 2100. Similarly, Realmonte et al (2019)[75] assumed a 20% p.a. growth rate based on comparison of similar technologies and established a 30 GtCO_2/year capacity limit (on all NETs combined), which the model appears to reach by late century (though only cumulative DACCS removals is reported). Realmonte et al (2019) also investigate a scenario that limits capacity to 3 GtCO_2/year. In the results of this study a maximum scale up rate of 1.5 GtCO_2/year is observed (where input growth limit assumption is based on analysis of a range of similar technologies), all during late century, after 2070, leading to cumulative DACCS to 2100 of approximately 800 GtCO_2 stored in both of the two IAMs applied.

Based on the review of uptake characterisation in IAMs above, it is apparent that estimates used regarding constraints on rate of uptake and total capacity limits for DAC have been relatively coarse, with only Realmonte et al (2019)[75] justifying assumptions. While no well-substantiated evidence on this topic was found in the literature review for this study, the following paragraphs discuss some of the main areas of relevance to the debate.

Siting factors may be an important consideration with respect to maximum feasible uptake rates and any capacity limits. Goldberg et al (2013)[93] noted opportunities for co-location with CO_2 storage and low-cost renewables to power the systems, either of which may be important for viability.

The possibility of siting DACCS with CO_2 storage sites may avoid the need for the extensive CO_2 transport infrastructure, which has in the past led to questions around the feasibility of some CCS-

[91] The 1.5°C target, political implications, and the role of BECCS. Fuss S., 2017.
[92] A comparative global assessment of potential negative emissions technologies. McLaren, D., 2012.
[93] Co-Location of air capture, subseafloor CO2 sequestration, and energy production on the Kerguelen Plateau. Goldberg, D., et al., 2013.

focused global mitigation scenarios. The available literature on this point is sparse, as credible assessments of storage capacity by location are only available for some regions. Estimates of storage capacity by region do exist, for example Hendricks et al (2004)[94], and are becoming more nuanced. IAM practitioners should monitor such literature for more detailed estimates of storage availability and adjust model inputs accordingly. Importantly storage aspects may impact regional uptake of DACCS (assuming global trade of CO_2 for storage does not become widespread), with some regions without historical oil and gas developments may struggle to access easier or lower cost storage.

Co-location of DACCS with renewable or other zero (or negative) carbon energy is another important factor that may accelerate or hinder uptake. This does not necessarily create challenges for IAMs, most of which have relatively sophisticated characterisations of regional renewables potentials, for example based on Chu et al (2020)[95], or opportunities for BECCS and nuclear power. However, as highlighted below, further research on overall spatial mapping of DACCS potential, cognisant of access to renewables, CO_2 storage, and water and land requirements would be a worthwhile exercise to refine potential uptake estimates in IAMs.

An alternative destination of CO_2 captured by DAC is CO_2 utilisation, which may be an important early market for DAC technology where CO_2 storage options are not available, or if simply because it is the best option in a particular situation. For example, captured CO_2 may be used in greenhouses or beverage manufacture (noting that most of these options do not result in permanent sequestration, but may displace other fossil sources of CO_2). CO_2 utilisation is generally seen as thermo-dynamically challenging, though could play a role in the manufacture of synthetic fuels for sectors that are otherwise extremely difficult to decarbonise, such as aviation. For example, in the IEA Energy Technology Perspectives' scenario[17] with limited CO_2 storage, CCU reaches 684 $MtCO_2$ by 2060. Furthermore, a very ambitious estimate of future CCU market potential[96] is 1-7 $GtCO_2$ by 2030. DAC can provide the CO_2 source for such facilities.

Finally, water consumption (and humidity) of siting may be important. A key advantage of DACCS, relative to BECCS/afforestation options, is the lack of necessity for arable land, but water requirements may also limit DACCS potential in some non-arable (e.g., desert) locations. This may limit DACCS sites to non-arable land without food related water constraints or put DACCS in competition with arable land uses. Further research is required to estimate land potential via consideration of these factors, though it should be noted that as the footprint of DACCS is small relative to measures such as afforestation and BECCS, land constraints are unlikely to be a genuine concern in terms of impact on overall DACCS uptake (i.e. from a land-use perspective DACCS will always be better than other NETs, making it straight forward to justify displacing a small amount of these technologies to accommodate DACCS).

5.3 Policy implications for IAMs

Given the high potential of DACCS discussed above, and the reducing estimates of cost over time (including those within this study), it is likely that IAM-based studies will continue to favour the technology and project strong uptake in global mitigation scenarios. It is therefore important that modellers are aware of policy implications of model results, framing of modelling results, and the possible need for consideration of policy or financing related constraints on uptake.

Based on recent IAM studies, a key insight has been the potential of DACCS technology to delay near-term climate change mitigation action on the basis that DACCS technology will materialise late-century to balance the carbon budget. Of course, this optimism may prove to be poorly founded, and the technology may not materialise or may have differing cost or performance credentials. The risks of this outcome have been pointed out in most IAM based studies, from Chen and Tavoni (2013)[71] through to Realmonte et al (2019)[75]. These studies have differing lenses on the implications of such an outcome, with the former noting

[94] Global carbon dioxide storage potential and costs. Hendriks, C. et al., 2004.
[95] A geographic information system-based global variable renewable potential assessment using spatially resolved simulation. Cheng-Ta, C., Adam, H., 2020.
[96] Article Link

benefits for fossil-intensive economies while the latter focused on the risk of technology failure leading to shortfall on the Paris Agreement targets.

Given that this issue is apparent to relevant policymaking and financing stakeholders, it is plausible that emerging policy instruments and financing treatment will seek to support DACCS in a way that ensures no detriment to near-term mitigation action, for instance by having separate CO_2 mitigation and removal targets. While each IAM may represent related policy instruments differently, some possibilities are ensuring Paris Agreement compliant uptake of non-DACCS mitigation measures in the near- to medium-term, for example via related constraints or modelling targeted financial policy instruments to support such uptake. In essence, IAM approaches to policy implementations should support innovation in DACCS, without undermining near- to medium-term mitigation that has the potential to meeting Paris Agreement targets even if DACCS does not materialise.

5.4 Overall summary of DACCS parameters for IAM modelling

Table 10 presents a summary of the information above. As noted in the literature, an extremely wide range of estimates of cost exist, and a significant portion of reference sources are from or closely affiliated with companies developing DACCS technology. Demonstrably independent sources tend to estimate higher costs than other sources.

Table 10: Summary of DACCS techno-economic parameters for a 1 $MtCO_2$/year plant for use in energy systems and integrated assessment modelling. Primary numbers outside brackets are those derived from this study, largely based on industry sources, and should be interpreted as more ambitious estimates of potential costs and performance. Figures in brackets in each cell represent the authors' judgement of literature-based estimates of potential costs and performances, with some cases being unknown due to far too few reference sources being available or being from sources affiliated with industry.

	FOAK Liquid	NOAK Liquid	FOAK Solid	NOAK Solid
Capital cost for 1 $MtCO_2$/year plant ($m)	1200 (2000)	600-700[84] (1400)	1129 (U)	626 (626[c])
Learning cost reduction		10-15%		
Labour and maintenance cost ($/$tCO_2$)	50-60 (42[c])	25-30 (30[c])	26.7 (U)	17.9 (30[c])
Lifetime (years)	30 (20)	30 (25)	10 (10)	25 (15)
Availability (%)	89%[a] (U)	92-95%[a] (90%)	90% (U)	90% (90%)
Thermal energy use (GJ/tCO_2 captured)	6.8[a] (U)	0[a] (8.1)	10.8[b] (7.2[c])	4.9[b] (4.4[c])
Electricity use (GJ/tCO2 captured)	2.2 – 3.7[a] (U)	7.2 – 9[a] (1.8)	2.3[b] (1.1[c])	1.6[b] (0.6[c])
Solvent/sorbent cost ($/$tCO_2$ captured)	$4 (1[c])	$3 (1[c])	180 (350[c])	31.5-72 (150[c])
Solvent/sorbent use (kg/tCO_2 captured)	~5kg KOH+$CaCO_3$[a] (unknown)	~3kg KOH+$CaCO_3$[a] (3.5 kg/tCO_2 $CaCO_3$, 0.4 kg/tCO_2 KOH)	Not provided (7.5)	Not provided (3)
Oxygen use (kgO_2/tCO_2 captured)	500[a] (U)	0[a] (0)	- (-)	- (-)
Water use (tH_2O/tCO_2 captured)	~2-4[a] (U)	~1-2[a] (4.7)	1.6 (1.6-12[c])	1.6 (1.6-12[c])
Land area (acres)	~100[a] (100[c])	~60[a] (60[c])	65 (65[c])	19 (19[c])

a- Data provided by Carbon Engineering but not used in modelled results in other parts of this report (where it was substituted with confidential data).

b- An electricity-only variant is also reported for solid DACCS, requiring 6.6 GJ/tCO_2 captured (FOAK) & 3.6 GJ/tCO_2 captured (NOAK).

c- Indicates too few independent references sources available for reliable estimation, with literature values reported in some cases. Use of these values in IAMs should be treated with caution.

U- Cases being unknown due to far too few reference sources being available or being from sources affiliated with industry.

6. Global policy review & suggestions to support DACCS deployment

This section aims to understand current direct and indirect global policy support for DACCS, as well as future policy recommendations which may accelerate DACCS deployment at climate relevant scales. Outputs of this section are drawn from the literature[23,97,98,99,100,101,102,103,104,105] and extensive discussions with stakeholders.

6.1 Key barriers, risks, and limitations for DACCS deployment

Before identifying existing and potential policy support for DACCS, it is important to understand the major barriers or risks for investors or project developers which may prevent DACCS from achieving large-scale deployment. Table 11 below lists some of the major barriers identified through the literature review and discussions with stakeholders. Future policy or actions should aim to remove or reduce these barriers.

Table 11: List of major barriers and risks for large-scale DACCS deployment

Barriers/risks	Description
Innovation and demonstration	• DACCS still needs to be demonstrated at large-scale and some DACCS technologies or components are at early R&D stages, requiring further innovation support. Future performance improvements are contingent upon continued R&D.
CO_2 transport and storage	• DACCS requires external CO_2 T&S infrastructure with high upfront capital investment, thus small, singular DACCS projects may struggle to justify investment in dedicated infrastructure and currently existing CO_2 T&S infrastructure is limited in availability.
Financial	• High upfront capital requirements (Capex) and lack of consistent and sufficient returns for removing carbon from air (lack of Opex recovery). • Negative emissions are currently not valued in many policy mechanisms and CO_2 accounting frameworks. • DACCS is currently significantly more expensive than many emissions reduction / removal options.
Accounting	• Lack of regulatory and accounting frameworks around monitoring and verification can create barriers to deployment of DACCS.
Policy	• Risk of governments discontinuing policy support. • Requirements to create innovative policies for DACCS as most existing policies for CCS are not likely to be sufficient for, or applicable to, DACCS.
Other	• Potentially very high long term CO_2 leakage liabilities faced by storage companies. • Cross-chain risks, where failure in either the capture or the storage business may affect the other. • Limited qualified workforce for DACCS and CO_2 T&S supply chains. • Lack of knowledge of DACCS and NETs among the public and policymakers.

[97] Lessons and perceptions: adopting a commercial approach to CCS liability. GCCSI, 2019.
[98] Policy priorities to incentivise large scale deployment of CCS. GCCSI, 2019.
[99] Greenhouse gas removal (GGR) policy options. Vivid Economics, 2019.
[100] Options for supporting carbon dioxide removal. New Climate Institute, 2020.
[101] Policy positions of Negative Emissions Platform- Link.
[102] Policies for the sixth carbon budget and net zero. UK Climate Change Committee, 2020.
[103] Recommendations for DAC research, development, and demonstration. Bipartisan Policy Center, 2020.
[104] European Union policy playbook: negative emissions technologies. Breakthrough Energy, 2021.
[105] Future role of CCS technologies in the power sector. Report for IEAGHG by Element Energy, 2020.

Box 4: Public perception and acceptance of DACCS

Like any technology, public perception/acceptance of DACCS may be a critical factor for its large-scale deployment or inclusion in decarbonisation roadmaps. Literature around public acceptance of DACCS is very limited, but a couple of studies can give us an indication of how the public may perceive DACCS in comparison to other NETs.

For example, a very large public engagement study[106] was carried out in the UK to investigate public attitudes towards combatting climate change. As shown in Figure 28 below, participants supported inclusion of forests and better forest management (99%), ecosystem restorations (85%), wood in construction (81%) and soil carbon storage (62%) in a UK net zero future portfolio. Support for both BECCS and DACCS were limited to 42%. Natural solutions were preferred for their perceived co-benefits. BECCS and DACCS suffered due to perceived leakage risk, being less natural and presenting a risk of distracting from emissions reductions.

Another study[107] conducted a survey across the UK and the United States, finding that the public in both countries had somewhat negative attitudes towards NETs because they were perceived to not be a short-term solution and not form part of an ideal long-term climate portfolio, since they imply continued emissions elsewhere in the economy. Response to DACCS was particularly muted because the technology was still relatively unknown.

Although these studies appear to suggest that public acceptance may be a major barrier for DACCS, we should note that DACCS is still a very novel technology. DACCS developers indicate that they have not faced any public backlash for their projects so far and some stakeholders highlight the possibility of synthetic risk bias in these studies. There is a strong belief that further and correct explanation of the technology, combined with positioning DACCS as a necessary measure to mitigate the remaining emissions, can improve public perception significantly.

Association of DACCS with certain industries, such as aviation or fossil fuels, may be risky in the future for its acceptance. Furthermore, as large-scale DACCS facilities are built, land footprint, visual aesthetics, noise, and other attributes will determine public attitudes towards DACCS, especially in regions close to population centres.

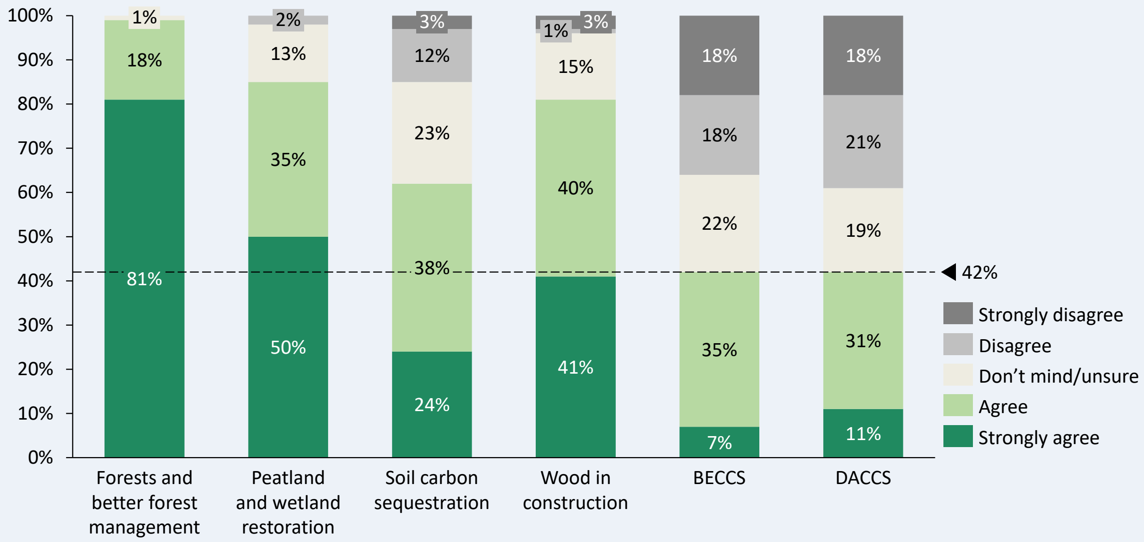

Figure 28: Opinion of the public as to whether a given NET should be included as part of the UK's decarbonisation strategy (image adopted from Climate Assembly UK).

[106] The path to net zero. Climate Assembly UK, 2020.
[107] Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Cox, E. et al., 2020.

6.2 Review of current policy support and future policy recommendations

This section thematically summarises major global existing DACCS policies and future policy recommendations identified in the literature review and through stakeholder engagement. Since current DACCS-specific support is extremely limited, key policies or actions supporting CCUS and NETs in general are also included in the analysis, as they may indirectly incentivise or enable DACCS.

The following sections cover, in order:

1. DACCS research and development policies.
2. DACCS demonstration policies.
3. Financial incentives for DACCS deployment/operation.
4. Regulations surrounding DACCS.
5. Policies to incentivise DAC with carbon utilisation (CCU).
6. Additional supporting policies.

The policies presented as recommendations here are not exhaustive and are not necessarily suggested to be implemented concurrently.

6.2.1 DACCS research and development

Although DACCS technologies can technically be deployed at scale today, high costs and an absence of sufficient incentives to remove CO_2 from air prevent more facilities from being deployed. Continued R&D support has the potential to reduce DACCS costs even further through achievements such as materials performance improvements, advanced process design, and optimisation of DACCS systems.

A major step for DACCS research and development support was the US Energy Act of 2020, which authorised a total of $447 million to be used in the next 4 years, (financial years 2021-2024), for RD&D of NETs, including DACCS, BECCS and agricultural options[108]. Similarly, the UK is completing a £8.6 million GGR Research and Development Programme (2017-2021), which was supported by the Department for Business, Energy & Industrial Strategy (BEIS) and multiple research councils[109].

Unlike the above examples, most current R&D support for DACCS is through general national or international research and innovation programmes, hence is difficult to track accurately. For example, Horizon Europe is the EU's main research and innovation (R&I) programme for funding NETs research, among many other technologies. Further funding is available in the EU for supporting innovative low-carbon companies through the European Institute of Innovation and Technology (EIT) and the European Innovation Council (EIC), although historically funding directed at NETs has been very low.

Elsewhere in the world DACCS research has been more limited. Zhejiang University in China has a DAC R&D programme which involves utilisation of captured gas as a fertiliser for crop growth in a greenhouse[20]. They operate a small demonstrator plant capturing 10 $kgCO_2$ per day.

R&D support for DACCS and carbon sequestration should significantly grow in the next decade for DACCS to become a viable technology against climate change. Earmarking a portion of funds within existing or future R&D programmes for DACCS would be beneficial and send a strong signal of commitment to stakeholders. Future R&D efforts should also encourage knowledge transfer and international collaboration.

According to the detailed analysis conducted by the US National Academy of Sciences on research requirements of NETs[22], key DACCS R&D priorities are:

- Simulating, synthesizing, and testing new capture chemicals (especially solid adsorbents due to high impact on solid DACCS costs).

[108] Webinar: Emerging CDR opportunities in US legislation by Institute of Carbon Removal Law and Policy- American University, accessed 31.03.2021- Link
[109] NERC Greenhouse Gas Removal Programme- Link

- Designing, modelling, and testing novel equipment and system concepts, some specifically targeting renewable integration. Some key areas of focus can be fully electric liquid DACCS systems, flexible operation, reduction of land and water requirements.
- Establishing independent evaluation for capture chemicals performance testing, characterization, and validation, as well as creation and management of a public capture chemicals database.
- Scaling capture chemicals synthesis to > 100 kg.
- Continuing CO_2 transport and geologic storage R&D for enabling DACCS. Efforts should focus on reducing seismic risk, increasing accuracy of site characterization, reducing MMV costs, improving simulation models, assessing and managing risks in compromised systems.

6.2.2 DACCS demonstration

A major barrier for new technologies is the so called “valley of death”, where progress stalls due to difficulty of bridging the gap between R&D level systems and large-scale fully developed plants. Support and policies for technology demonstration are essential to avoid the valley of death and acquire enough public operational data to enable more detailed techno-economic modelling.

As with R&D policies, demonstration support for DACCS has been very limited and is mostly part of general NETs funding. Some of the notable demonstration policy examples are:

- **The US Energy Act of 2020** which will provide grants for FEED studies and large-scale pilot demonstrations through the $447 million fund. The bill also introduces DAC prizes for pre-commercial ($15 million) and commercial ($100 million) technologies[108].
- **The UK’s GHG Removal Innovation Competition** which provides £100 million to fund development of multiple NETs project feasibility studies and a few demonstration plants, including a focus on DACCS[110].
- **The Canadian government’s direct investment** of CAD$25 million into Carbon Engineering to demonstrate the company’s emerging DACCS technologies[111].
- **Australian CCUS Development Fund** which will provide AUS $50 million to CCS and CCU pilot and demonstration projects in the next 3 years, although none is specifically earmarked for DAC[112].
- **Germany’s CO_2 avoidance and use funding directive** which will mobilise a total of €585 million until 2025 for CO_2 transport and storage infrastructure around North Sea, CCS, CCU, DACCS and BECCS projects, particularly in the industry sector[113].
- **Germany’s support for a pilot synthetic liquid fuels plant** which is commissioned by Federal Ministry of Transport will supply at least 10,000 tonnes of fuel per year and may use CO_2 from air.
- **Several other EU funds**, such as the Innovation Fund and Connecting Europe Facility, which offer financial support for deploying CCS projects and infrastructure. Although they do not target NETs specifically, initial DACCS demonstration projects are likely to benefit from these instruments.

Current DACCS demonstration support levels are too low to unlock large-scale deployment in the medium term. Grants and innovation vouchers for feasibility studies and demonstration projects, creation of knowledge transfer networks, and pre-commercial procurement programmes are some mechanisms governments can use to provide demonstration support for DACCS in the future. Furthermore, the US National Academy of Sciences recommends[22] establishing national DACCS test centres to support pilot plant demonstration projects, developing third-party FEED and economic analysis and maintaining public record of pilot plant performance.

[110] The UK’s GHG Removal Innovation Competition- Link
[111] News article- Link
[112] News article- Link
[113] News article- Link

6.2.3 Financial incentives

Since DACCS does not offer any other benefits besides carbon removal, reaching climate-relevant scales requires significant levels of financial support for mass deployment.

A carbon price is one mechanism reflecting the value of avoiding or removing CO_2 in an economy. Figure 29 below shows various regional, national, and sub-national carbon price systems around the world[114]. Although prices are mostly far lower than required levels to support DACCS (estimated to be \$350-\$700/tCO_2 in 2020s according to our analysis), they can provide an indication of a government's commitment to decarbonisation. For example, EU Emissions Trading Scheme (ETS) prices were around €40/tonne at the end of Q1 of 2021. Around the world, some of the highest carbon prices (€60-€110) are observed in Sweden, Switzerland, Lichtenstein, and Finland[115]. Norway proposes[116] to increase its carbon price from €60 in 2021 to €200 by 2030 while Canada plans[117] to increase its carbon tax from \$30 to \$170 by 2030. However, DACCS or other NETs are currently not recognised in most of these carbon pricing mechanisms.

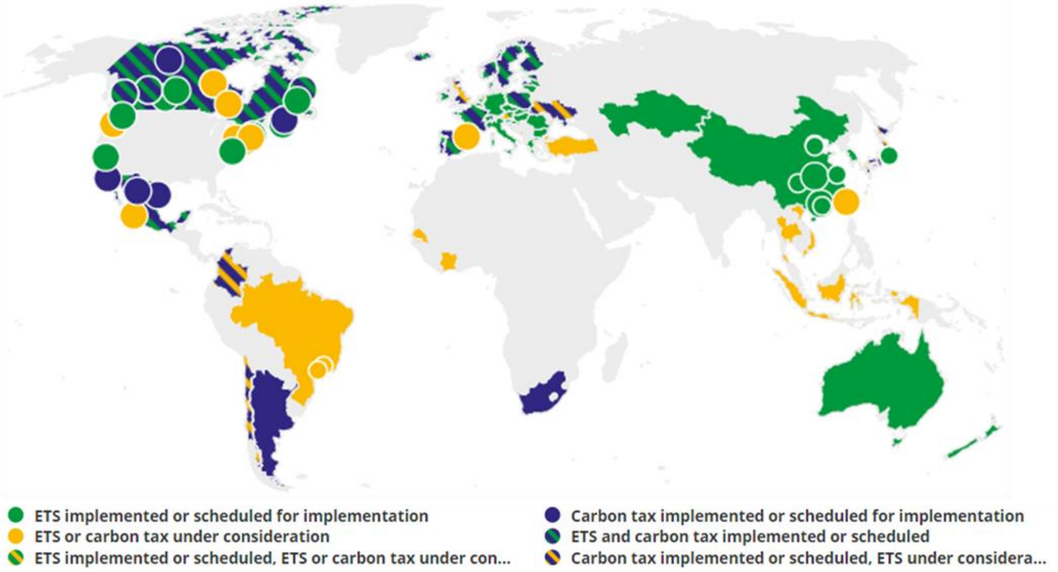

Figure 29: Summary of regional, national, and sub-national carbon pricing initiatives[114]

In addition to general carbon pricing, 3 key policies in the US have emerged as potential drivers for some initial DACCS projects:

- **The 45Q tax credits** award tax alleviation worth \$35 or \$50/tCO_2 when CCS (including DACCS) is used for EOR or dedicated geological storage, respectively. DACCS can directly use this incentive in conjunction with other US incentives. To qualify, facilities must capture at least 100 ktCO_2/year and start construction before 2026.
- **California's Low Carbon Fuel Standards** (LCFS) require fuel suppliers in the state to reduce their carbon intensity over time or purchase credits to make up the difference. LCFS allows DAC facilities producing synthetic fuels to sell into this market or sell carbon removal credits to fuel suppliers if DACCS is used for permanent storage. LCFS credits were worth \$190-200/tCO_2 in early 2021[118].
- **Buy Clean California Act** will require state agencies to purchase construction materials below a threshold of carbon intensity. CCUS and DACCS can be used to reduce embedded emissions of these materials, providing a procurement policy support.

[114] World Bank Carbon Pricing Dashboard- Link
[115] Tax Foundation- carbon taxes in Europe- Link
[116] News article- Link
[117] News article- Link
[118] Neste California low carbon fuel standard credit price- Link

Although these policies are encouraging some DACCS projects, such as the 1 $MtCO_2$/year capacity Carbon Engineering plant planned to be built in Texas[119], enhancements to the 45Q credits are needed to incentivise DACCS specifically. Potential improvements to the policy include increasing credits awarded to dedicated geographical storage, reduction of the minimum annual capture limit, extension of the deadline to start plant construction, and making direct payments to project developers rather than providing tax credits[120].

There are many financial support mechanisms suitable for incentivising large scale DACCS deployment and countries may choose to adopt one or more of these policies depending on their preferences and previous experiences. Some key policies aiming to reduce the burden of high upfront capital investments and reduce cost of capital are:

1. **Tradable tax credits** based on total upfront capital investment, similar to 48 a/b credits in the US,
2. **Loan guarantees or low interest loans**
3. **Master limited partnerships** to reduce cost of capital,
4. **Private activity bonds** allowing tax exempt financing,
5. **Accelerated depreciation** increasing short-term tax reduction**,**
6. **Capital support** through government grants or direct equity investment,
7. **Affordable finance** through progressive financing, international financing institutions or export credit agencies.

Some other policy mechanisms provide financial support proportional to the operations of CO_2 captured by facilities, providing revenues for the DACCS businesses. These are:

1. **Inclusion of DACCS in existing ETS** or carbon pricing mechanisms.
2. **Negative emissions trading scheme** with tradeable negative emissions credits serving two purposes:
    a. **A GGR obligation scheme** with tradable certificates where obligated parties (e.g. fossil fuel suppliers or emitters) must remove or purchase credits for an increasing proportion of their total emissions.
    b. **Voluntary** parties may purchase credits to ‘offset’ their emissions.
3. **Clean energy standards** where utilities would be required to source a portion of their power of fuel from low-carbon sources. Like California LCFS, DACCS can be awarded credits in this type of a scheme.
4. **Tradable tax credits** granted on a \$/tCO_2 basis with bands specific for DACCS (similar to 45Q credits in the US).
5. **Direct procurement of GGR**, where governments would award service contracts to DACCS projects after competitive bidding.
6. **Contract for differences** (CfD) linked to a carbon price, where the government guarantees a strike price to DACCS developers for a period, reflecting the cost of technology. As shown in Figure 30, the government pays the difference between the strike price and the actual carbon price in the market if prices are low and vice versa if prices increase substantially.

[119] News article- Link
[120] Carbon 180, Enhancing and expanding the 45Q tax credit for direct air capture- Link

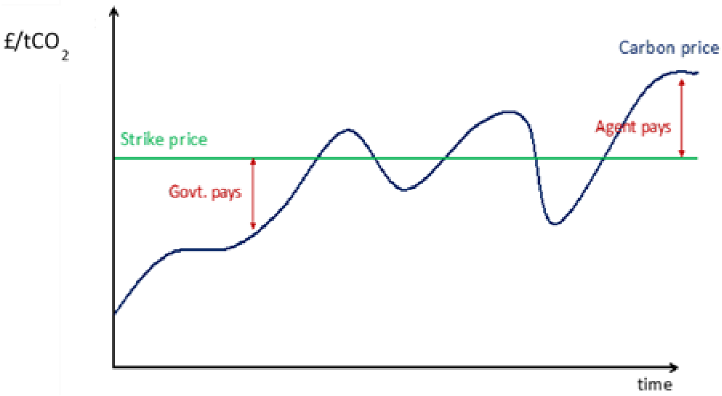

Figure 30: Schematic representing the Contract for Differences (CfDs).

The policies listed above would be suitable for the capture businesses, however, separate consideration should be given to CO_2 transport and storage (T&S) companies, which are essential parts of the overall DACCS supply chain. We are not focusing on policies for CO_2 T&S in this study, however, other studies have covered this topic in greater detail[121].

T&S costs can be significantly reduced by situating plants in clusters, oversizing initial infrastructure and utilising existing assets. CO_2 T&S companies are likely to be monopolies in their regions, so state-owned finance models or using a Regulated Asset Based (RAB) model may be more efficient ways to supporting them. Under the RAB model, the government closely monitors all of a company's spending and determines a fair service charge. These models have been used successful in the UK with monopoly utilities.

Lastly, it is important to recognise the importance of private patient capital and philanthropy in financing many early-stage technologies, including DACCS. Elon Musk's $100 million carbon removal competition[122], Bill Gates' investment in Carbon Engineering[123] and many corporate pledges[124] made in the recent years energised the DACCS community and have driven DACCS projects from R&D level to demonstration scale at a time when most governments were struggling with the Covid-19 crisis. In the future, incentivising and enabling further private investment and philanthropy should be a priority for governments as a compliment to public support for DACCS.

6.2.4 DACCS regulations

Regulations and laws around DACCS and CCS are just as important as financial incentives to enable DACCS deployment. Initial DACCS projects may be greenlit by special bilateral arrangements between governments and project developers, but once DACCS is rolled-out at large-scale, liability provisions and compliance with other regulations affect the pace and cost of technology deployment.

At the time of writing, we are not aware of any DACCS specific regulations in the world, as the technology has not been implemented at large scale yet. Still, regulations and provisions relating to CCS are very valuable for understanding regulatory maturity of countries, since CCS regulations are essential for the CO_2 T&S part of the DACCS value chain. GCCSI's Legal and Regulatory Indicator[125] maps comprehensiveness of provisions relating to long-term CO_2 storage liabilities, ease of CCS applications/permitting and frameworks around all aspects and phases of a CCS process chain. Band A countries with most developed CCS regulatory frameworks as of 2018 were Australia, Canada, Denmark, the UK, and the USA. On the other hand, some countries with high dependence on fossil fuels, such as China, Russia, India, and

[121] CO_2 transportation and storage business models. Report by Pale Blue Dot for BEIS, 2018.
[122] News article- Link
[123] News article- Link
[124] Institute for Carbon Removal Law & Policy- Carbon removal corporate action tracker- Link
[125] CCS Legal & Regulatory Indicator. GCCSI, 2018.

Indonesia- performed poorly regarding regulatory development. Short term DACCS opportunities may be limited in these regions until further frameworks are developed.

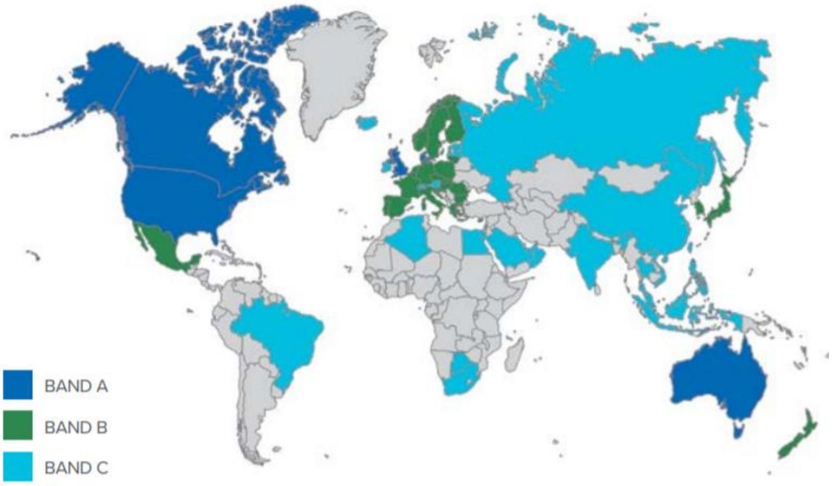

Figure 31: GCCSI's global CCS legal and regulatory indicators[125]

Federal and state governments of Australia, Canada, the US, and the EU have put in place regulatory provisions addressing different parts of the CCS value chain[97]. These relate to ownership of the pore space for CO_2 storage, liabilities to be borne during operation, MMV requirements, post-closure (of wells) time limit for liability transfer to the state, conditions, and scope of liability transfer.

In general, federal level provisions in Canada and the US are under-developed despite strong state level regulations. Australia has wide ranging federal liability provisions, but there is little in common with state provisions concerning long-term liability and post-closure stage of storage sites. The European Commission's Storage Directive provides the basis of EU wide regulations and allows a degree of flexibility to member states. Some countries, like the UK, implemented models that go beyond the directive.

In light of the above discussion on regulatory experience from CCS and discussions with DACCS stakeholders, the following are identified as key steps to allow deployment at climate relevant levels:

- Establishing **regulatory consistency** (e.g. on CO_2 liabilities), especially between neighbouring states, will facilitate cross border projects in the US.
- Ensuring **fair sharing of post-closure CO_2 storage liabilities** between companies and governments. Allowing **transfer of reasonable post-closure liabilities** to the government in a timely fashion.
- **Resolving surface land and pore space ownership issues,** mostly faced in Western USA[61], through legal clarification at state and federal level.
- **Streamlining and accelerating permitting for DACCS** projects, including CO_2 storage, to reduce development timeframes and costs.
- **Improving the permitting process for renewables** in relevant locations, as well as the required electricity infrastructure since access to low-cost renewables is essential for DACCS.
- Establishing a **robust NETs certification framework**, supported by **effective measurement, monitoring and verification (MMV) standards**, is needed to improve confidence in carbon removal and to administer most NETs related policies accurately. International regulatory alignment on these would enable trading of DACCS credits across borders.

6.2.5 Support through carbon utilisation

As discussed in section 4.2 carbon capture and utilisation (CCU), which may not always result in net carbon removals, may aid initial market creation for technologies such as DAC, ultimately reducing DACCS costs. DAC + CCU options such as EOR or cement production may result in various levels of negative emissions, but production of chemicals and fuels typically release all the captured CO_2 back into the atmosphere, so are at best net carbon neutral.

CCU is currently supported by general RD&D programmes and policies aiming to reduce carbon intensities of various products, such as Germany's new pilot synthetic fuel production plant, California's LCFS and the Buy Clean Act as described above. Furthermore, the US Energy Act of 2020 allocates $280 million specifically for CCU research and establishes a carbon utilisation research centre. Some other policies, such as the Swiss Aviation carbon tax[126], act as an incentive for carbon intensity reduction of aviation fuels, which may benefit synthetic fuel production from DAC. Additionally, there are some more direct regional CCU support, such as New York State's recently announced[127] $10 million Carbontech Development Initiative for carbon-to-value research and commercialisation.

Some policies/actions to further support DAC with CCU are:

- Additional RD&D support for CCU products, including knowledge transfer networks and coordination of DAC and CCU researchers/developers.
- Creation and maintenance of public CCU product databases to support green procurement programmes.
- Market creation support for CCU products including:
    - Internationally recognised certification of CCU products like cement and synthetic fuels, including definition and separation of fuels derived from air captured carbon and other origins.
    - Inclusion of DAC credits or DAC-based products in future sustainable fuels policies or clean product standards.
    - Inclusion of DAC driven products in existing and future public procurement programmes, like California's Buy Clean Programme or the EU's Green Public Procurement policy.
    - Information campaigns, green labelling schemes and regulations to help with market creation for carbon tech products.
    - Requirements of minimum blends of fuels derived from air captured carbon.

6.2.6 Additional supportive policies

In addition to the policies discussed above, several other key global developments directly or indirectly enabling DACCS are:

- The US Energy Act 2020, specifically:
    - Introduction of a $800 million programme for carbon storage, validation, testing and demonstration over the next 5 years.
    - Establishment of a Carbon Removal Program within US Department of Energy (DOE) with the goal of advancing NETs.
    - Formation of a Carbon Dioxide Removal Taskforce to advise US DOE and prepare a report on the need and a pathway to achieve carbon removal in the US.
- The UK considering DACCS in its national decarbonisation roadmap. Although no commitments are made, DACCS is used at scales of 5-15 $MtCO_2$/year by 2050 in three of the five future pathways[128].
- The EU indicating, in its new Circular Economy Action Plan, its interest to develop a robust regulatory framework for certification of carbon removals by 2023.
- Emergence of several carbon removal marketplaces such as Nori[129] and Puro Earth[130].

126 A new tax on airplane tickets between CHF 30-120 depending on travel distance- Link
127 News article- Link
128 The sixth carbon budget methodology report. UK Climate Change Committee, 2020.
129 Nori website
130 Puro Earth website

- Emergence of several carbon removal related NGOs and initiatives such as Carbon 180[131], Negative Emissions Platform[132], and UK Carbon Removal Centre[133].

Still, many additional policies and actions are needed in the future to address barriers and risks DACCS faces. Some of the more prominent and direct actions include:

1. **Separate targets for CO_2 mitigation and removal**: For example, a target of 95% emissions reduction and >5% removal can ensure that pursuing NETs does not distract from or reduce emissions mitigation efforts. In additional, a target for carbon removal improves the confidence of technology developers and investors that a country / region is committed to carbon removals at scale.
2. **Securities for leakage**: Future certification of carbon removals should address the leakage risk through requiring financial securities. Provisions for DACCS should be risk-based and may be integrated with regulations for CCS, i.e. the CCS Directive.
3. **Infrastructure and industrial clusters**: Besides financial support for national and cross-border CO_2 T&S infrastructure, industrial CCS clusters should be encouraged to incorporate NETs relying on CCS, such as BECCS and DACCS (where the location is cost-effective).
4. **CO_2 storage assessments**: Additional funding and data sharing around storage site appraisal is needed to develop storage resources around the world. Establishment of a comprehensive and transparent global storage database would help this point further.

Other less direct policy support or actions to enable DACCS roll-out are:

1. **Governance**: Effective governance, directionality and policy integration through national and international carbon removal institutions.
2. **Social considerations**: The wider public should be included in NETs discussions; understanding of the co-benefits and social value should support positive perception and act as an enabler.
3. **International cooperation and leadership**, especially for MMV standards and cross-border CO_2 T&S infrastructure.
4. **In countries with favourable conditions for DACCS, inclusion of DACCS in national decarbonization roadmaps** would indicate long-term commitment to the technology and promote deployment.
5. **Skilled workforce training** including assessment of current capacity and future skills needs.
6. **Supporting further renewables deployment** which would allow access to low-cost, low-carbon energy.
7. **National or international carbon markets/trading** and support for voluntary offsets. Having a separate market for carbon removal can allow more accurate representation of NETs prices and would be particularly useful if removals and mitigation have separate targets so that their prices can be controlled by their respective markets.
8. **Further evidence and independent assessment** of DACCS, such as comprehensive life-cycle assessments and detailed techno-economic models and to fill public data gaps and update knowledge as the technology evolves.

In conclusion, the main barriers to DACCS deployment today are lack of a sufficient financial value for carbon removal, further R&D and large-scale demonstration requirements, and need to better inform and engage with the public. Dedicated DACCS policy support is extremely limited and most current initiatives to enable DACCS is bundled together with general CCS and NETs support. Notable existing policies are the 45Q tax credits in the US, California's LCFS, various R&D and demonstration funds in the US, the UK, and the EU, as well as relatively well-established CCS regulations in North America, Europe, and Australia. Key policy priorities of governments wishing to accelerate DACCS deployment in the future should be

[131] Carbon 180 website
[132] Negative Emissions Platform website
[133] UK Carbon Removal Centre website

providing further dedicated R&D and demonstration funding, developing financial incentives which represent fair value of achieving negative emissions, and establishing regulatory frameworks to enable large-scale roll-out DACCS and supporting technologies.

7. Conclusion and recommendations for further work

7.1 Key implications and conclusions

This study improves the current DACCS cost-performance evidence base by synthesising data from the recent literature and technology developers to explore the economic feasibility of different DACCS technologies across timescales, capacities, configurations, and numerous global siting factors. It shows that although DACCS is more expensive than many carbon mitigation and removal options, careful plant siting and rapid learnings can achieve significantly more competitive DACCS costs.

Compared to other NETs, DACCS has some advantages due to its smaller land footprint and water consumption, as well as potential for easy scalability. NETs relying on biomass and ecosystems, such as afforestation, soil carbon storage and BECCS, require significant water and arable land. Other chemical NETs, such as enhanced weathering, risk changing the chemistry of oceans and rivers. DACCS avoids many of these limitations as it has a comparatively small land footprint, but does require a sustainable energy source, geological CO_2 storage to operate, and is relatively immature technology with as-yet unproven deployment potential.

The technoeconomic modelling of base case DACCS configurations (summarised in section 3.5) showed that the lifecycle emissions associated with DACCS range from 7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants if low carbon energy is used. These are mostly associated with energy carbon intensities, underlining the importance of access to low-carbon energy. Early DACCS projects in the 2020s are likely to range from ~$400-$700/net-tCO_2 stored when global average solar PV costs are used, which drop to ~$350-$550/net-tCO_2 with low-cost renewables. LCODs for NOAK plants in the 2050s fall to ~$194-$230/net-tCO_2 due to reduced electricity prices, financing costs and upfront capital investment. For liquid systems, large-scale plants are significantly more cost-effective due to economies of scale. Solid DACCS costs scale more linearly with size and are likely to be the more cost-effective option for smaller plants (<100ktCO_2/year), with significant potential for cost reduction through innovation. Capex, electricity prices and solid adsorbent costs are found to be the most influential parameters on costs.

An exploration of key global siting factors on DACCS costs and viability (summarised in section 4.7) reveals that access to CO_2 storage, land and water requirements are not expected to limit global DACCS potential but may determine where plants are built. CO_2 T&S costs are found to be ~6-15% of total LCODs which may be reduced by $20-$25/tCO_2 if plants use shared infrastructure. Energy costs are found to be as much as 50% of long-term liquid DACCS costs. DACCS costs in the range of ~$150-$200/net-tCO_2 may be achieved in the long-term if very low-cost solar energy is used. However, long-term costs are likely to be significantly higher than the industry target of $100/t$CO_2$ captured, except under the most ambitious cost-performance assumptions and favourable conditions. The most favourable regions for DACCS will have access to excess low-cost & low-carbon power and heat, CO_2 storage resources, have strong commitments to reducing their emissions and have regulatory/policy support for DACCS, CCS and NETs. In the short-medium term, some ideal locations for DACCS may be parts of North America, Western Europe (North Sea), Australia, Middle East and Eastern China, and Japan.

To date **DACCS representation in IAMs** has been relatively simplistic. Despite seemingly large DACCS deployment potential in existing IAM-based studies, most have focused only on liquid DACCS. Models necessarily rely on relatively sparse and divergent literature for estimates of DACCS cost. Technical parameters compiled and developed throughout this study (summarised in Table 10) can be used for representation of DACCS technologies in future IAM studies. IAM practitioners should consider differentiating between DACCS technologies and considering multiple plant configurations, including those running on electricity only and a mix of heat and electricity. Practitioners should also take care to ensure consistent treatment of financing costs for all technologies across their models. Furthermore, operating and labour costs are likely to be region dependent and IAMs can use reference tables to estimate how these costs would differ between countries. The availability of CO_2 storage, renewables, water, and land are key global siting factors which should be investigated further in IAM parameterisation with regional granularity to determine the locations with high DACCS viability and ultimately provide a more nuanced view of overall DACCS potential. Lastly, IAM studies may want to better integrate emerging climate policies, such as separate targets for emissions reduction and negative emissions, by developing alternative scenario designs placing constraints on the ability of NETs to accommodate short term GHG overshoots.

Most current **DACCS policy support** consists of generic RD&D funding, and financial support aimed at wider NETs or CCS technologies. The US, UK, EU, and Australia are key regions with relatively developed CCS regulations and R&D and demonstration programmes targeting carbon removal or general CCS projects. The 45Q tax credits in the US and California's LCFS are the only financial mechanisms available for large-scale DACCS projects. The key policy priorities of governments wishing to accelerate DACCS deployment in the future should be providing further dedicated RD&D funding, developing financial incentives which represent fair value of achieving negative emissions, and establishing regulatory frameworks to enable large-scale roll-out DACCS and supporting technologies.

7.2 Recommendations for further work

To further assess the role and potential of DACCS as part of a portfolio of decarbonisation strategies, the following future work is recommended:

- **Further independent engineering analysis of DACCS** performance and costs to verify and support commercial data.
- **Expansion of the LCA study** to include potential leakage from CO_2 T&S infrastructure, the impact of non-carbon by-products of solvent/sorbent manufacture and energy requirements for mass production of capture chemicals.
- **Demonstrations of a range of DACCS technologies** and configurations at scale to provide real-world data. Since current demonstrators are only at <5 ktCO_2/year scales, estimates of large-scale applications have considerable inherent uncertainties.
- **Detailed review of geographical locations and differences,** including costs of external factors as well as siting influence on technical requirements (e.g., water consumption), combined with **further research on overall spatial mapping of DACCS potential**, cognisant of access to renewables, CO2 storage, and water and land requirements to refine potential uptake estimates in IAMs.
- **RD&D on solid sorbents and electric calciners** to improve performance and drive down costs.
- **Continued R&D on novel DACCS concepts** currently at low maturity levels, such as DACCS with passive air flow.
- **Exploration of value and technical feasibility of flexible DACCS systems**, including pilots and wider energy system analysis.
- **Better estimates of the potential for roll-out of DACCS systems**, considering limitations around construction, chemical production, CO_2 storage site development and renewables roll-out rates.
- **Knowledge sharing and collaboration** between academia, technology developers and third-party assessors to make information accessible and accelerate progress.

8. References

100% clean, renewable energy and storage for everything. Jacobson, M. Z. Cambridge University Press, 2020. https://web.stanford.edu/group/efmh/jacobson/Articles/I/NatGasVsWWS&coal.pdf

A comparative global assessment of potential negative emissions technologies. McLaren, D. *Process Safety and Environmental Protection* 90(6), p. 489-500, 2012. https://doi.org/10.1016/j.psep.2012.10.005

A geographic information system-based global variable renewable potential assessment using spatially resolved simulation. Cheng-Ta, C., Adam, H., *Energy* 193 116630, 2020. https://doi.org/10.1016/j.energy.2019.116630

A process for capturing CO_2 from the atmosphere. Keith et al. *Joule* (8), p. 1573-1594, 2018. https://www.sciencedirect.com/science/article/pii/S2542435118302253

Amine-based nanofibrillated cellulose as adsorbent for CO2 capture from air. Gebald et al., *Environ. Sci. Technol.* 45, 20, p. 9101–9108, 2011. https://doi.org/10.1021/es202223p

An inter-model assessment of the role of direct air capture in deep mitigation pathways. Realmonte, G., Drouet, L., Gambhir, A. et al., *Nat. Commun.* 10, 3277, 2019. https://doi.org/10.1038/s41467-019-10842-5

Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. Strefler J., et al., *Environ. Res. Lett.* 13 044015, 2018. https://iopscience.iop.org/article/10.1088/1748-9326/aab2ba

Biophysical and economic limits to negative CO2 emissions. Smith et al., *Nature Climate Change* (6), p.42-50, 2015. https://www.nature.com/articles/nclimate2870

Capture of carbon dioxide from ambient air. Lackner, K. *Eur. Phys. J. Spec. Top*. 176, 93–106, 2009. https://doi.org/10.1140/epjst/e2009-01150-3

Capturing leadership: policies for the US to advance direct air capture technology. Rhodium Group, 2019. https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/

CCS deployment at dispersed industrial sites. By Element Energy for BEIS, 2020. https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-deployment-at-dispersed-sites

CCS legal & regulatory indicator. GCCSI, 2018. https://www.globalccsinstitute.com/resources/publications-reports-research/legal-regulatory-indicator-ccs-lri/

CCS policy indicator. GCCSI, 2018. https://www.globalccsinstitute.com/resources/publications-reports-research/ccs-policy-indicator-ccs-pi/

CCS storage indicator. GCCSI, 2018. https://www.globalccsinstitute.com/wp-content/uploads/2020/04/CCS-Storage-Indicator-CCS-SI-DIGITAL-1.pdf

CDR Primer. J. Wilcox, B. Kolosz, & J. Freeman, 2021. https://cdrprimer.org/

Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, 2014. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf

Co-Location of air capture, subseafloor CO2 sequestration, and energy production on the Kerguelen Plateau. Goldberg, D., et al., *Environ. Sci. Technol.* 47, 13, p. 7521–7529, 2013. https://doi.org/10.1021/es401531y

CO_2 transportation and storage business models. Report by Pale Blue Dot for BEIS, 2018.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/677721/10251BEIS_CO2_TS_Business_Models_FINAL.pdf

Cost Analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States. McQueen, N., et al., Environ Sci Technol. 54 (12) p. 7542-7551, 2020. https://doi.org/10.1021/acs.est.0c00476

Direct air capture of CO_2 and climate stabilization: A model based assessment. Chen, C., Tavoni, M., *Climatic Change* 118, 59–72, 2013. https://doi.org/10.1007/s10584-013-0714-7

Direct air capture of CO2 from ambient air. Sanz-Perez et al., *Chem. Rev*. 116, 19, 11840–11876, 2016. https://doi.org/10.1021/acs.chemrev.6b00173

Direct air capture of CO2 with chemicals: a technology assessment for the APS panel on public affairs. APS, 2011. https://www.aps.org/policy/reports/assessments/upload/dac2011.pdf

Direct air capture of CO2 with chemicals: optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor. Mazzotti, M., Baciocchi, R., Desmond, M.J. et al., *Climatic Change* 118, 119–135, 2013. https://doi.org/10.1007/s10584-012-0679-y

Enabling the deployment of industrial CCS clusters. By Element Energy for IEAGHG, 2018. https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/960-2018-01-enabling-the-deployment-of-industrial-ccs-clusters

Energy technology perspectives 2020. IEA, 2020. https://www.iea.org/reports/energy-technology-perspectives-2020

Energy technology perspectives 2020: special report on CCUS. IEA, 2020. https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf

European Union policy playbook: negative emissions technologies. Breakthrough Energy, 2021. https://www.breakthroughenergy.org/eu-policy-overview/cross-cutting-policies#anchor-negative-emissions-technologies-nets

Feasibility of air capture. Manya Ranjan, Howard J. Herzog, *Energy Procedia,* 4 pp 2869-2876, 2011. https://doi.org/10.1016/j.egypro.2011.02.193

Future of solar photovoltaic. IRENA, 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf

Future role of CCS technologies in the power sector. Report for IEAGHG by Element Energy, 2020. http://documents.ieaghg.org/index.php/s/YKm6B7zikUpPgGA?path=%2F2020%2FTechnical%20Reports

Geoengineering potential of artificially enhanced silicate weathering of olivine. Kohler, P., et al., *Proc. Natl. Acad. Sci. Unit. States Am.* 107 (47), p. 20228-20233, 2010. https://www.pnas.org/content/107/47/20228

Global carbon dioxide storage potential and costs. Hendriks, C. & Crijns-Graus, W. & Bergen, F. 2004. https://www.researchgate.net/publication/260095614_Global_Carbon_Dioxide_Storage_Potential_and_Costs

Greenhouse gas removal. UK Royal Society, 2018. https://royalsociety.org/topics-policy/projects/greenhouse-gas-removal/

Greenhouse gas removal (GGR) policy options. Vivid Economics, 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/833145/Greenhouse_Report_Gas_Removal_policy_options.pdf

IPCC Special Report Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. 2018. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf

Lessons and perceptions: adopting a commercial approach to CCS liability. GCCSI, 2019. https://www.globalccsinstitute.com/resources/publications-reports-research/adopting-a-commercial-approach-to-ccs-liability/

Levelised cost of carbon abatement: an improved cost-assessment methodology for a net-zero emissions world. Friedmann J., et al., 2020. https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/LCCA_CGEP-Report_101620.pdf

Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Deutz, S., Bardow, A. *Nat Energy* 6, 203–213, 2021. https://doi.org/10.1038/s41560-020-00771-9

Life cycle GHG emissions of renewable and non-renewable electricity generation technologies. Ostfold Research, 2019. https://reinvestproject.eu/wp-content/uploads/2019/11/OR_RE-INVEST_Life-cycle-GHG-emissions-of-renewable-and-non-renewable-electricity.pdf

Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. Krey et al., *Energy* 172, p. 1254-1267, 2019. https://doi.org/10.1016/j.energy.2018.12.131

Natural gas vs. electricity for solvent-based direct air capture. McQueen et al. *Front. Clim*., 2021. https://doi.org/10.3389/fclim.2020.618644

Negative emissions—Part 2: Costs, potentials and side effects. Fuss et al. *Environmental Research Letters* 13 (6), 2018. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta

Negative emissions and international climate goals—learning from and about mitigation scenarios. Hilaire, J., Minx, J.C., Callaghan, M.W. et al. *Climatic Change* 157, 189–219, 2019. https://link.springer.com/article/10.1007/s10584-019-02516-4

Negative emissions technologies and reliable sequestration: a research agenda. National Academies of Sciences, Engineering, and Medicine, 2019. https://doi.org/10.17226/25259.

Net zero by 2050: a roadmap for the global energy sector. IEA, 2021. https://iea.blob.core.windows.net/assets/beceb956-0dcf-4d73-89fe-1310e3046d68/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

Options for supporting carbon dioxide removal. New Climate Institute, 2020. https://newclimate.org/wp-content/uploads/2020/07/Options-for-supporting-Carbon-Dioxide-Removal_July_2020.pdf

Policies for the sixth carbon budget and net zero. UK Climate Change Committee, 2020. https://www.theccc.org.uk/wp-content/uploads/2020/12/Policies-for-the-Sixth-Carbon-Budget-and-Net-Zero.pdf

Policy priorities to incentivise large scale deployment of CCS. GCCSI, 2019. https://www.globalccsinstitute.com/resources/publications-reports-research/policy-priorities-to-incentivise-large-scale-deployment-of-ccs/

Potential for large-scale CO2 removal via enhanced rock weathering with croplands. Beerling et al., *Nature*, 583, p. 242-248, 2020. https://www.nature.com/articles/s41586-020-2448-9

Potential ways the gas industry can contribute to the reduction of methane emissions. Gie and Macrogaz, 2019. https://ec.europa.eu/info/sites/info/files/gie-marcogaz_-_report_-_reduction_of_methane_emissions.pdf

Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Cox, E., Spence, E. and Pidgeon, N. *Nature Climate Change* (10), p. 744-749, 2020. https://www.nature.com/articles/s41558-020-0823-z?proof=t

Putting costs of direct air capture in context. Ishimoto Y., et al., FCEA Working Paper Series: 002, 2017. http://dx.doi.org/10.2139/ssrn.2982422

Recommendations for DAC research, development, and demonstration. Bipartisan Policy Center, 2020. https://bipartisanpolicy.org/blog/recommendations-for-dac-research-development-and-demonstration/

Reducing the cost of Ca-based direct air capture of CO2. Zeman F. *Environ. Sci. Technol*. 48, 19, p. 11730–11735, 2014. https://doi.org/10.1021/es502887y

Renewable power generation costs in 2019. IRENA, 2020. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf

Shipping CO_2: UK cost estimation study. By Element Energy for BEIS, 2018. https://www.gov.uk/government/publications/shipping-carbon-dioxide-co2-uk-cost-estimation-study

Techno-economic assessment of CO_2 direct air capture plants. Fasihi et al., *Journal of Cleaner Production* 224, p. 957-980, 2019. https://www.sciencedirect.com/science/article/pii/S0959652619307772

Technology readiness and costs of CCS. GCCSI, 2021. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/CCS-Tech-and-Costs.pdf

The 1.5°C target, political implications, and the role of BECCS. Fuss S., *Climate Science*, 2017. https://doi.org/10.1093/acrefore/9780190228620.013.585

The costs of CO_2 storage: post-demonstration CCS in the EU. Zero Emissions Platform, 2010. https://www.globalccsinstitute.com/archive/hub/publications/119816/costs-co2-storage-post-demonstration-ccs-eu.pdf

The future of hydrogen: seizing today's opportunities. IEA, 2019. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

The global tree restoration potential. Bastin et al., *Science* 365 (6448), p. 76-79, 2019. https://science.sciencemag.org/content/365/6448/76

The path to net zero. Climate Assembly UK, 2020. https://www.climateassembly.uk/recommendations/index.html

The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. Marcucci, A., Kypreos, S. & Panos, E., *Climatic Change* 144, 181–193, 2017. https://link.springer.com/article/10.1007/s10584-017-2051-8

The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. C. Beuttler, et al., *Front. Clim.*, 2019. https://doi.org/10.3389/fclim.2019.00010

The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. E. Kriegler, et al., *Climatic Change* 123, 353–367, 2014. https://doi.org/10.1007/s10584-013-0953-7

The sixth carbon budget methodology report. UK Climate Change Committee, 2020. https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-Methodology-Report.pdf

Thermodynamics, economics and systems thinking: what role for air capture of CO2? Pritchard C., Yang A., Holmes P., Wilkinson M., *Process Safety and Environmental Protection*, Volume 94, p. 188-195, 2015. https://doi.org/10.1016/j.psep.2014.06.011

WACC the dog: the effect of financing costs on the levelized cost of solar PV power. Ondraczek J., Komendantova N., Patt A. *Renewable Energy* 75, p. 888-898, 2015. https://doi.org/10.1016/j.renene.2014.10.053

World Energy Outlook 2020. IEA, 2019. https://www.iea.org/reports/world-energy-outlook-2019

World Energy Outlook 2020. IEA, 2020. https://www.iea.org/reports/world-energy-outlook-2020

9. Appendix

9.1 Appendix 1: Liquid and solid DACCS technoeconomic parameters

Table 12 shows the technoeconomic parameters of Carbon Engineering's liquid DAC technology. The exact values used in this study cannot be shared due to commercial sensitivity, however the below ranges can be used as approximates.

Table 12: Public techno-economic data provided by Carbon Engineering

Parameter	CE Regenerating Liquid Sorbent DAC	
1 Mt/year of Atmospheric CO_2 Captured	Early Plants	Nth Plants and Variants
Plant Related		
Capex	~1,200 Million	$700-600M (@4-6 doublings in cumulative plant capacity and 10-15% Learning rate)
Capital Cost Reduction (Learning rate)	Learning rate of 10-15% for each doubling of cumulative plant capacity built.	
Plant Uptime	89%	92-95%
Plant Lifetime	30 years	30 years
Cost of Capital	9-10%	5-7%
Land Area	~100 acres	~60 acres
Embodied Emissions - Plant Construction	0.01 tCO_2/tCO_2	0.01 tCO_2/tCO_2
Energy		
Energy Source	Renewable Electricity/NG hybrid	100% Renewable Electricity, NG hybrid option
Energy Demand	~2.5-3 MWh/t CO_2 total (1.9 MWh NG CO_2 release, Remainder RE)	~2-2.5 MWh/tCO_2 100% Renewable Energy
Energy Cost	Location dependent, $25/MWh RE and 10-15$/MWh NG	Location dependent $10-25/MWh
Upstream Energy Emissions	~0.1 tCO_2 /tCO_2 for locations with low upstream energy emissions	~0.1 tCO2/tCO_2
Sorbent and Material Consumables		
Sorbent and Chemicals Consumption	~5 kg KOH+$CaC0_3$/tCO_2, 0.5t O_2/tCO_2	~3 kg KOH+$CaCO_3$/tCO_2
Sorbent and Chemicals Used	KOH, $CaCO_3$, Oxygen (for oxyfire NG calcination)	KOH, $CaCO_3$, (O_2 for NG option)
Water Requirement	~2-4 tH_2O/tCO_2 depending on site temperature and humidity	~1-2 tH_2O/tCO_2 depending on site temperature and humidity
Operations		
Operating and Maintenance Costs	~$50-60/$tCO_2$	$25-30/$tCO_2$
Levelized Cost of Removal*	**~$250/$tCO_2$**	**$150-100/$tCO_2$**

* Net Atmospheric CO_2 removed, including plant embodied emissions, upstream energy and co-captured process emissions for RE/NG hybrid plants

Table 13: Solid DACCS data and assumptions used in the model

Parameter	Units*	FOAK Heat + Electric	NOAK Heat + Electric	FOAK Electric Only	NOAK Electric Only
Capacity	Mt/y Atm CO2 Captured	1	1	1	1
Plant Related					
Capex	$ million	1,129[134]	626[135]	1,129[134]	626[135]
Capex scaling exponent		0.95[134]	0.95[134]	0.95[134]	0.95[134]
Plant Uptime	%	90%[134]	90%[134]	90%[134]	90%[134]
Plant Lifetime	Years	10[22, 135]	25[134]	10[22, 135]	25[134]
Cost of Capital	%	10%[134]	5%[134]	10%[134]	5%[134]
Land Area	Acres	~65[90]	~19[90]	~65[90]	~19[90]
Plant Construction Emissions	$kgCO_2/tCO_2$	6[90]	6[90]	6[90]	6[90]
Energy					
Electricity demand[136]	MWh/tCO_2	0.64[90]	0.45[90]	1.82[90]	1.01[90]
Heat demand[136]	MWh/tCO_2	3.01[90]	1.36[90]	-	-
1Mt to 100kt energy & consumable scaling multiplier		1.1[134]	1.1[134]	1.1[134]	1.1[134]
Sorbent and Material Consumables					
Adsorbent cost	$\$/tCO_2$	180[137]	72[134] (low case of 31.5[137])	180[137]	72[134] (low case of 31.5[137])
Adsorbent emissions	$kgCO_2/tCO_2$	24[90]	9.6[90]	24[90]	9.6[90]
Water requirement	tH_2O/tCO_2	1.6[22]	1.6[22]	1.6[22]	1.6[22]
Water price	$/t	2.22[138]	2.22[138]	2.22[138]	2.22[138]
Operations					
Operating cost[136]	$\$/tCO_2$	6.2[135]	4.2[135]	6.2[135]	4.2[135]
Maintenance cost[136]	$\$/tCO_2$	20.5[135]	13.7[135]	20.5[135]	13.7[135]
1Mt to 100kt O&M scaling multiplier	Based on Capex ratios	1.12[134]	1.12[134]	1.12[134]	1.12[134]

[134] Element Energy's assumption.
[135] Cost Analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States. McQueen, N., et al., 2020.
[136] Values from the literature are assumed to represent 100kt plant, demand for a 1 Mt plant is back calculated using scaling.
[137] From discussion with Climeworks.
[138] Global water tariffs survey 2020- Link

9.2 Appendix 2: Energy price and emissions assumptions

Electricity assumptions

Table 14: Electricity price and carbon intensity assumptions

Electricity	Price - $/MWh	Emissions $kgCO_2/MWh$
Solar 2020 Low	39.00[139]	50.9[140]
Solar 2020 Medium	68.00[139]	50.9[140]
Solar 2020 High	85.00[139]	50.9[140]
Solar 2050 Low	14.00[141]	24.8[140]
Solar 2050 Medium	32.00[141]	24.8[140]
Solar 2050 High	50.00[141]	24.8[140]
Onshore wind 2019 Low	35.00[39]	16.4[140]
Onshore wind 2019 Medium	45.00[39]	16.4[140]
Onshore wind 2019 High	55.00[39]	16.4[140]
Onshore wind 2040 Low	35.00[39]	16.4[140]
Onshore wind 2040 Medium[1]	40.00[39]	16.4[140]
Onshore wind 2040 High	45.00[39]	16.4[140]
Offshore wind 2019 Low	75.00[39]	16.4[140]
Offshore wind 2019 Medium	102.50[39]	16.4[140]
Offshore wind 2019 High	130.00[39]	16.4[140]
Offshore wind 2040 Low	80.00[39]	16.4[140]
Offshore wind 2040 Medium	45.00[39]	16.4[140]
Offshore wind 2040 High	55.00[39]	16.4[140]
Nuclear 2020 Low	65.00[142]	12[22]
Nuclear 2020 Medium	105.00[142]	12[22]
Nuclear 2020 High	150.00[142]	12[22]
Nuclear 2050 Low	65.00[142]	12[22]

139 Renewable power generation costs in 2019. IRENA, 2020.
140 Life cycle GHG emissions of renewable and non-renewable electricity generation technologies. Ostfold Research, 2019.
141 Future of solar photovoltaic. IRENA, 2019.
142 World Energy Outlook 2020. IEA, 2019.

Nuclear 2050 Medium	100.00[142]	12[22]
Nuclear 2050 High	110.00[142]	12[22]
NG CCS 2019 Low	60.00[39]	38[143]
NG CCS 2019 Medium	75.00[39]	38[143]
NG CCS 2019 High	90.00[39]	38[143]
NG CCS 2040 Low	60.00[39]	38[143]
NG CCS 2040 Medium	92.50[39]	38[143]
NG CCS 2040 High	125.00[39]	38[143]
Grid 2020 Low	70.00[144]	237[142]
Grid 2020 Medium	98.00[144]	237[142]
Grid 2020 High	156.00[144]	237[142]
Grid 2050 Low	108.00[144]	81[142]
Grid 2050 Medium	123.00[144]	81[142]
Grid 2050 High	158.00[144]	81[142]
Geothermal	53.00[68]	26[68]

[143] 100% clean, renewable energy and storage for everything. Jacobson, M. Z., 2020.
[144] The future of hydrogen: seizing today's opportunities. IEA, 2019.

Heating assumptions

Carbon Engineering's (CE) system design captures all CO_2 released from oxy-combustion of natural gas, hence heating for CE's system is assumed to be emissions free, except for upstream methane leakage.

CE natural gas (NG) prices represent prices of natural gas, whereas other NG prices are costs of heat generation using natural gas at 85% conversion efficiency. This is done because energy demand for liquid DACCS is given as gas demand whereas energy demand for solids is given as heat demand.

Table 15: Heat energy cost and carbon intensity assumptions

Heat	Price - $/MWh	Emissions $kgCO_2/MWh$
Nuclear	19.30[135]	4[22]
Geothermal	7.95[145]	3.9[145]
NG 2020- Low	9.39[146]	267[147]
NG 2020- Medium	21.12[146]	267[147]
NG 2020- High	42.24[146]	267[147]
NG 2050- Low	9.39[146]	267[147]
NG 2050- Medium	21.12[146]	267[147]
NG 2050- High	42.24[146]	267[147]
CE NG 2020- Low	8.47[39]	0
CE NG 2020- Medium	19.05[39]	0
CE NG 2020- High	38.11[39]	0
CE NG 2050- Low	8.47[39]	0
CE NG 2050- Medium	19.05[39]	0
CE NG 2050- High	38.11[39]	0

Upstream methane emissions[68]

GWP for 100 years is used where CH_4 is 32 times more harmful than CO_2. Upstream methane leakage is 2.3%. Local gas distribution is not included. Upstream and supply chain methane leakage accounts for 0.018 tCO_2eq/GJ or 0.065 tCO_2/MWh of natural gas. Methane emissions are expected to fall in the future. OGCI countries have a voluntary target of 2.7% reduction in methane emissions per year[38]. Considering that DACCS plants would run 10-30 years, we assume that for FOAK plants 24% leakage reduction (49.4 $kgCO_2/MWh$) is achieved (in 10 years) and for NOAK plants 67% reduction (21.7 $kgCO_2/MWh$) in the next 40 years will be achieved.

[145] Geothermal heat data is calculated from geothermal power assuming that heat generation is 100% efficient and power generation is only 15% efficient. Based on Deutz, S. & Bardow, A., 2021.
[146] Natural gas (NG) heat prices are based on NG prices used for liquid technologies (CE NG) but applies an 85% gas to heat conversion efficiency.
[147] Based on 85% efficiency and "Negative emissions technologies and reliable sequestration: a research agenda. National Academies of Sciences, Engineering, and Medicine, 2019."

These are the emissions assumed for the liquid DACCS because energy demands provided were for natural gas. For solids using natural gas, boiler efficiency must be considered. Considering an 85% efficiency, FOAK methane leakage is assumed to be 61.18 kgCO_2/MWh and NOAK is assumed to be 25.6 kgCO_2/MWh. Similarly, an efficiency of 60% is applied for future unabated gas plants and 50% for gas CCS plants when calculating methane leakage from power generation.

9.3 Appendix 3: CO_2 transport and storage cost assumptions

The CO_2 transport cost assumptions used in this model are shown in Table 16 and are based on Element Energy's internal assessment[46].

- Trucking: Low, medium, high are for 25, 50, 100 km. Plant size does not affect cost.
- Shipping: Low/medium/high refer to 100, 300, 1000 km.
- Onshore pipelines: Low/medium/high refer to 50, 100, 300 km.
- Offshore pipelines: Low/medium/high refer to 50, 100, 300 km.

Table 16: CO_2 transport cost assumptions

Transport	1 Mt/year plant - $/tCO$_2$	100 kt/year plant - $/tCO$_2$
Trucking- Low	9.21	9.21
Trucking- Medium	13.39	13.39
Trucking- High	21.77	21.77
Shipping- Low	12.65	29.83
Shipping- Medium	13.13	33.25
Shipping- High	17.68	40.55
Onshore pipe- Low	2.96	11.34
Onshore pipe- Medium	4.34	19.09
Onshore pipe- High	11.28	46.75
Offshore pipe- Low	5.12	19.02
Offshore pipe- Medium	8.18	27.53
Offshore pipe- High	19.94	81.69

Low, medium, and high CO_2 storage costs used in this study (shown in Table 17) are based on the low, medium, and high estimates in the ZEP (2010) study[47] and the combination of depleted oil and gas reservoirs or existence of legacy infrastructure. The values are converted from 2010 Euros to 2020 US dollars.

- Onshore: assumed values are: €2, €4, €10
- Offshore: assumed values are: €3, €9, €14

Table 17: CO_2 storage cost assumptions

Storage	Both 1 Mt/year and 100 kt/year plants - $/tCO$_2$
Onshore- Low	3.15
Onshore- Medium	6.30
Onshore- High	15.75
Offshore- Low	4.73
Offshore- Medium	14.18
Offshore- High	22.05

9.4 Appendix 4: Parameters used for base case analysis

Table 18 below lists the main parameters used to assess base case calculations in this study. References to the parameters can be found in the rest of the appendix. These parameters do not describe a specific DACCS configuration but represent fair values which can be seen for global average DACCS systems.

Solar PV costs in 2050 are assumed to be the "high" option ($50/MWh) for the base case. This is due to the fact that solar is an intermittent source of electricity and operating DACCS continuously is likely to acquire additional storage or grid balancing costs. IEA's World Energy Outlook[39] calculates a parameter called value added levelised cost of electricity (VALCOE) which considers the impact of a generation source on system flexibility. The average VALCOE for the countries included in 2040 for the stated policies scenario is $50/MWh, which forms the basis of our assumption.

Table 18: Parameters used for base case DACCS LCOD calculations

Parameter	FOAK Liquids	NOAK Liquids	FOAK Solids	NOAK Solids
Electricity Price and Emissions	Solar PV Medium $68/MWh 50.9 kg$CO_2$/MWh	Solar PV High $50/MWh 24.8 kg$CO_2$/MWh	Solar PV Medium $68/MWh 50.9 kg$CO_2$/MWh	Solar PV High $50/MWh 24.8 kg$CO_2$/MWh
Heat Price and Emissions	Natural Gas Medium $19.1/MWh 49.4 kg$CO_2$/MWh[148]	Natural Gas Low $8.5/MWh 21.7 kg$CO_2$/MWh[148]	Nuclear Waste Heat $19.3/MWh 4 kg$CO_2$/MWh	Nuclear Waste Heat $19.3/MWh 4 kg$CO_2$/MWh
Cost of Capital	10%	5%	10%	5%
CO_2 Transport	1Mt plant: Offshore Pipe Medium $8.2/t$CO_2$ 100 kt plant: Trucking Medium $13.4/t$CO_2$	1Mt plant: Offshore Pipe Medium $8.2/t$CO_2$ 100 kt plant: Trucking Medium $13.4/t$CO_2$	1Mt plant: Offshore Pipe Medium $8.2/t$CO_2$ 100 kt plant: Trucking Medium $13.4/t$CO_2$	1Mt plant: Offshore Pipe Medium $8.2/t$CO_2$ 100 kt plant: Trucking Medium $13.4/t$CO_2$
CO_2 Storage	Offshore Pipeline Medium $14.2/t$CO_2$	Offshore Pipeline Medium $14.2/t$CO_2$	Offshore Pipeline Medium $14.2/t$CO_2$	Offshore Pipeline Medium $14.2/t$CO_2$

[148] Natural gas use in liquid DACCS systems does not directly emit CO_2 since all CO_2 from combustion is co-captured. Emissions shown here are from upstream methane leakage from the natural gas supply chain.

9.5 Appendix 5: Technoeconomic DACCS data collected from literature

Below are some of the technoeconomic DACCS data gathered during the review of most recent studies. These are representative values and are not necessarily used in the study.

Table 19: Representative technoeconomic DACCS parameters from selected literature studies

Parameter	Liquid Solvent Systems	Solid Sorbent Systems
Main tech developers	Carbon Engineering (Canada)	Climeworks (Switzerland), Global Thermostat (USA)
Energy source	NG only, NG and electricity or only electricity	Electricity only or electricity and low temperature low carbon heat
Energy demand	8.81 GJ/tonCO_2 NG or 5.25 GJ/tonCO_2 NG and 366 kWh/tonCO_2 electricity[15]	3.4-4.8 GJ/tCO_2 heat + 153-306 kWh/tCO_2 electricity (medium estimates)[22]
Load factor	90% - potentially lower in first/earlier year(s)	90% - potentially lower in first/earlier year(s)
Lifetime	25-30 years[15]	10 years[22] (longer for NOAK, 20 years)
LCA emissions	~0.1 tCO_2 per tCO_2 captured from air[15] with carbon free electricity	~0.06 t/tCO_2 (waste heat) or ~0.19 t/tCO_2 (heat pump) w/ solar PV (80 kgCO_2/MWh)[90]
Land Area	6- 1730 acres[22] (direct and indirect estimates for 1Mt/year capacity)	300-425 acres[22] (only core DAC unit, 1Mt/year capacity)
Capex	FOAK: \$160/tCO_2, NOAK: \$66/tCO_2[15] incl, financing and 20% contingency	Nuclear: \$192/tCO_2, Geothermal: \$200/tCO_2[135]
Fuel cost	\$31/tCO2 (NG only), \$29-40/tCO_2 (NG + elec)[15]	Nuclear: \$93/tCO_2, Geothermal: \$70/tCO_2[135]
O&M cost	FOAK: \$42/tCO_2, NOAK: \$30/tCO_2[15]	Nuclear: \$42/tCO_2, Geothermal: \$42/tCO_2[135]
Levelised cost of removal	FOAK: \$232/tCO_2, NOAK: \$126/tCO_2[15]	FOAK: Nuclear: \$328/tCO_2, Geothermal: \$313/tCO_2[135], NOAK: \$89-166/tCO_2[22]

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