Appendix A – DACCS Technology Description

DACCS technology involves capturing atmospheric CO2, either through absorption in a liquid medium or adsorption on a solid medium. The process requires substantial energy due to CO2's low atmospheric concentration of 420 ppm, which necessitates processing large air volumes and an energy-intensive desorption process (Keith et al., 2018).

Among the various DACCS methods, three leading companies—Carbon Engineering, Climeworks, and Global Thermostat—are notable for their technology's maturity and operational projects. Carbon Engineering's approach, detailed in Figure A1, employs a gas-fired, high-temperature liquid sorbent process, using two chemical loops: the contactor and the calciner. In the contactor loop, air reacts with a potassium hydroxide solution, capturing CO2. The second loop releases CO2 as a pure gas through heating calcium carbonate to around 900°C in the calciner, producing water, CO2, and CaO, with the latter being recycled (McQueen et al., 2021). While Carbon Engineering's process benefits from continuous operation and the use of established industrial equipment, it requires high temperatures and natural gas, impacting the overall CO2 balance. The process's efficiency, compared to those using renewable energy, is also a consideration. The levelized cost for a first-of-a-kind plant capturing 1Mt of CO2 annually is estimated to range from USD2018 94 to 232 per ton of CO2 removed (Keith et al., 2018; McQueen et al., 2021).

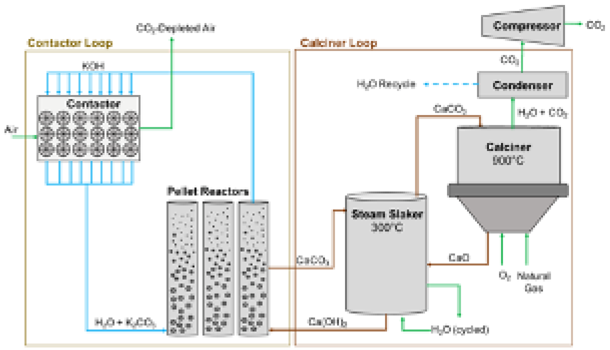

Figure A1: Carbon Engineering direct air carbon capture process. Two chemical loops are represented. Liquids are in blue, solids in brown and gas in green. The liquid solvent (potassium hydroxide, KOH) is regenerated in the pellet reactor and can be re-fed to the contactor. This figure was taken from McQueen et. al., 2021.

Carbon Engineering's pilot plant in Squamish, British Columbia, launched in 2015, captures 365 tons of CO2 annually and produces synthetic fuel since 2017. The company's first large-scale project, set to begin in the Permian Basin (USA) by the end of 2024, aims to capture 0.5 – 1Mt CO2 per year, supporting net-zero strategies of various firms[1]. Funded by Occidental Petroleum's Oxy Low Carbon Ventures, this plant will also facilitate CO2 usage for Enhanced Oil Recovery+ (EOR+)[2]. Additionally, Air Canada and Airbus have partnered with Carbon

[1] "Carbon Engineering | Direct Air Capture of CO2 | Home," Carbon Engineering. https://carbonengineering.com/ (accessed Jan. 22, 2023).
[2] "Oxy and Carbon Engineering partner to Combine Direct Air Capture and Enhanced Oil Recovery storage," Global CCS Institute. https://www.globalccsinstitute.com/news-media/latest-news/oxyand-carbon-engineering-partner-to-combine-direct-air-capture-and-enhanced-oil-recoverystorage/ (accessed Jan. 23, 2023).

Engineering for carbon dioxide removal certificates and sustainable aviation fuels, with Air Canada investing 5 million USD[3].

Climeworks in Zürich uses a modular, low-temperature, solid sorbent adsorption technology based on amines. Their process, involving an adsorption phase and a temperature-vacuum-swing desorption phase, captures CO2 on a solid amine-based sorbent. The desorption requires temperatures of 80-120°C and a pressure of ~30 mbar, typically using steam from nearby waste-incineration or thermal power plants. The resulting CO2 is then condensed and stored (Beuttler et al., 2019; McQueen et al., 2021).

Climeworks' technology benefits from modular contactors, fitting standard 40-foot transport containers, enabling easier transport and cost-effective mass production. This modularity is key for scaling DACCS globally. The low-temperature requirement also allows flexibility in energy sourcing, from geothermal to industrial waste heat (Beuttler et al., 2019). The cost of capturing CO2 is around USD2017 500-600 per ton (Erans et al., 2022; McQueen et al., 2021). Climeworks launched the commercial DAC plant in Hinwil, Switzerland in 2015, capturing 900t CO2 annually until 2022. The Orca plant in Iceland, operational since 2021 and located near the Hellisheidi geothermal power plant, captures 4,000t CO2 yearly[4]. Carbfix, a partner in carbon sequestration, supports these operations. Climeworks' upcoming Mammoth plant, expected to start by the end of 2024, aims to capture 36,000t CO2 annually[5]. Funded through equity financing and CDR certificate sales, Climeworks secured 650 million USD in April 2022 for future projects[6].

Global Thermostat, a New York-based company, uses a low-temperature, amine-based, solid sorbent adsorption process with a unique monolith reactor and dual module configuration, similar to Climeworks' method. Their process employs a temperature-pressure swing for CO2 desorption, with optimal steam temperatures of 105-130°C, and reuses water vapor between cooling and heating modules, providing significant energy savings[7]. The patented technology includes a honeycomb monolith contactor for efficient reaction surface and lower pressure drop, theoretically leading to cost and energy reductions (McQueen et al., 2021). However, due to limited data on completed projects, precise cost estimates remain uncertain.

Global Thermostat has collaborated with Georgia Tech and Stanford University and operated a demo-plant at Menlo Park capturing 1,000-10,000t CO2 annually. Their first commercial plant in Huntsville, Alabama, was expected to capture 4,000t CO2 per year but is now presumed decommissioned (Lackner et al., 2012). Recently, they partnered with HIF's Haru Oni plant in Chile, supplying carbon capture equipment for producing e-Fuels from CO2,

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[3] "Airbus, Air Canada to Invest in Canadian Firm Carbon Engineering," Carbon Capture Technology Conference & Expo North America 2022. https://www.ccus-expo.com/industry-news/airbus-aircanada-invest-canadian-firm-carbon-engineering (accessed Mar. 09, 2023).

[4] Achieve net zero targets with Climeworks direct air capture." https://climeworks.com (accessed Jan. 22, 2023).

[5] Climeworks closes a chapter in early carbon removal tech," The Verge, Oct. 20, 2022. https://www.theverge.com/2022/10/20/23414385/climeworks-carbon-removal-direct-aircapture-plant-capricorn-hinwil-switzerland (accessed Feb. 23, 2023).

[6] "Climeworks raises CHF 600 million (US $650 million) in equity." https://climeworks.com/news/equity-fundraising (accessed Feb. 23, 2023). "Partners Group and GIC Leads $650m Equity Round in Climeworks," Private Equity Insights, Apr. 05, 2022. https://www.swfinstitute.org/news/92045/partners-group-and-gic-leads-equity-roundin-climeworks (accessed Mar. 09, 2023).

[7]] Global Thermostat, "Dr. Chichilnisky Gives Talk on Carbon Negative Power Plants and Their Impact on Environment - Puerto Madryn, Argentina 10/23," Global Thermostat, Oct. 23, 2018. https://globalthermostat.com/2018/10/dr-chichilnisky-gives-talk-on-carbon-negative-powerplants-and-their-impact-on-environment-puerto-madryn-argentina-10-23/ (accessed Jan. 23, 2023).

water, and wind energy. Their research has been partially financed by agreements with companies like ExxonMobil, though specific details are not public[8].

[8] "ExxonMobil expands agreement with Global Themostat sees promise in direct air technology," ExxonMobil. https://corporate.exxonmobil.com:443/news/newsroom/newsreleases/2020/0921_exxonmobil-expands-agreement-with-global-thermostat-re-direct-aircapture-technology (accessed Feb. 23, 2023).

Appendix B – BECCS Technology Description

Bioenergy with carbon capture and storage (BECCS) is a hybrid negative emission technology. It uses both nature's capacity to capture CO_2 in plants via photosynthesis and man-made technology to capture CO_2 after the combustion process as shown in Figure B1. If more CO_2 is stored than is released during each of the steps in all associated supply chains and indirect impacts on ecosystems and natural sinks, then the total carbon footprint is net negative. BECCS is an interesting technology as it provides CO_2 capture on top of producing energy.

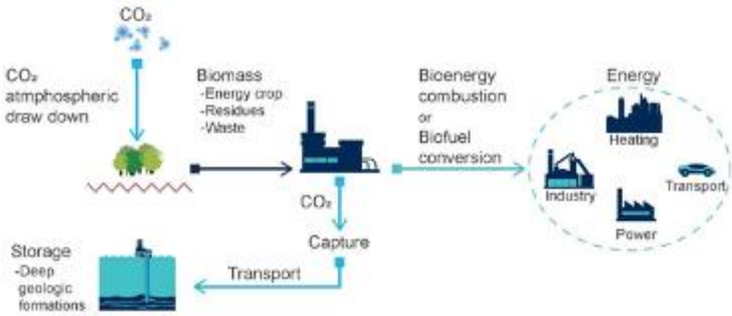

Figure B1: Bioenergy with carbon capture and storage process (Donnison et al., 2020)

In the following, different BECCS plant configurations including possible feedstocks and CO_2 capture processes are presented. Additionally, brownfield and greenfield plants as well as potential barriers to deployment are discussed.

Feedstocks such as wood pellets, municipal waste, agricultural and forestry residues, and dedicated crops can be used in a BECCS power plant. First, wood pellets can be provided from sustainably managed working forests or from residues of forest practices and related industries. In terms of process intensity, their production requires the milling of the material, compression into pellets and transport to the power plant site[9]. Their compact size allows for simple transport and storage and their high energy density makes pellets a good combustion fuel[10]. Second, solid municipal waste (SMW) is an interesting feedstock due to the increasing amount of waste produced worldwide (Pour et al., 2018). This waste is currently, in most cases, burned to produce heat at SMW combustion plants leading to GHG emissions or left in landfills where it is at risk of decomposing and releasing GHG or contaminating soil and water[11]. Finally, short rotation crops (SRC) are bioenergy feedstocks with high energy density. Examples of SRC are poplar, willow trees and miscanthus. These crops are often mentioned in the literature due to their high yield even on marginal land (land not fit for agriculture) and less destructive impact on the ecosystem compared to other crops used for biofuels such as corn, wheat, sugar cane and sugar beet (Donnison et al., 2020; Lark et al., 2022).

An essential part to the BECCS process is the integration of a **CO_2 capture unit** to the process. This is a decisive step to ensure that the energy produced leads to a negative carbon footprint. The CO_2 capture process step is slightly different for BECCS than for DACCS, due to the higher gas concentration in the flue gas. This leads to less energy intensive capture

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[9] "Wood Pellets Archives," Drax Global. https://www.drax.com/tag/wood-pellets/ (accessed Jan. 23, 2023)
[10] "Sourcing Sustainable Biomass," Drax US. https://www.drax.com/us/sustainability/sustainablebioenergy/sourcing-sustainable-biomass/ (accessed Jan. 23, 2023).
[11] "Where Does Our Garbage Go?," Rockefeller Institute of Government. https://rockinst.org/blog/where-does-our-garbage-go/ (accessed Jan. 23, 2023).

mechanisms. There exist three different industrial processes to capture CO_2 from flue gas: pre-combustion capture, post-combustion capture and oxy-combustion capture. Post-combustion CO2 capture involves using solvents (like monoethanolamine or piperazine), sorbents, or membranes, often containing amine-rich molecules for efficient CO2 absorption. As flue gas passes through an absorber, CO2 is absorbed into the solution and then desorbed using steam in a desorber, separating CO2 from water, which is then compressed for transport and storage (Zanco et al., 2021). Post-combustion capture is generally between 90 to 99% (Thangaraj et al, 2018).

There are several barriers to the deployment of BECCS. Each BECCS plant is a one-of-a-kind project, involving a specific feedstock, supply chain, CO_2 capture process and downstream processes. Projects are either the retrofit of a plant (brownfield) or a new project (greenfield). These differ widely in their realisation, supply chain and costs. In case of a retrofit, the boilers must be changed to accommodate the new feedstock. Second, the plant's supply chain is influenced by pre-existing supply chains and the country's energy goals. Finally, retrofitted plants use post-combustion capture processes to benefit from the add-on flexibility of the equipment, and new builds might consider any of the other capture processes. These factors show the complexity and lack of standardization of BECCS projects (Fajardy et al., 2019). There are currently 19 Bioenergy production facilities with CCS facilities around the world either in operation, piloting or under construction. From the estimated 2Mt of CO_2 captured every year with bioenergy, a major part of it is converted to bioethanol applications. Notable facilities are the Decatur plant in the USA with an annual capture potential of 1Mt CO_2 for ethanol production and the Norcem plant in Norway storing CO_2 in cement material[12]. In Europe two bioenergy projects with forthcoming durable geological storage have gained significant attention and are discussed below.

The Drax power plant in Selby, North Yorkshire is one of the major energy producers in the UK. It is responsible for 15TWh of power per year representing 6% of total UK electricity needs[13]. The site decommissioned from coal in 2021 after closing its last two coal units. Currently it uses sustainably sourced wood pellets to power four of the six boilers[14]. Drax announced in 2021 an innovative BECCS pilot project and states that the first fully operational BECCS unit could come online as soon as 2030. The first pilot started operations in 2019 and the second in 2020, together they capture 1.3t CO_2 per day[15].

Stockholm Exergi AB, a company responsible for energy and district heating in Stockholm inaugurated in 2019 a research facility aiming at retrofitting the Värtan combined heat and power (CHP) plant into a BECCS plant. Värtan is already one of the largest biomass-fired CHP plants in Europe with 280MW of heat and 130MW of boilerplate capacity produced annually[16]. Opened in 2016, the original CHP plant was a big step towards sustainable energy production due to the use of various wood residues as feedstock. The plant currently save 126'000t of CO_2

[12] "Bioenergy with Carbon Capture and Storage – Analysis," IEA. https://www.iea.org/reports/bioenergy-with-carbon-capture-and-storage (accessed Jan. 23, 2023).

[13] "Drax kickstarts application process to build vital negative emissions technology," Drax Global. https://www.drax.com/press_release/drax-kickstarts-application-process-to-buildvital-negative-emissions-technology/ (accessed Jan. 24, 2023).

[14] "Drax Power Station - Drax Global." https://www.drax.com/about-us/our-sites-andbusinesses/drax-power-station/ (accessed Jan. 24, 2023).

[15] "Drax BECCS – CCUS around the world – Analysis," IEA. https://www.iea.org/reports/ccus-aroundthe-world/drax-beccs (accessed Jan. 24, 2023).

[16] "BECCS – Negative emissions - Stockholm Exergi." https://www.stockholmexergi.se/en/bio-ccs/ (accessed Jan. 24, 2023).

emissions per year compared to energy production based on fossil fuels and by integrating BECCS it aims at capturing about 800’000t of CO_2 per year[17].

Appendix C – Baseline Cost and Assumptions

DAC System Assumptions

The DAC system is based on the low-temperature Climeworks process. The adsorption process is the same temperature-vacuum swing process as described in Appendix A. The units are assumed to be near the injection site to minimize transport. Six Climeworks collectors form a collector container, which is referred to here as a “unit” or a “collector unit”. The current capture capacity of one unit is assumed to be ~ 500t CO_2 per year (Beuttler et al., 2019). Table C1 shows the cost breakdown assumed for a first of a kind (FOAK), 1 Mt CO_2 capture capacity plant located in Europe with a solid sorbent adsorption system.

Table C1: Key assumptions of a DAC system based on Climeworks’ technology. A medium cost transportation at 16$$_{2021}$/t$CO_2$ was assumed. The reported figures were adjusted from USD_{2020} to EUR_{2021} and from EUR_{2021} to EUR_{2020} respectively (Smith et al., 2021; Lehtveer and Emanuelsson, 2021).

Cost Type	*EUR_{2020}/tCO_2*
CAPEX	179
OPEX	202
Energy costs	181
CO_2 transport, storage & monitoring	18
Total costs	*581*

BECCS System Assumptions

For BECCS, a 500MW thermal power plant for heat and power production located in Europe with an amine-based post-combustion carbon capture was studied. The plant has the capacity to capture up to 909.5kt of CO_2 per year. The plant was said to be based on the DRAX or Stockholm Exergi plants depending on the plant with which the expert was most familiar with.

At first, the following two assumptions were provided: the feedstock was miscanthus and a 100km^2 area was set around the plant for feedstock sourcing and transport. These assumptions were later dropped as pilot experts found them too stringent. Following this, experts were asked which feedstock they see fit for the plant. This change did not influence the 2020 cost breakdown. Table C2 shows the cost breakdown for BECCS technology in 2020. The total costs are based on a conference announcement from DRAX placing current costs at GBP_{2022} 150/tCO_2 (Gratton, 2022).

Table C2: Total costs of a BECCS system based on the DRAX power plant with 2020 costs equivalents. Cost breakdown and assumptions are based on the Chiquier’s and Gratton’s work and adapted. Both a conversion rate from GBP_{2022} to GBP_{2020} and from GBP_{2020} to EUR_{2020} is used (Chiquier, 2022; Gratton, 2022).

Cost Type	*EUR_{2020}/tCO_2*
CAPEX	164
OPEX	30
Feedstock costs	105
Energy revenues	-165
CO_2 transport, storage & monitoring	38
Total costs	*172*

[17] “8-LargeCHP-Värtaverket_SE_Final.pdf.”

Appendix D – Scalability Scenarios Assumptions

To compare experts' beliefs on how policies influence the scalability potential of the technologies in Europe, they were asked to estimate the development for two policy scenarios. The two selected scenarios are the IEA's Stated Policies Scenario (STEPS) and Net Zero Emissions by 2050 Scenario (NZE).

STEPS is defined by the World Energy Outlook as a scenario where it is not assumed that governments meet their 1.5°C pledges. This scenario considers the various sectors' energy-related pledges that have been put in place or that are mentioned to be soon put in place. No specific outcome is expected from this scenario as policymakers do not steer future developments in any way. Using STEPS in this study allows us to set a benchmark to evaluate what would happen if only voluntary market forces were considered. NZE is defined as a 'normative' scenario which shows the pathway to global net zero emissions for the energy sector by 2050. This scenario is useful for discussing the volume of negative emissions required to achieve this narrow target[18].

Figure D1 shows the projected global CO_2 emissions under the STEPS announced pledges and the NZE scenarios. STEPS projects global CO_2 emissions of 35Gt by 2030 and 34Gt by 2050. This scenario does not specify any carbon price or need for negative emissions. NZE projects 21Gt of global CO_2 emissions by 2030 and 0Gt by 2050[19]. This scenario assumes that additional methods are needed to reduce CO_2 emissions and remove excess CO_2 from the atmosphere. NZE relies on BECCS to annually remove 227Mt of CO_2 by 2030. BECCS power production would reach 28GW by 2030 and up to 152GW in 2050[20]. In terms of carbon price levels, this scenario stipulates the need for a carbon price of USD 250/tCO_2 in advanced economies and USD 200/tCO_2 in other economies[21]. These scenarios represent different policy contexts in which NETPs could be deployed. Therefore, experts can make different projections about the potential scalability of BECCS or DACCS under each scenario.

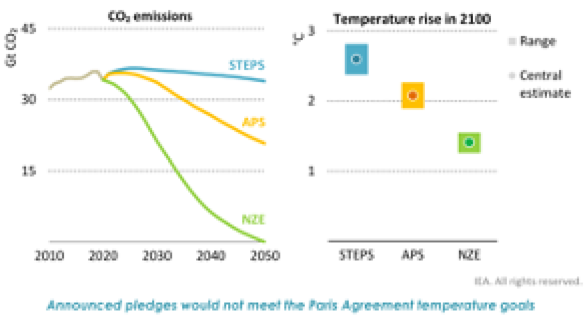

Figure D1: Global CO_2 emissions under different policy scenarios and associated temperature increases. Adapted from the World Energy Outlook 2021.

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[18] "World Energy Outlook 2021"
[19] "World Energy Outlook 2021"
[20] "Report-IEA-Net-Zero-2050-RF.pdf."
[21] "World Energy Outlook 2021 – Analysis," IEA. https://www.iea.org/reports/world-energy-outlook2021 (accessed Feb. 01, 2023).