bericht

report

BECCS

Bioenergy with carbon capture and storage – basics and opportunities

Date	10 April 2025
Number	971 TR C-31-109-0
Project manager	Christoph Strasser christoph.strasser@best-research.eu
Employees	Christa Dißauer
	Doris Matschegg
Scientific partner	BOKU University Institute of Chemical and Energy Engineering
Commercial partner	Bioenergy Europe
Project number	C-31-109-0
Project duration	1 December 2023 – 31 March 2025

BEST - Bioenergy and Sustainable Technologies GmbH

Head Office Graz
Inffeldgasse 21b
A 8010 Graz
T +43 5 02378-9201
office@best-research.eu
www.best-research.eu
FN 232244k
District Court Graz
VAT-No. ATU 56877044

v01

Executive Summary

This report investigates the **Bioenergy with Carbon Capture and Storage (BECCS)** potential in Europe. BECCS involves capturing, transporting, and permanently storing CO_2 from processes where biomass is converted into fuels or energy. While the specific biomass source and conversion pathway can vary, BECCS offers the potential to be a carbon-negative form of energy production when done sustainably. The report outlines various **CO_2 separation and capture technologies**, including post-combustion, pre-combustion, and oxy-fuel methods, with a focus on **post-combustion capture** due to its maturity and possibility of retrofitting in existing bioenergy plants. Different post-combustion technologies like absorption (using amine-based solvents being the most mature), adsorption, membrane, and cryogenic processes are discussed, along with their respective characteristics and challenges. A current focus of research activity is the development of innovative solvents (e.g. “advanced amines”), with companies developing proprietary solvent compositions with the objective of reducing energy requirements.

The report presents **key figures for BECCS**, including CO_2 capture rates (typically around 90-95%) and the associated energy demand for different capture technologies. The energy demand, also referred to as energy penalty, describes the amount of heat and/or power needed for the capturing process and reduces the energy output of the bioenergy plant. The ratio of the energy penalty as well as the type of energy (heat or electricity) depends on the capture technology.

The **costs of CO_2 capture** (excl. transport and storage) are also explored, noting significant fluctuation ranges (40 – 240 €/t $CO_{2captured}$) due to various assumptions regarding electricity and heating demand and costs, materials or absorbers used, country and time-dependent assessment of investment costs, assessment of CO_2 prices, etc. However, the main cost drivers are the CO_2 partial pressure and the scale of CO_2 to be captured. Further cost drivers such as the specific technology selected, the targeted CO_2 capture percentage, energy and cooling costs, flue gas pre-treatment, and location of the plant all have influencing properties on the overall cost of carbon capture.

Furthermore, the **bioenergy carbon capture implementation potentials in Europe are assessed** considering key sectors such as CHP, power-only, heat-only, pulp & paper, and waste-to-energy plants. According to the POTEnCIA model (scenario 3, reaching a reduction of 90% GHG emissions by 2040) in the impact assessment report on “Europe´s 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society”, the industrial carbon removals with **BECCS** could reach **80 Mt CO_2 in 2040** (EC, 2024). With the sectors considered and assuming a capture rate of 95%, an **implementation rate of 38%** would be required to reach this target. An implementation rate of 50% would lead to a capture of biogenic CO_2 of about 105 MtCO_2/year.

The total energy demand (energy penalty) for capturing 80.06 $MtCO_2$ when applying a monoethanolamine (MEA) based post-combustion capture technology with an average energy penalty of about 3.5 MJ/kg CO_2, the energy penalty account for about 280 PJ/a. The lowest energy penalties are to be expected with the implementation of chemical looping combustion (CLC, TRL 5-6), amounting to 92 PJ/a (± 12).

As mentioned above, the uncertainties and thus the ranges for the capture costs are high. When applying MEA technology with costs between 44 and 240 €/tCO_2, the total costs for capturing 80.06 $MtCO_2$/year are between 4.6 and 12 billion €/a. The costs can be reduced, for example, by using advanced amines, optimizing process parameters or integrating a heat pump to increase the overall efficiency of the system.

Several **bioenergy carbon capture projects in Europe**, in various stages of operation, pilot, or construction, are highlighted, including projects by Stockholm Exergi, RWE (Amer and Eemshaven), Ørsted, Hofor, Vattenfall, Hafslund Celsio, and Drax Power Station. These projects utilize different biomass feedstocks and aim for significant biogenic CO_2 capture.

Major efforts are still required to realize this potential. A **SWOT analysis** outlines the strengths, weaknesses, opportunities, and threats associated with BECCS implementation. Strengths include its potential for carbon negativity and the maturity of certain capture technologies, while weaknesses involve energy losses and limited reference plants. Opportunities lie in achieving emission reduction goals and potential market development for CO_2 removal certificates, whereas threats include open questions regarding missing storage and transport infrastructure and a lack of clear policy frameworks. Thus, this report derives a set of **policy recommendations**, which are presented in the final chapter.

Table of Content

1 Introduction

The European Union aims at reducing its net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, and at achieving carbon neutrality by 2050. Within the European Strategic Energy Technology Plan (SET Plan) strategy, carbon capture and storage (CCS) and carbon capture and utilisation (CCU) (CCUS all together) are essential in addressing climate change due to the ability to achieve negative emissions. Negative emissions refer to the process to remove more carbon from the atmosphere than the one emitted. Once extracted, the carbon can be stored in geological reservoirs such as saline aquifers or in other mineral forms within the Earth's crust or used in different sectors.

Bioenergy with Carbon Capture and Storage (BECCS) is seen as a critical technology for addressing climate change because it offers a potential way to not only reduce the amount of carbon dioxide (CO_2) being emitted into the atmosphere but also to actively remove CO_2 from it. Hence, the development of BECCS as CO_2 capture technology in combination with CO_2 storage needs further exploration. To support the Union's climate and energy targets, it is crucial that energy from biomass is produced sustainably. To achieve this, the Renewable Energy Directive (revised Renewable Energy Directive EU/2023/2413), includes a targeted strengthening of the sustainability and greenhouse gas (GHG) emissions saving criteria for biomass (Article 29).

Biomass is a natural resource with a wide range of applications, including food, construction materials, paper, chemicals, plastics, pharmaceuticals and various types of fuel. As such, it has a vital contribution to make to a circular economy. Sustainable biomass offers opportunities to reduce emissions rapidly, replace non-renewable resources in existing technologies and infrastructure, for example when used as bioenergy for electricity and heat generation. Furthermore, biomass is also easy to store, making it valuable as a complement to other intermittent renewable energy sources. In the long-term, biomass has the potential to reduce emissions in hard-to-abate sectors such as construction and transport, including aviation and shipping. But it must always be remembered that the capacity for terrestrial ecosystems to supply sustainable biomass and other products is not unlimited, and that some practices involved in biomass production can be detrimental (Strengers et al. 2024). Hence, the sustainable management of biomass is an essential prerequisite for all biomass technologies to demonstrate that the biomass used meets the Renewable Energy Directive (RED) sustainability criteria. Only then bioenergy with carbon capture and storage, can contribute to net negative emissions.

This report gives an **overview** on possible **carbon capture technologies** for bioenergy plants (without going into the biomass supply or technical details) and compares the energy efficiency of bioenergy and direct air carbon capture (DACC) technologies. Based on the results and scenario assumptions basic modelling has been performed to roughly estimate costs and energy demand for implementing BECCS in Europe. The main objective of this study is to evaluate the potential for the deployment of BECCS and suggest policy recommendations to further promote it.

2 Carbon Dioxide Removal (CDR)

Carbon Dioxide Removal (CDR) refers to technologies, practices, and approaches that remove and store carbon dioxide (CO_2) from the atmosphere. There are many different CDR methods and associated implementation options (see Figure 1), with different timescales and risk factors (IPCC CDR Factsheet).

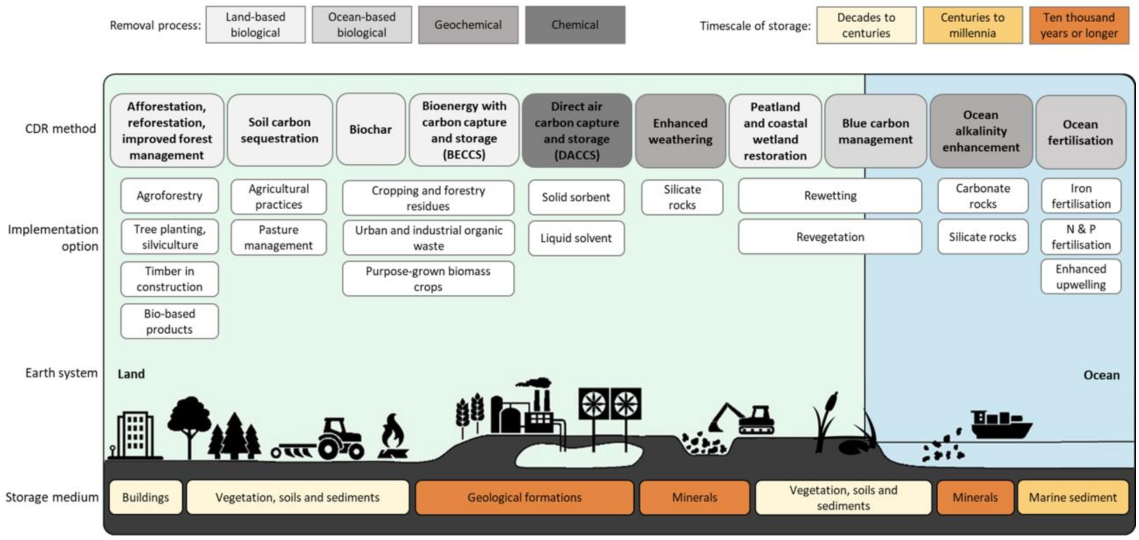


Figure 1: Carbon dioxide removal taxonomy according to the IPCC sixth assessment report. Methods are categorised based on removal process (grey shades) and storage medium (for which timescales of storage are given, yellow/brown shades). Source: Castellanos et al. 2022

BECCS involves capturing, transporting and permanently storing CO_2 from processes where biomass is converted into fuels or directly converted to energy[1].

The selected biomass source and conversion pathway differ depending on the BECCS project at hand, which in turn influences the CDR potential. The biomass source may be forest or agricultural residues, by-products from the wood processing as well as pulp and paper industry, wood pellets, solid municipal waste or dedicated crops, whilst conversion pathways involve biological or thermochemical processes. In addition, though the carbon capture process needs energy provided by the bioenergy plant, still more energy is produced than used during the capture process. Hence, BECCS is a CDR technology that still produces energy. When done sustainably by also taking CO_2 balances into consideration, transforming biomass into energy does not increase net levels of CO_2 in the atmosphere and can play a fundamental role in the energy transition. Bioenergy is a carbon-neutral form of energy that aligns with the natural growth and decay cycle of biomass, converting it into energy instead of allowing it to decompose

[1] Adapted from: IEA (2024): https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage#overview

naturally. The sustainable management of forest ensures the amount of carbon stored in the ecosystem remains stable or even increases over time. By capturing and storing the CO_2 accumulated during the growth of the biomass and released during the biomass conversion, BECCS can be more than carbon neutral, in compliance with sustainability criteria it has the potential to be a carbon-negative form of energy production. Each BECCS plant is unique, involving a specific feedstock, supply chain, CO_2 capture process and downstream processes.

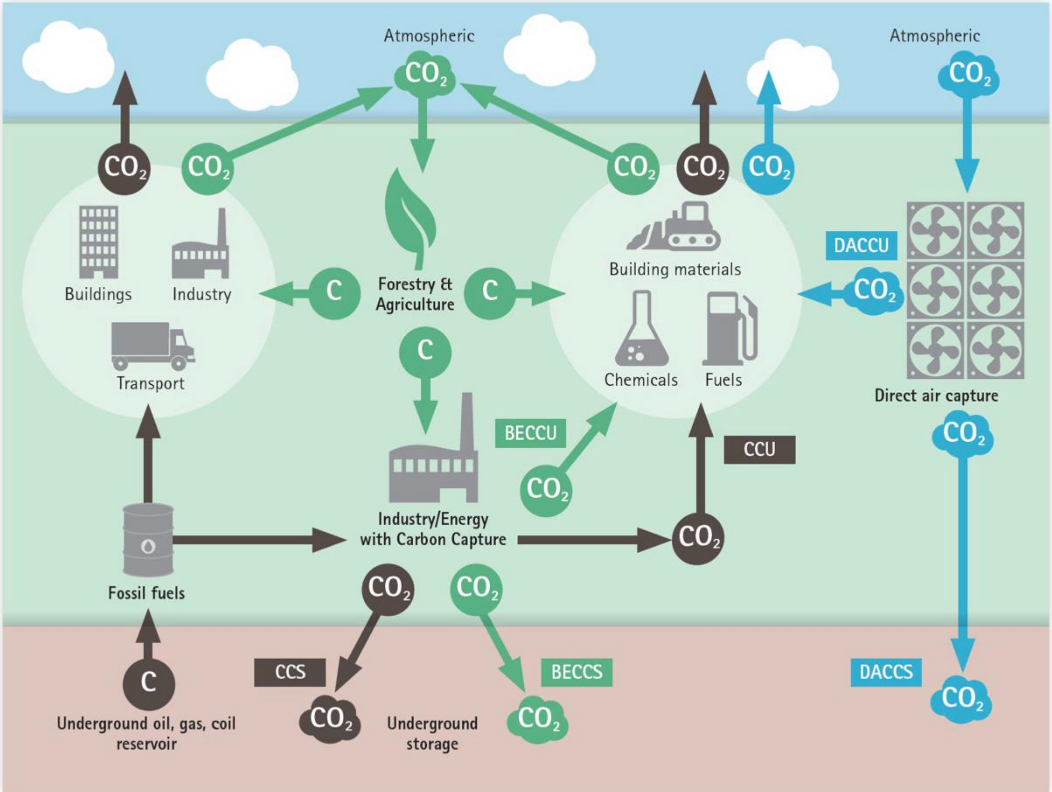


Figure 2: Schematic illustration of BECCS, BECCU, CCS, CCUS, DACCU and DACCS. Source: Austrian Biomass Association

There are currently (beginning of 2024) 19 bioenergy production facilities including BECCS around the world either in operation, in pilot stage or under construction (for more details see chapter 5: Main bioenergy carbon capture projects in Europe). Some leading European projects in the field include Drax and Stockholm Exergi with the intention of capturing 8 Mt CO_2/yr and 0.8 Mt CO_2/yr respectively followed by permanent geological storage (H2020 Project NEGEM).

Another biomass related CDR method is biochar production through pyrolysis which creates carbon sinks by incorporating biochar into soil or durable construction materials, thereby creating a durable carbon removal. During the pyrolysis process heat is generated which can serve for drying the biomass feedstock or even generating electricity. Carbon capture technologies can also be implemented in the biogas upgrading process to address the co-production of biomethane and CO_2 as high purity co-products. Furthermore, in bioethanol plants, the fermentation of sugar-containing biomass (e.g. wheat, sugar beet, lignocellulosic waste) produces a highly pure CO_2 stream in addition to bioethanol. While these processes are relevant biomass-related CDR methods, they fall outside the scope of this report and are mentioned here for context only.

Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere.[2] The process of separating CO_2 from the other components of ambient air is either accomplished through absorption or adsorption. Two common approaches used to capture CO_2 directly from the air are direct air carbon capture and storage (DACCS) technologies using a solid sorbent or a liquid solvent. In the liquid solvent DACCS process, high-grade heat (900°C) is supplied by natural gas or hydrogen, with electricity sourced from the power grid. In the solid sorbent DACCS process, heat and electricity are both obtained from the power grid, using an industrial heat pump which converts electricity to low-grade heat (100°C). Another option is to use geothermal heat. As of February 2024, there are over 20 DAC/DACCS initiatives in Europe. The current capacity at one of the largest plants in operation (ORCA) is using geothermal energy and is on the scale of 0,004 million tons of CO_2 each year (H2020 Project NEGEM). In the U.S., the STRATOS facility is currently under construction in Ector County, Texas. Once complete this facility is expected to be the largest direct air capture facility in the world. It is designed to capture up to 0,5 Mt of CO_2 per year and is expected to be commercially operational in mid-2025. However, capturing CO_2 from the air is the most expensive application of carbon capture. The CO_2 in the atmosphere is much more dilute than in, for example, flue gas from an energy plant. This contributes to DAC's higher energy needs and costs relative to these applications.

The two technologies BECCS and DACCS are not in competition but rather complement each other. Which technology is chosen should essentially depend on the suitable regional geographical potential. DACCS is better suited if there is a regional energy surplus. BECCS is advantageous for regions where energy is needed anyway.

2.1 CO_2 separation and capture technologies

The utilization of CO_2 capture technologies by industry has a long history, dating back to the separation of CO_2 as a product gas or the removal of CO_2 from natural gas streams where it is not wanted. Currently, there are three primary methods for point source CO_2 capture: post-combustion, pre-combustion, and oxy-fuel (Figure 3).

[2] https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture

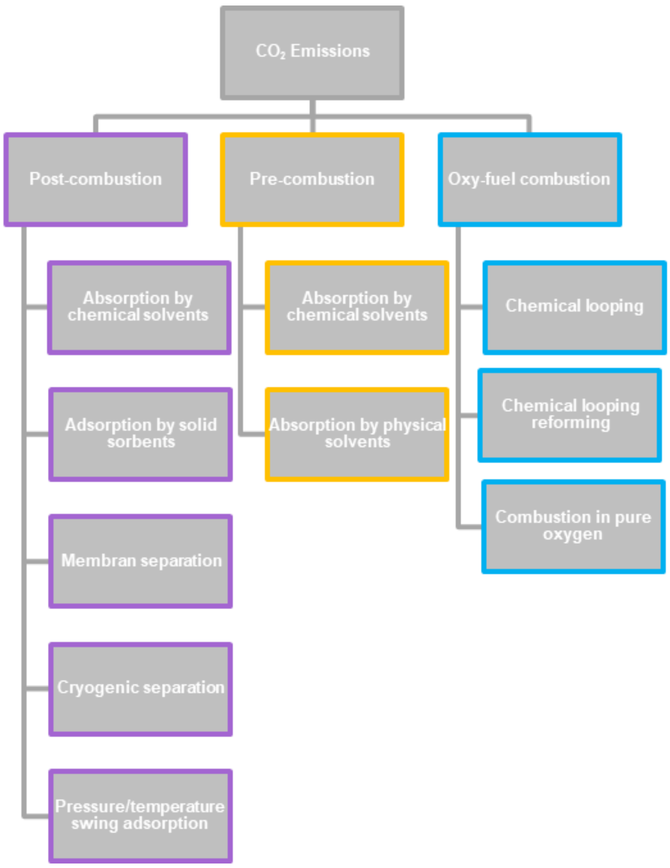


Figure 3: Overview carbon capture technologies (Adapted from Shabaz et al. 2021)

The **pre-combustion system** is characterised by the removal of CO_2 prior to the combustion of the gas. This removal system is applicable to high carbon concentration streams, typically higher than 20% of the total volume (Leung et al. 2014). This system is characterised by first gasifying the fuel with a controlled amount of air/oxygen or steam. The reaction product (syngas) is then fed together with steam into a catalytic reactor where a water-gas shift reaction takes place. At this stage the CO_2 is captured and H_2 can be utilised (Shabaz et al. 2021).

The **post-combustion** system captures carbon after combustion and before emissions are released into the atmosphere. This technology can be easily integrated into bioenergy plants and does not require any major configuration changes or pre-engineering compared to other carbon removal systems. An additional advantage of this technology is the ease with which process parameters of the carbon capture technology can be regulated without interrupting the main combustion operation of the power plant, as it is implemented at the final stage of the treatment system (Ben-Mansour et al. 2016). This process is equally suitable for gasification and combustion-based power plants (Shabaz et al. 2021).

In the oxy-fuel combustion approach, an air separation unit is employed to separate nitrogen from oxygen prior to combustion. In an oxy-fuel combustion, fuel is combusted in an oxygen environment, instead of air, removing the N_2 and increasing the concentration of CO_2 in the flue gas. The CO_2 in the flue gas is available in high concentrations, approximately 80% to 98%. However, this technology is not yet mature (Anwar et al. 2018, Shabaz et al. 2021).

The chemical looping combustion (CLC) has the potential to be an efficient and low-cost technology capable of contributing to the reduction of the atmospheric concentration of CO_2 in the future. CLC is considered an unmixed combustion technology, where air is never mixed with fuel to avoid diluting the CO_2 with nitrogen. In this process, a metal oxide replaces the oxygen introduced with the fuel and acts as an oxygen carrier. The supply of oxygen necessary for the combustion is provided by the oxygen carrier, which is transported between two different chemical reaction zones. In the air reactor, oxygen is taken up from the air, where the oxygen carrier is oxidised. The oxidised material is transported to the fuel reactor, where a second reaction occurs. In this zone, oxygen is transferred to the fuel, resulting in combustion of the fuel with pure oxygen. The generated gas consists of CO_2 and H_2O. The loop of CLC is closed by transporting the reduced material back to the air reactor (Fleiß et al. 2024).

Depending on the type of fuel used, the CO_2 concentration and the flue gas pressure the most efficient technology path can be selected. While post-combustion is an advantageous approach for low CO_2 concentration streams, pre-combustion is usually suggested for processes with high CO_2 concentration streams. However, the post-combustion absorption approach is considered to be the most mature technology, as it is relatively easier to implement as a retrofit option in current bioenergy plants. Post-combustion involves the scrubbing of CO_2 out of flue gases from combustion processes. The pre-combustion and oxyfuel combustion systems require unique configurations and can usually only be integrated into new-build power plants (Shabaz et al. 2021). Oxyfuel involves combusting fuel in recycled flue gas enriched with oxygen to produce a CO_2-rich gas. Pre-combustion uses a gasification process followed by CO_2 separation to yield a hydrogen fuel gas. Oxyfuel combustion has been demonstrated in the steel manufacturing industry (von Scheele 2022), and the related oxy-coal combustion method is currently being demonstrated. Demonstration of pre-combustion CO_2 capture from an integrated gasification combined cycle power plant has not yet been achieved. However, elements of the pre-combustion capture technology have already been proven in other industrial processes (IEA 2010). Chemical Looping Combustion (CLC) is an oxy-combustion technology used to convert biomass and fossil fuels in order to obtain a flow of pure CO_2 which should be suitable for low-cost capture. Though the TRL is currently only 5-6, there is the Chinese-European Emission-Reducing Solutions (CHEERS[3]) project which involves a 2nd generation chemical-looping technology tested and verified at laboratory scale (up to 150 kW_{th}). Until 2027, the core technology will be developed into a $3MW_{th}$ system prototype for demonstration in an operational environment.

[3] The CHEERS project: https://cheers-clc.eu

2.2 Post-combustion Carbon Capture

Post-combustion CO_2 capture is the technology to be used to capture existing emission sources among the currently available CCS technologies. The chemical absorption using amine-based solvent is regarded as the first CO_2 capture technology that was applied in industrial scale in post-combustion technology for CO_2 capture, where the first commercial large scale (Sleipner gas field project) was installed and started in 1996 in Norway due to high carbon tax (Raza et al. 2018). The application of amine-based solvent for CO_2 capture has drawn a large amount of interest, thus leading to a substantial improvement in CO_2 post-combustion technology. It is currently the most promising approach and become a benchmark for CO_2 capture technology (Hussin and Aroua 2020). Absorption, adsorption, membrane and cryogenic processes are depicted in Figure 4, Figure 5 and Figure 6. The TRL level is presented by the colouring (green = TRL 9, yellow = TRL 5-8, bright orange = TRL 3-4, dark orange =TRL 2).

Absorption is considered the most mature approach to CO_2 removal. Absorption can be based on chemical or physical solvents (Figure 4). Physical solvents are adequate in high CO_2 partial pressure applications. Although physical absorption is constrained to high-pressure flue gas, physical solvents provided higher performance in CO_2 separation process. Chemical absorption is more suitable for a lot of industrial process due to the flue gas conditions: ambient pressure, low CO2 concentration and large volume (Vega et al. 2018). Chemical absorption is based on the neutralization reaction between CO_2 (acid) and a liquid solvent (basic). CO_2 reacts with the solvent to form an intermediate compound during the separation process, which is then broken-down using heat (for details regarding the needed energy please refer to chapter 4.2.2). Chemical solvents have been used for decades; they are well-tested and used in mature carbon capture technologies available. Conventional solvents rely on chemical absorption to remove carbon dioxide. They usually contain an amine that will react selectively with carbon dioxide. The most well-known solvents include monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA), diglycolamine (DGA). Carbon capture is still dominated using amine and N-heterocyclic solvents such as monoethanolamine (MEA) or proprietary formulations of blends of amines and N-heterocyclic molecules. MEA has become the de facto standard as it has shown good performance in terms of capture capability. However, it has several drawbacks: high energy penalty during regeneration, thermal degradation and corrosion. As a result, new solvent candidates and new solvent blends are being investigated (see Nessi et al. 2021 and McDonagh et al. 2024 for more details). Novel compositions of amines or non-amine solvent options may enhance CO2 capture operations. Research and development for solvents focuses on improving the absorption and desorption characteristics of amine and non-amine solvents to reduce the size of capital equipment required and the operating needs of a CO2 capture plant (Barlow et al. 2025). The potassium carbonate (K_2CO_3) is a non-amine-based solvent that can be used as a promoter for the CO_2 capture with amine-based solvent or other class of amine, like a sterically hindered amine. (Leung et al. 2014, Samanta et al. 2012, Vega et al. 2018, Shabaz et al. 2021).

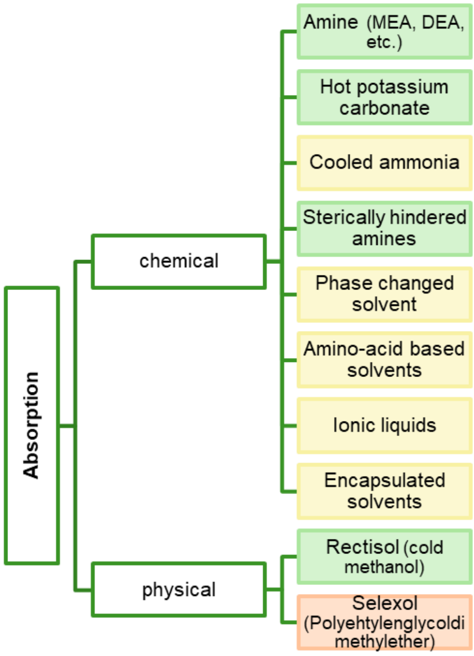


Figure 4: Absorption processes (the colour is related to the technology readiness level – TRL, from dark orange = 2 to green = 9)

TRL 2 | TRL 3-4 | TRL 5-8 | TRL 9

Adsorption is a process in which CO_2 attaches to a solid surface sorbent such as zeolites, activated carbon, lithium zirconate, hydrotalcite and calcium oxides (Figure 5). The choice of the ideal adsorbent depends on many aspects, mainly related to the volume of CO_2 to be removed, kinetics, pore size and structure of the adsorbent, etc. The CO_2 fixed on the solid sorbent can then be removed by either temperature or pressure swing adsorption techniques, where either pressure or temperature is increased after adsorption to desorb the CO_2 (Anwar et al., 2018, Leung et al. 2014, Shabaz et al. 2021).

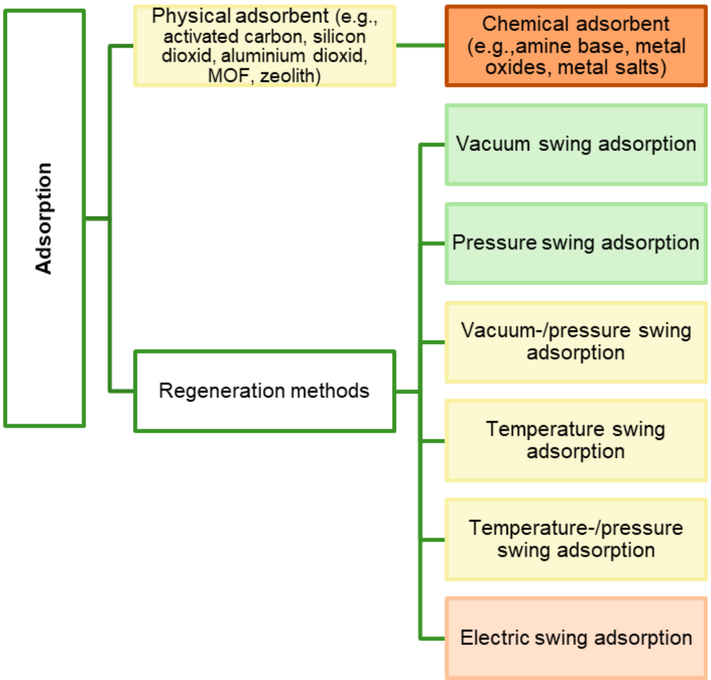


Figure 5: Adsorption processes (the colour is related to the technology readiness level – TRL, from dark orange = 2 to green = 9)

TRL 2 | TRL 3-4 | TRL 5-8 | TRL 9

Furthermore, there are also membrane and cryogenic processes which can be used for CO2 capture (Figure 6).

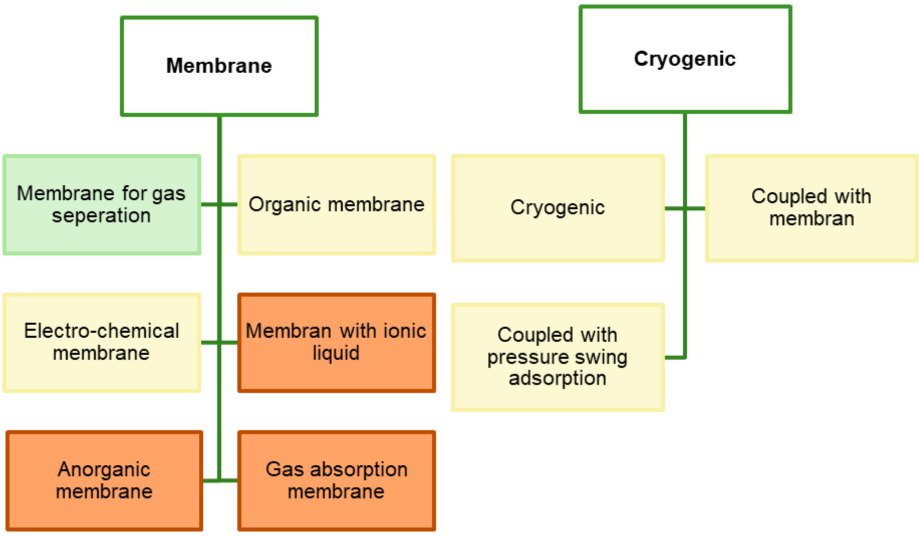


Figure 6: Membrane and cryogenic processes (the colour is related to the technology readiness level – TRL, from dark orange = 2 to green = 9)

TRL 2 | TRL 3-4 | TRL 5-8 | TRL 9

Several technologies that are applied in post-combustion CO_2 capture are compared in Table 2-1 (see for further details: Hussin and Aroua 2020).

Table 2-1: Overview of different post-combustion CO_2 capture technologies (adapted from Hussin and Aroua 2020)

CO_2 capture technologies	**Characteristics**	**Challenges**
Absorption	Chemical absorption using amine-based solvent (e.g. Monoethanolamine (MEA)) is the first post-combustion technology that is applied worldwide on a large scale in several industrial processes. New solvent candidates and new solvent blends are being investigated. The potassium carbonate (K_2CO_3) is a non-amine-based solvent that can be used as a promoter for the CO_2 capture with amine-based solvent or other class of amine, like a sterically hindered amine.	- High equipment corrosion rate - High energy consumption. - Large energy penalty for regeneration - Large absorber volume - Solvent degradation due to SO_2 and O_2 in flue gas - Environmental impacts due to solvent emissions - Additional compression work requirement for the captured CO_2 transportation and storage
Adsorption	The adsorption process is suitable to be used for CO_2 capture because it is reversible, high adsorption capacity, less energy extensive and low cost of adsorbent material. There are different types of adsorption technologies such as: (i) pressure-swing adsorption (PSA), (ii) temperature-swing adsorption (TSA), (iii) electric-swing adsorption (ESA), (iv) vacuum swing adsorption (VSA) and (v) combination of pressure/ vacuum- swing adsorption (PVSA) etc.	- Challenges in selecting adsorbent materials - Low CO_2 selectivity - Intermittent operation and it needs periodic regeneration of the adsorbents - Pressure drop can be large in flue gas application

CO_2 capture technologies	Characteristics	Challenges
Membrane	Very high selectivity, high driving force, simple of installation, low capital cost and energy consumption despite the low partial pressure of CO_2 The membrane gas separation is currently an established technology, but the compromise between permeability and selectivity hinders the application of membrane technology on a large-scale. Due to relatively low CO_2 concentration and pressure, the driving force for membranes to perform properly is weak for CO_2 capture.	- Requirement of compression work for driving force - High membrane manufacturing cost - Requirement of high selectivity (due to CO_2 concentration and low pressure ratio) - Fouling effect - High membrane surface area is required to accommodate the high flow rate of industrial flue gas - Moisture adversely affected the permeability of polymeric membrane - Performance is affected by operating condition (i.e. temperature and pressure) - Not proven industrially, however this technology is used for upgrading biogas to biomethane[4]
Cryogenic	Used commercially for high concentration and high-pressure gases. Because of the high capital expenditure of cryogenic separation, this method is economically feasible only if the percentage of CO_2 is high in the stream.	- High energy requirement - More suitable for high CO_2 concentration (>50%) - Moisture must be removed from the gas mixture before cooling to prevent blockage - Continuous build-up of solidified CO_2 on heat-exchanger surfaces adversely affects heat transfer and reduces the process efficiency

[4] EBA Statistical Report 2022: About 47 % of the biomethane plants in Europe are using this upgrading technology.

3 BECCS key figures

This chapter presents relevant key figures, such as costs and energy demand, for different BECCS technologies. Energy balances are depicted with Sankey Diagrams.

3.1 CO_2 capture rate and energy demand

The capture rate describes the share of total CO_2 emitted which will be captured from a plant. As shown in Table 3-1, for most technologies this rate lies around 90 – 95 %. While there are no technical barriers to increasing capture rates beyond 90% for the most mature capture technologies, capture rates of 98% or higher, the economic viability will limit the capture rate. For DACCS there is a bigger uncertainty since it also depends on the energy source. Using renewable heat, e.g. geothermal heat, or renewable electricity has a very positive effect on the overall capture rate as they are low emission energy sources. Using fossil energy sources, the efficiency in terms of CO_2 capture must be a case-by-case consideration.

The energy demand, also referred to as energy penalty, describes the amount of heat and/or power needed for the capturing process. The ratio of the energy penalty as well as the type of energy (heat or electricity) depends on the capture technology. For instance, using waste heat from power only plants reduces the ratio of the energy penalty. When implementing MEA, the heat penalty is higher compared with other BECCS technologies. However, it would be possible to combine the MEA technology with a heat pump to reduce the heat loss. Heat pumps can significantly improve the energy efficiency of the carbon capture process. For example, the scrubber at the top of the desorber and the amine cooler are suitable heat sources. Currently, the waste heat is released to the environment via the cooling water. A favourable integration of a heat pump is to use the cooling water flow from the amine cooler[5] and the desorber to place the heat pump close to the reboiler where the steam is consumed. Therefore, the carbon capture process can be supplied with steam generating heat pumps (Wilk et al. 2024). Furthermore, a current focus of research activity is the development of innovative solvents, with companies developing proprietary solvent compositions with the objective of reducing energy requirements. As an example, data from test and research facilities are presented in the column "Advanced Amine" in Table 3-1

[5] The amine cooler is typically an air cooler which lowers the lean amine temperature before it enters the absorber.

Table 3-1: CO_2 capture rate and energy demand for carbon capture

	MEA	Advanced Amine	TSA	HPC	CLC	DACC (solid)	DACC (liquid)
CO_2 capture rate [%]	88-98	80-95	90	90	up to 100	50-95	50-95
Total additional energy demand for carbon capture[6] [MJ/kg CO_2 captured]	3.49	2.99 – 3.39	3.25 - 3.73	1.7-2.35	1	5.8-34.1	6.5-13.1
thereof additional Heat demand [MJ/kg]	3	2.5 - 2.9	3.21 -3.64	-	0.5	4.1-25.8	4.9-10.8
Thereof additional electricity demand [MJ/kg CO_2 captured]	0.49	0.49	0.04-0.09	1.7-2.35	0.5	1.7-8.3	1.6-2.3
Source	Pröll 2019	Nessi et al. 2021, McDonald et al. 2024,	Zerobin 2020	Gustafsson 2021	Pröll 2019	Keith 2018, Zerobin 2020	IEAGHG 2021

Explanation: MEA = Monoethanolamine, TSA = Temperature Swing Adsorption, HPC = Hot Potassium Carbonate, CLC = Chemical Looping Combustion, DACC = Direct Air Carbon Capture

[6] The additional energy demand is in literature also often referred as “energy penalty”, since the energy for the carbon capture technology is produced by the bioenergy plant and reduces the energy output of the plant.

3.2 Costs of CO_2 capture

The costs from the literature for CO_2 removal are subject to large fluctuation ranges. The reasons for the large fluctuation ranges are manifold: different assumptions regarding electricity and heating demand and costs, materials or absorbers used, country and time-dependent assessment of investment costs, assessment of CO_2 prices, etc. The main cost drivers are the CO_2 partial pressure and the scale of CO_2 to be captured. Further cost drivers such as the specific technology selected, the targeted CO_2 capture percentage, energy and cooling costs, flue gas pre-treatment, and location of the plant all have influencing properties on the overall cost of capture (Barlow et al. 2025). Among the post-combustion technologies, the MEA approach is the most tried and tested one but also has its drawbacks. However, using heat pumps instead of external steam supply for the carbon capture process has economic benefits on the overall process (Wilk et al. 2024). In terms of costs, the chemical looping approach is promising for future new-built plants (Fleiß et al 2024).

DACCS is currently expensive, and its future cost is hard to predict. Experts believe that economies of scale, process optimisation, including the development of more efficient and less costly sorbents, will eventually decrease sorbent fabrication costs. Greater availability and subsequent lower cost of renewable energy could significantly reduce the energy costs of the technology. Options include novel configurations/tech that use carbonation cycles rather than sorbent materials (H2020 NEGEM).

A literature review has been performed to list total capture costs and CAPEX and OPEX ranges (in percent of total costs) for different carbon capture technologies. Data gaps for less developed technologies, variations in process parameters and assumptions as well as uncertainties lead to large cost ranges for all the technologies, see Table 3-2. The table only contains the respective minimum and maximum values per technology. Lowest costs are attributed to the chemical looping technology, followed by MEA. These costs for advanced amines are within the range of the MEA, whereby a maximum of 150 €/t CO_2 can be found in the literature. In comparison, costs for DACCS tend to be higher than for BECCS. In addition to the costs for capturing, there are also costs for transportation and storage (which are not depicted in Table 3-2).

Table 3-2: Indications for carbon capture costs (excl. transport and storage) in €/t captured CO_2

	MEA	TSA	HPC	CLC	DACC
Total cost [€/tCO_2]	44 – 240	60 – 240	60 – 240	40 – 75	86 – 456
CAPEX [%]	19 – 83	77		77	25 – 44
OPEX [%]	17 – 81	23		23	56 – 75
Source	Garðarsdóttir 2019, dAmore 2021, adapted and updated from Budinis 2018 & Fleiß 2024	Sun 2022, adapted and updated from Budinis 2018 & Fleiß 2024	Adapted and updated from Budinis 2018 & Fleiß 2024	Sun 2022, adapted and updated from Budinis 2018 & Fleiß 2024	IEAGHG 2021

Explanations: MEA = Monoethanolamine, TSA = Temperature Swing Adsorption (using Zeolite 13X), HPC = Hot Potassium Carbonate, CLC = Chemical Looping Combustion, DACC = Direct Air Carbon Capture

4 Bioenergy Carbon Capture Implementation Potentials

4.1 BECCS key sectors and potentials in Europe

Carbon capture technologies can be integrated in existing plants and infrastructure. Options include:

- **Integrating CCS into existing biomass-based industries (CHP, bioethanol, pulp and paper etc.).**
- Integrating CCS into carbon-intensive heavy industry, while implementing a fuel switch from fossil fuels to biomass.
- Integrating CCS into novel biobased production pathways for carbon-based chemicals (e.g. fuels, olefins).

Assuming implementing carbon capture technologies in existing biomass-based industries as well as heavy industry, the potential for carbon removal technologies is high. The cement production in Europe alone emits 123 $MtCO_2/a$ (EEA, 2021). However, for the further assessment, the current utilization of biomass is considered (**Retrofitting CCS into existing biomass-based industries**). According to the EUROSTAT database the consumption of primary solid biofuels (including residential and commercial use) in the EU accounted for 4,045,615.8 TJ in 2023. The amount of renewable (biogenic) municipal waste accounted for 401,425.7 TJ in 2023. The trend is positive for both values considering the last ten years. These amounts provide an indication of the current theoretical potential of biogenic CO_2. Assuming that the total amounts are combusted and that a maximum of 367kg CO_2[7] (Pröll and Zerobin 2019) are emitted per MWh, the theoretical potential for biogenic CO_2 accounts for up to 453 Mt biogenic CO_2/a.

Additionally, biogenic CO_2 can be obtained from biogas and biomethane production. Based on the volume produced in Europe in 2023 (22 billion m^3), the potential is about 29 Mt biogenic CO_2/a (EBA, 2024). In total, this results at the moment (2023) in a theoretical potential of 482 Mt biogenic CO_2/a.

Following, the theoretical potential is narrowed down to a technical potential. Existing facilities in Europe has been researched to assess the biogenic CO_2 of selected sectors which could be removed from the atmosphere with BECCS. The selected sectors are CHP, power-only, heat-only, pulp & paper and waste-to-energy plants. Two databases have been used, a public

[7] Stochiometric (50% carbon content, typical value of ISO 17225-1 for a mixture of coniferous and broad-leaf wood)

database from the European Environmental Agency[8] as well as a plant list provided by Bioenergy Europe.

For CHP, heat only and power only plants a database of Bioenergy Europe, which provided a list of plants per country including capacity categories (1-5 MW, 5-20 MW and > 20 MW) was used. After removing plants with below 5 MW capacity from the list, there were 1,669 plants remaining, 612 CHP plants, 971 heat only plants and 86 power only plants. For the average CO_2 emissions, a factor of 367 kg/MWh has been used, which is the amount of CO_2 being emitted during combustion. It is assumed that all the plants are using 100% biomass in the assumed 8,000 operating hours (for heat only plants 3,120 annual operating hours were assumed), resulting in all the CO_2 emitted being biogenic.

As for pulp & paper and waste-to-energy plants, a public database from the European Environmental Agency has been used to assess biogenic CO_2 content. This database includes industrial reporting under the Industrial Emission Directive 2010/75/EU and European Pollutant Release and Transfer Register Regulation (EC) No 166/2006. The database provides information on plants and their emissions, including total CO_2 emissions and for some of the plants the biogenic CO_2 content. For the plants without information on the biogenic CO_2 content a factor (average biogenic share of the sector) has been used for calculation, 61%[9] for pulp & paper and 55%[10] for waste-to-energy plants. Table 4-1 lists total and biogenic CO_2 emissions of the selected sectors.

Table 4-1: Biogenic CO_2 emitted by selected industry sectors in Mt/a

Industry	Total CO_2 [Mt/a]	Biogenic CO_2 [Mt/a]
Power only plants	17.3	17.3
Heat only plants	14,5	14,5
CHP plants (incl. some Pulp & Paper*)	92.7	92.7
Pulp & Paper (additional)	59.7	50.4
Waste-to-Energy	83.4	46.8
Total	**267.6**	**221.7**

* Some pulp & paper plants are already included in the CHP sector

Table 4-2 lists the calculated biogenic CO_2 potentials by country[11] and sector. In Figure 7 a map shows the potential per country. Figure 8 shows the potential per country and sector in total and Figure 9 in relative values. Countries with the highest amount of biogenic CO_2 emissions are

[8] https://sdi.eea.europa.eu/catalogue/srv/eng/catalog.search#/metadata/3da7d329-beea-4a7b-89bc-d45fc1c4b8ac

[9] https://www.cepi.org/wp-content/uploads/2023/07/2022-Key-Statistics-FINAL.pdf

[10] Mean value from Rosa et. al. 10.1039/d1ee00642h and an IPPC background paper https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf

[11] EU-27, plus UK and Switzerland (Cyprus and Malta have no BECCS potential)

Sweden, Germany and the United Kingdom. Highest potential for BECCS is seen for CHP plants, followed by pulp and paper plants. Since two different databases have been combined, there are overlaps between CHP and pulp and paper plants. Thus, the industry sectors have been divided in the groups CHP (including pulp & paper) and Pulp & Paper (additional).

Table 4-2: Calculated biogenic CO_2 potential per sector and country in Mt/a

Country	CHP (incl. Pulp & Paper)	Power only	Heat only	Pulp & Paper (add.)	Waste-to-energy	Total biogenic CO_2
Austria	4.86	-	0.72	1.23	1.23	8.03
Belgium	0.56	0.13	0.12	0.23	1.23	2.27
Bulgaria	0.40	-	0.26	-	-	0.65
Croatia	0.23	-	-	-	-	0.23
Czech Republic	1.55	-	0.23	1.44	0.27	3.50
Denmark	5.35	-	0.44	0.02	0.76	6.57
Estonia	0.46	-	0.49	0.24	-	1.19
Finland	8.37	0.11	1.34	14.23	0.06	24.12
France	5.98	-	3.68	3.15	4.31	17.12
Germany	28.06	0.34	0.40	3.18	9.67	41.66
Greece	-	-	0.03	-	-	0.03
Hungary	0.13	0.17	-	-	0.20	0.50
Ireland	0.10	0.07	0.09	-	0.74	1.00
Italy	7.20	2.44	0.13	0.27	1.86	11.90
Latvia	0.30	-	1.22	-	-	1.52
Lithuania	0.76	-	0.79	0.13	-	1.68
Luxembourg	0.03	-	-	-	0.11	0.15
Netherlands	0.36	0.26	0.14	0.39	5.21	6.37
Poland	2.35	1.05	0.26	0.66	0.27	4.59
Portugal	0.40	0.66	-	0.64	0.69	2.39
Romania	0.53	-	0.04	0.16	-	0.73
Slovakia	0.53	0.13	0.05	-	-	0.22
Slovenia	0.10	-	0.86	0.07	-	1.52
Spain	1.99	1.93	0.61	1.29	0.65	6.48
Sweden	11.99	-	2.63	22.59	3.05	40.26
Switzerland	-	-	-	-	2.23	2.23
United Kingdom	10.11	10.01	-	0.49	14.29	34.89

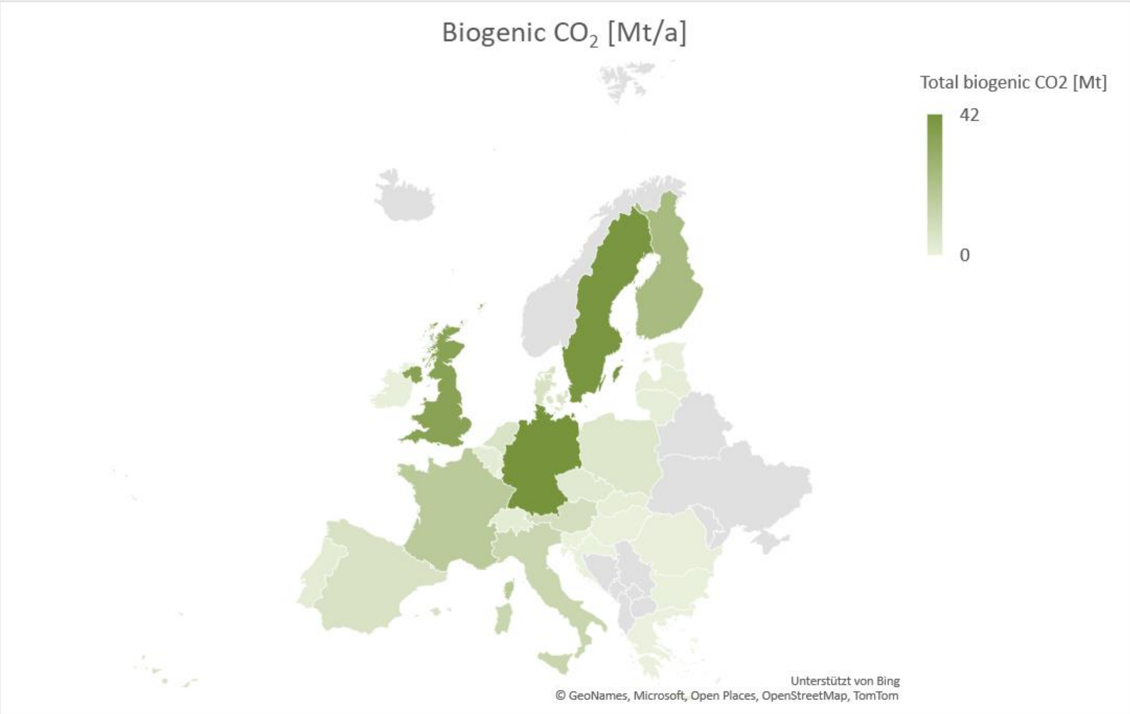


Figure 7: Map of biogenic CO_2 emissions in Mt/a (own illustration; data from Table 4-2)

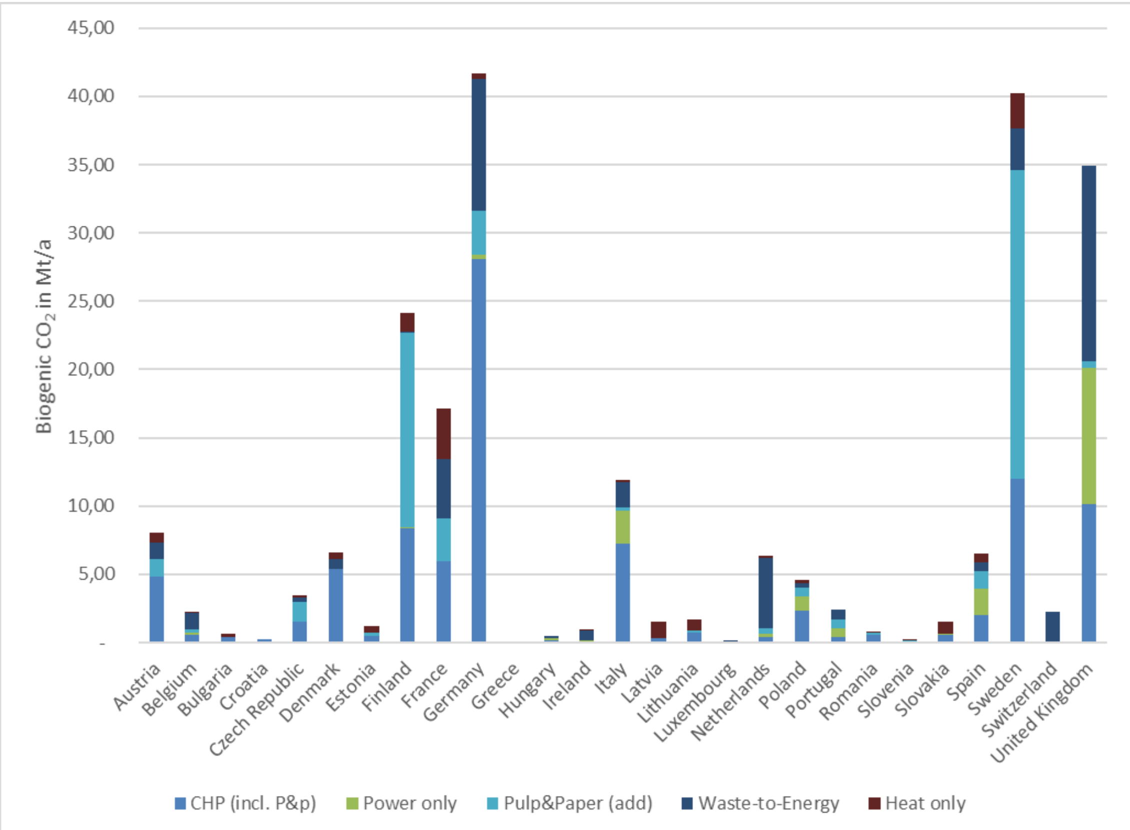


Figure 8: Biogenic CO_2 emissions per sector and country in Mt/a (own illustration; data from Table 4-2)

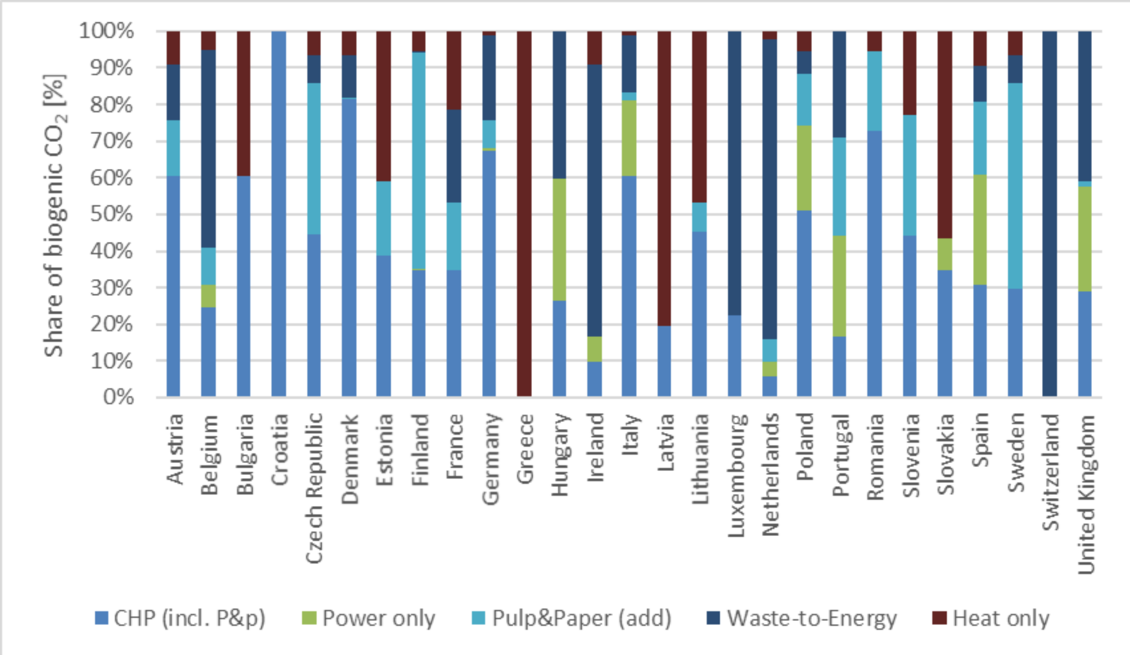


Figure 9: Share of biogenic CO_2 emissions per sector and country in % (own illustration; data from Table 4-2)

Major efforts are still required to realize this potential. Within the H2020 project NEGEM, limiting factors for the implementation of DACCS and BECCS were derived by conducting expert interviews, see Figure 10. The frequency of occurrence and ranking are given for each factor. Ranking figures indicate the most to least limiting factors from 1-10 with 1 representing the most limiting factor. An asterisk means the factor was added throughout the interviews. A geospatial assessment has been conducted by Rosa et. al. also highlighting the need for well distributed storage sites or a Europe-wide distribution network, since the location of storage sites are rather unfavourable and thus further reduces the potential of biogenic CO_2 mitigation.

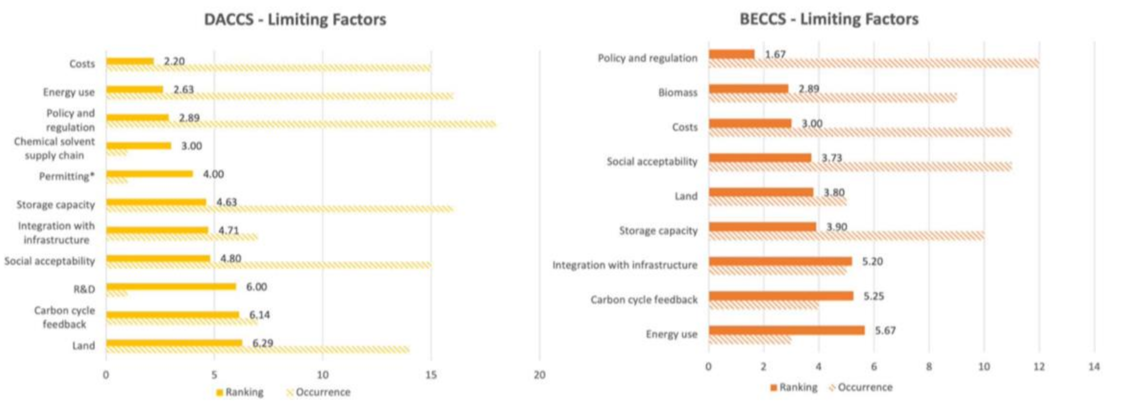


Figure 10: Limiting Factors based on expert interviews conducted within the H2020 project NEGEM[12]

[12] H2020 Project NEGEM https://www.negemproject.eu/

4.2 Consequences of further BECCS implementation

This chapter draws from the literature research on key figures and the assessment on biogenic CO_2 potentials from different key sectors in Europe. In the following basic modelling principles have been applied to quantify CO_2 mitigation benefits as well as financial and energetical consequences from BECCS implementation.

4.2.1 Basic modelling of CO_2 mitigation benefits from BECCS

The overall biogenic CO_2 emitted by the selected industry sectors-(**Retrofitting CCS into existing biomass-based industries-** account for about 221.7 million tons of CO_2 per year (see Table 4-1). For assessing the potential for BECCS also the capture rate of CO_2 at the plant as well as the implementation rate of carbon removal technologies have to be considered. Figure 11 illustrates the potential of BECCS in dependence of the implementation rate assuming a capture rate of 95%. With the sectors considered in this report, an implementation rate of 38% would be required to reach this target.

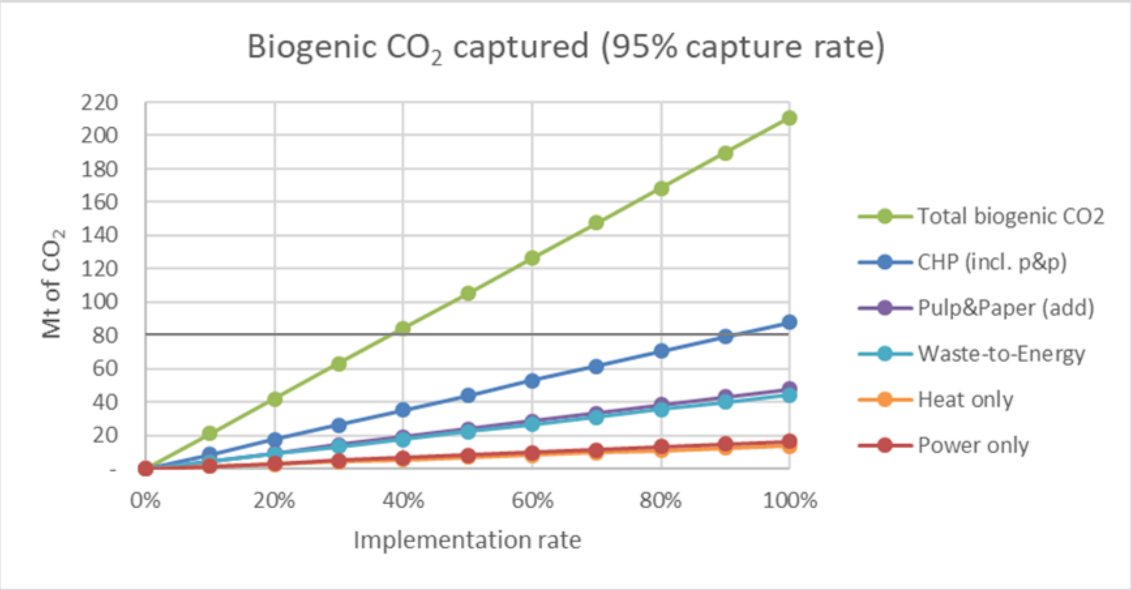


Figure 11: BECCS potential depending on the implementation rate with a capture rate of 95%

When assuming an implementation rate of 38% over all selected industry sectors, 80.06 $MtCO_2$/year can be captured. An implementation rate of 50% would lead to a capture of biogenic CO_2 of about 105 $MtCO_2$/year.

4.2.2 Energy quantification

This chapter presents examples of the implementation of carbon capture technologies (BECCS and DACCS). The energy balances were derived from literature and depicted as Sankey diagrams. These give an indication of the energy penalty/demand for the capture of 1 tCO_2.

The energy balances for an exemplary CHP plant with and without the implementation of MEA are depicted in Figure 12 (in total numbers and percentages). These examples show the energy penalty for the capture of 1 tCO_2. In both cases, 891 kg of biomass with a water content of 30% is required. It can be seen that the heat penalty in case of MEA is considerable, as around 50% of the heat generated is lost. Therefore, the use of MEA can be advantageous, especially for power-only plants. Figure 13 shows the implementation of MEA in biomass power only plant. In this case, it is assumed that the heat demand can covered by waste heat. As described in chapter 3.1, an additional heat pump can increase the overall efficiency of a CHP plant by enabling the utilization of waste heat.

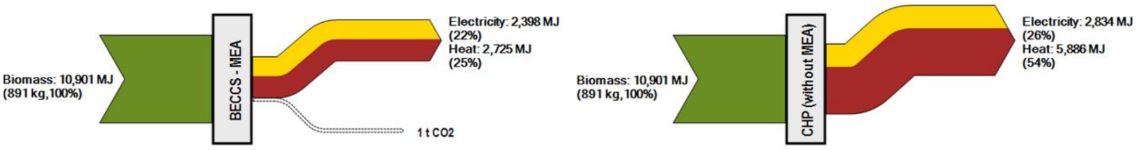


Figure 12: Example MEA implementation - left illustration, compared with the same CHP plant without carbon capture – right illustration (own illustrations, data from Pröll 2019)

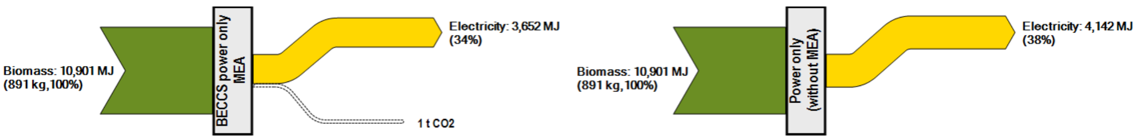


Figure 13: Example MEA implementation in a power only plant - left illustration, compared with the same power only plant without carbon capture – right illustration (own illustrations)

Figure 14 shows another exemplary CHP plant, with and without the implementation of the Hot Potassium Carbonate technology (HPC). For HPC the heat penalty can almost be avoided, but requires heat recovery at rather low temperatures. Thus, when implemented in a CHP plant, a 3rd generation district heating network[13] is required. This kind of district heating network allows for waste heat utilization, leading to higher heat efficiency, but with a lower temperature level. The temperature of the waste heat is higher compared to MEA, where its utilization would only be

[13] The 3rd generation of District heating networks (3GDHNs) can be defined by not requiring superheated water for its operation. The IEA DHC ExCo suggests using the term for heat networks operating between 100 °C and 70 °C.

possible with an additional heat pump. However, the implementation of HPC leads to a power penalty.

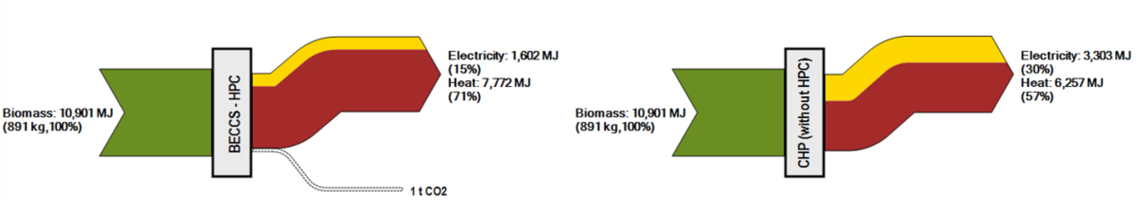


Figure 14: Example HPC implementation – left illustration, compared with the same CHP plant without carbon capture – right illustration (own illustrations, data from Gustafsson 2021)

For comparison, the energy balances of two different exemplary DACCS approaches for capturing 1 tCO_2 are shown in Figure 16 (heat and power, solid sorbent) and Figure 16 (natural gas, liquid solvent). In contrast to BECCS, DACCS is a stand-alone system that does not generate any energy. The energy demand must be covered by another source, which it is why it is not referred to as an energy penalty. Due to a lack of data availability of reference plants, the indications for the energy demand varies significantly in literature, see Table 3-1. As described in chapter 2, there are two common approaches for DACCS, capturing CO_2 with either solid sorbents or liquid solvents. When using solid sorbents, heat and electricity are drawn from the power grid using an industrial heat pump. Alternatively, also geothermal heat can be used. As for the liquid solvents, high-grade heat is supplied by natural gas or hydrogen.

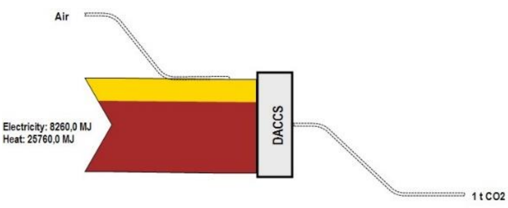


Figure 15: Example DACC implementation with heat and power (own illustration, data from Zerobin 2020)

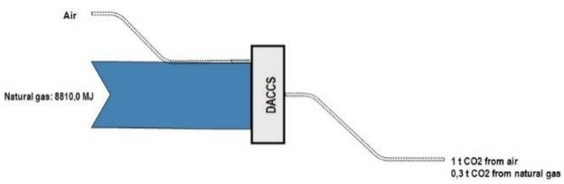
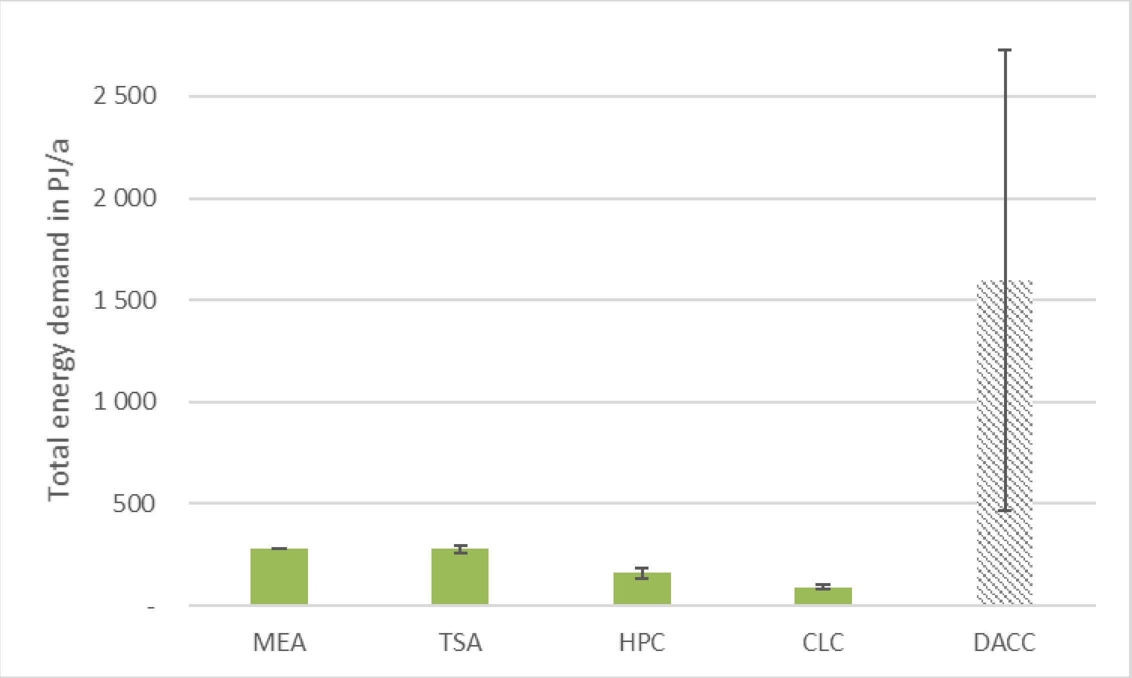


Figure 16: Example DACC implementation with natural gas (own illustration, data from Keith 2018)

When modelling a scenario with a potential of 221.7 million tons of biogenic CO_2 per year (see Table 4-1), a capture rate of 95% and an implementation rate of 38%, about 80 $MtCO_2$/year of biogenic CO_2 can be captured, which corresponds to the 2040 BECCS target described in chapter 4.2.1. (Figure 17). The green bars show the total energy demand for capturing 80.06 $MtCO_2$ with one of the selected carbon capture technologies, based on the described scenario and assumptions. When applying MEA technology with an energy penalty of about 3.5 MJ/kg CO_2, the energy penalty account for about 280 PJ/a. The lowest energy penalties are to be expected with the implementation of CLC, amounting to 92 PJ/a (± 12). The highest energy demands, but also the greatest uncertainties, occur when applying DACCS, accounting for about 1,595 PJ/a (± 1,130). Whereas BECCS is capturing CO_2 from flue gas with a comparably high CO_2 concentration, DACCS is capturing CO_2 from the atmosphere with a low CO_2 concentration, which is reflected in the overall energy demand of the process. As DACCS is an autonomous system that does not generate energy, the energy requirement must be covered from other sources.



Explanations: MEA = Monoethanolamine, TSA = Temperature Swing Adsorption, HPC = Hot Potassium Carbonate, CLC = Chemical Looping Combustion, DACC = Direct Air Carbon Capture

Figure 17: Total energy demand for capturing 80 $MtCO_2$ in PJ/a per technology (38% implementation rate, 95% capture rate)

It has to be noted that these energy penalties decrease the overall provision of bioenergy in the EU, since the present study is only taking existing facilities into account. With this assumption there is no additional biomass demand since there are no additional capacities, but bioenergy is decreased by the energy penalty. In contrast, implementing DACCS requires additional energy demand.

4.2.3 Financial quantification

In the following, two case studies are being described to show examples of the economic consequences of implementing BECCS technologies. For both case studies a 10 MW CHP plant was assumed, with an efficiency of 26%$_{el}$ and 54%$_{th}$ for MEA (Pröll, 2019) and 30%$_{el}$ and 57%$_{th}$ for HPC (Gustafsson, 2021). It was calculated with the following energy costs for the plant operators: 10 €ct/kWh power and 3 €ct/kWh heat. Green bars show the revenues from heat and power without BECCS implementation. Blue bars show the losses caused by the energy penalty when implementing MEA (Figure 18) or HPC (Figure 19). The grey bars show the revenue of the CHP plant decreased by the energy penalty and the revenue from CO_2 certificates (dashed bar) needed to compensate for the energy penalty only. The CO_2 certificate would need to reach 40€/t CO_2 for MEA and 50€/t CO_2 for HPC implementation only to compensate for the lower turnover of the bioenergy plant. It has to be stated that this is a simplified approach without considering other costs then for energy (CAPEX, non-energy related OPEX and costs for maintenance, transport and storage are not being included), resulting in a minimum requirement for CO_2 certificates, only to compensate for the energy penalties.

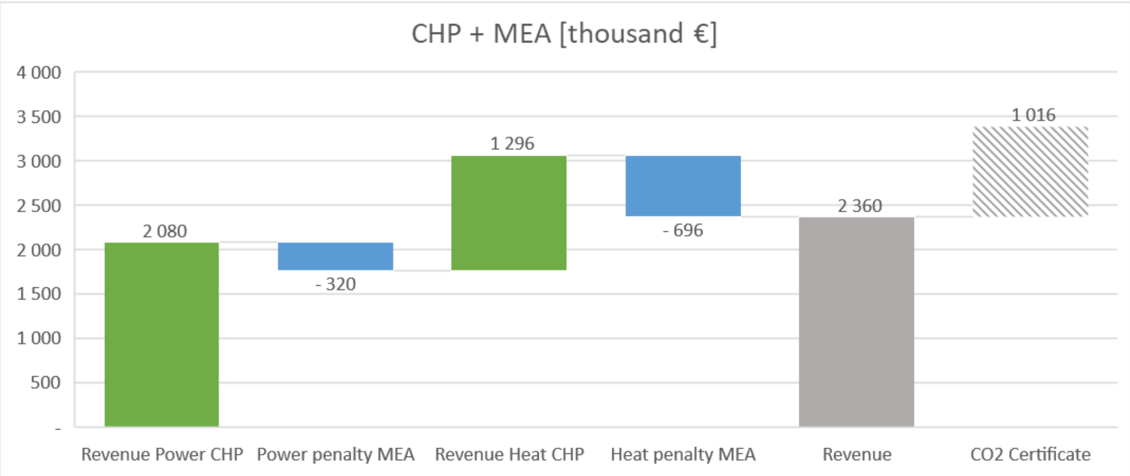


Figure 18: Case study MEA implementation (simplified approach) – Minimum revenue from CO_2 certificates to compensate for the lower turnover of the bioenergy plant due to energy penalties

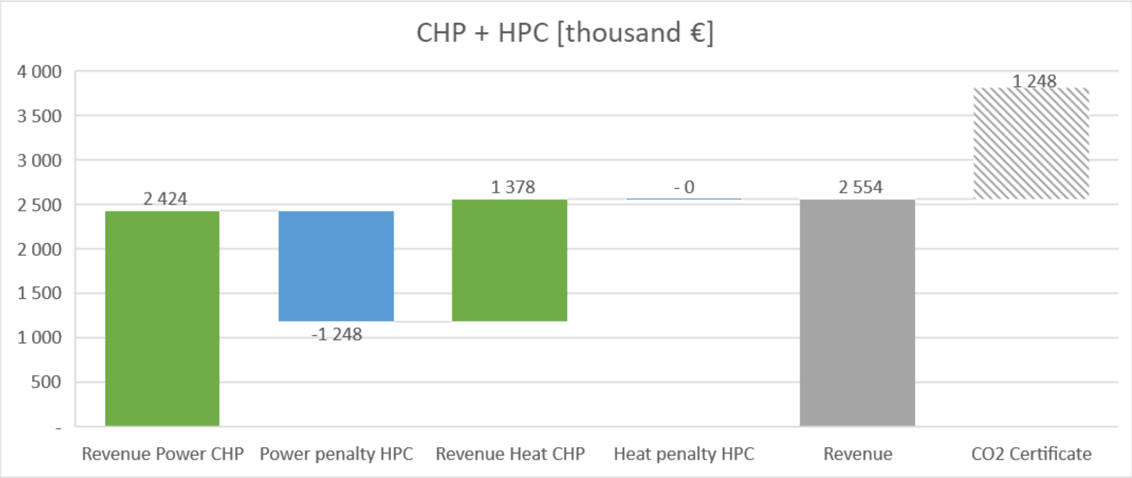
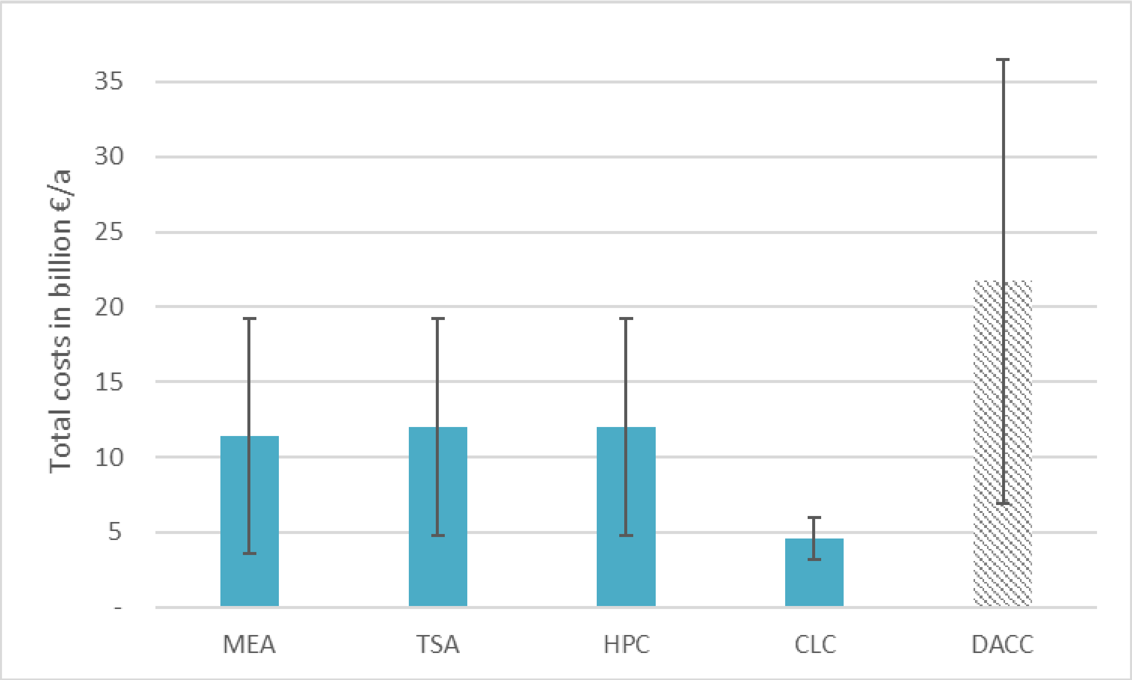


Figure 19: Case study HPC implementation (simplified approach) – Minimum revenue from CO_2 certificates to compensate for the lower turnover of the bioenergy plant due to energy penalties

With a potential of about 221.7 Mt biogenic CO_2 (see Table 4-1) and assuming an implementation rate of 38% and a capture rate of 95%, a total of 80.06 Mt of biogenic CO_2 can be captured per year, which corresponds to the 2040 BECCS target described in chapter 4.2.1. The capture costs are depending on the technology used. As can be seen in Figure 20, the uncertainties and thus the ranges for the capture costs are high. When applying MEA technology with costs between 44 and 240 €/tCO_2 (see Table 3-2), the total costs for capturing 80.06 MtCO_2/year account for 11.4 billion € (± 7.8). One promising technology regarding costs could be CLC (though currently only TRL 5-6), the least favourable seems to be DACCS. The scenario simplifies by assuming that all biogenic CO_2 is captured with one technology respectively. Based on the described scenario and assumptions, the total costs for capturing 80.06 Mt of biogenic CO_2 are between 4.6 and 12 billion €/a for BECCS (depending on the capture technology) and 21.7 billion €/a (± 14.8) for DACCS. The costs can be reduced, for example, by using advanced amines (Nessi et al. 2021, McDonagh et al. 2024), optimizing process parameters or integrating a heat pump to increase the overall efficiency of the system.



Explanations: MEA = Monoethanolamine, TSA = Temperature Swing Adsorption, HPC = Hot Potassium Carbonate, CLC = Chemical Looping Combustion, DACC = Direct Air Carbon Capture

Figure 20: Total costs for capturing 23.2 $MtCO_2$ in PJ/a per technology (10% implementation rate, 95% capture rate)

5 Main bioenergy carbon capture projects in Europe

There are several bioenergy carbon capture projects ongoing in Europe, an overview is shown in Table 5-1. For example, **Stockholm Exergi** (SE) plans for a facility that can capture 800,000 tonnes of CO_2 each year at the combined heat and plant in Värtan. In January 2025, Stockholm Exergi has been awarded more than $1.8 billion in the reverse auction for BECCS launched by the Swedish Energy Agency.

As of 2024, in addition to coal **Amer and Eemshaven (RWE, NL)** power plants are running on organic residuals (biomass) which account for an 80% and 20% share of fossil fuel, respectively. The project is currently in the design phase. Licence applications are submitted. Both Amer and Eemshaven power plants could be fully converted by 2029. By 2030 a 100% biomass as well as the operating start of the carbon capture unit should be realized. The project is currently in the permission stage for BECCUS.

Table 5-1: Overview Main BECCUS projects in Europe, Source: Henning C., Bang C., et al. 2024, IEA Bioenergy

Project/company	Location	Type of primary energy facility	Facility capacity	Feedstock	Capture biogenic CO_2 Mt/a	Completion planned
Eemshaven/RWE	Netherlands	Currently co-firing (15%); planned in 2030: 100% biomass	2 x 785 MW_{el}	Hard coal, wood pellets, agropellets	8-10	2030
Amer/RWE	Netherlands	Currently co-firing (80%), planned in 2025: 100% biomass	645 MW_{el} 350 MW_{th}	Hard coal, wood pellets, agropellets	3-4	2030
Asnaes CHP Station Kalundborg/ Orsted	Denmark	Biomass combustion	25 MW_{el} 129 MW_{th}	Wood chips	0.28	2025
Avedare Power Station Kopenhagen /Orsted	Denmark	Biomass combustion	757 MW_{el} 918 MW_{th}	Straw, pellets	0.15	2025
Amagervaerket 4/ Hofor	Denmark	Biomass combustion	150 MW_{el} 415 MW_{th}	Wood chips	0.9	Tbd
BECCS Stockholm/ Stockholm Exergi	Sweden	Biomass combustion	130 MW_{el} 280 MW_{th}	Wood chips	0.8	2027
Jordbro/Vattenfall	Sweden	Biomass combustion	279 MW_{el} 20 MW_{th}	Wood chips, waste wood	0.5	2028
Klemetsrud/Hafslund Celsio	Norway	Waste-to-energy (50% biogenic share)	55.4 MW_{el} 10.5 MW_{th}	Municipal waste, waste from industry	0.2	2026
Drax Power Station	United Kingdom	Biomass combustion	2.6 GW_{el}	Wood pellets	8	First unit 2030, second unit 2031/32

At **Ørsted**, from end 2025 430.000 tonnes of CO_2 from two of heat and power plants should be captured and stored in the North Sea. The carbon capture units are supplied by Aker Carbon Capture to capture around 280.000 tonnes of CO_2 per year at the woodchip-fired Asnæs Power Station in Kalundborg and around 150.000 tonnes of CO_2 per year at the Avedøre Power Station in Greater Copenhagen. The capture units absorb the CO_2 with amine solvents, separating it from the flue gas from the heat and power plant. The CO_2 is then purified, compressed, and liquefied ready for transport. Until a pipeline is available, the CO_2 captured from Avedøre Power Station in Greater Copenhagen will be transported by truck to Asnæs Power Station in Kalundborg. Northern Lights will then ship the CO_2 from Kalundborg to their onshore terminal in Øygarden, Norway.

Asnæs Power Station will serve not only as a hub for shipping their CO_2, but potentially also for shipping CO_2 from other emitters. From the Northern Lights onshore storage facilities in Øygarden, Norway, the CO_2 will be pumped through a subsea pipeline to the Aurora storage complex around 100 km offshore. The CO_2 will be injected into the storage complex, which is a 2.6 km deep saline aquifer. The aquifer has two primary storage units (sand reservoirs) and an overlaying sealing layer (cap rock) that ensures the CO_2 containment. The sand reservoirs have pore space between a rock framework, and this porous space is currently filled with brine (saline water). The CO_2 will displace the brine and stay trapped in the porous space, where a small portion will mineralise, some of it will dissolve in the brine, and most of it will be permanently structurally trapped.

The carbon removals are certified by an independent third party under the VERRA standard. Microsoft has agreed to purchase 3.67 million tonnes of certified carbon removal. This will help Microsoft meet their climate commitments. The Danish Energy Agency has awarded a 20-year subsidy contract for Ørsted Kalundborg CO_2 Hub[14].

[14] For more details: https://orsted.com/en/what-we-do/renewable-energy-solutions/bioenergy/carbon-capture-and-storage

6 SWOT analysis

STRENGTHS	WEAKNESSES
• Carbon removal technology that produces energy • Allows for carbon negativity in EU Carbon Removals and Carbon Farming Certification (CRCF) Regulation • Effectively addresses point sources with higher CO_2 concentrations in flue gas streams, enhancing capture efficiency) • Can be retrofitted in existing bioenergy plants • Retrofitting maintains existing installations and jobs supporting a just energy transition • Availability of a market mature CDR - technology (e.g. MEA) • Cheaper compared to other carbon removal technologies (e.g. DACCS), at least in the EU (dependent on energy costs) • Offers the potential for CO_2 to be either permanently stored or utilized in industrial processes in the future	• Absence of clear mechanisms to account for the costs of carbon capture in current markets. Carbon removal requires energy, resulting in energy loss (heat/electricity penalty) • Limited reference plants, therefore weak data basis for realistic CAPEX and OPEX • Low TRL for some Carbon Capture - technologies • Retrofitting may be limited by physical space constraints in existing facilities. • Many industries do not yet integrate carbon removal into their business models or strategies. • Solvent degradation products (e.g. aerosols) of some capture approaches
OPPORTUNITIES	**THREATS**
• Offers a significant tool for achieving emission reduction and climate neutrality goals. • Possibility to decarbonize the industry • Supported by strategies and roadmaps (from some countries and initiatives) • Energy loss can lead to further process improvement and optimization, for instance use of recovered heat as district heat • Potential development of markets for CO_2 removal certificates or credits could provide financial incentives. • Feedstock diversification allows for implementing the technology in different sectors (e.g. pulp and paper industry) • A high carbon price could encourage market development and overcome or at least reduce threats and weaknesses • Applying BECCS in Combined Heat and Power (CHP) plants may improve the economic viability of bioenergy.	• High CO_2 storage and transport costs could have a negative impact on business development • The carbon removals market is still nascent and not yet integrated into compliance markets like the EU ETS. • Lack of sufficient infrastructure for CO_2 pipelines and storage could delay deployment. • Negative public perception (e.g. concerns about large plants and leaks during transport and storage) • Increasing demand for biomass (to substitute energy penalty) can lead to feedstock competition • Lack of clear policy and regulatory framework and thus policy support (e.g. no incentives in compliance carbon market) • Potential misalignment between frameworks like CRCF and RED III could complicate the calculation of carbon removal certificates. • Insufficient understanding among policymakers about the role of bioenergy and BECCS in achieving climate neutrality.

7 Policy Recommendations

1. Ensure regulatory stability to encourage investment in BECCS

The European Union should prioritize the consistent and predictable implementation of the existing legal framework, ensuring that regulations are applied uniformly, non-discriminatorily, and proportionately. For example, instead of introducing new limitations on biomass usage for BECCS applications under CRCF or other Directives and Regulations, the focus should be on the effective and coherent enforcement of the sustainability criteria already established under the Renewable Energy Directive. This will provide investors with the long-term certainty needed to commit to BECCS projects, avoiding unnecessary regulatory shifts that could increase investment risks and hinder deployment. Furthermore, it is essential to recognize the significantly different economic and environmental value of BECCS compared to other energy uses, ensuring that policies reflect its unique role in achieving carbon removals and long-term climate objectives.

2. **Develop a Compliance Market for Carbon Dioxide Removals to support demand**

To unlock large-scale investment in BECCS, the EU must establish a compliance market(s) for permanent carbon removals. This would create stable and predictable demand, ensuring a long-term revenue stream beyond the current reliance on government subsidies and the Voluntary Carbon Market (VCM). A well-structured compliance market would uphold the polluter-pays principle, making carbon removals an integral part of the EU's climate strategy while addressing the current funding gaps that hinder deployment.

3. **Establish Separate Targets for different types of Carbon Removals and differentiate from Emission Reductions**

The European Union should set a distinct carbon removal target separate from gross emission reductions, further differentiating between permanent and temporary removals. This approach aligns with the like-for-like principle, which requires that fossil fuel emissions be balanced exclusively with permanent carbon removals, as defined by the CRCF. By reinforcing this principle, the EU would ensure that climate compensation claims maintain integrity, preventing organizations from offsetting fossil CO_2 emissions with short-term removals.

By distinguishing between these types of removals and embedding the like-for-like principle into climate policy, the EU would send a strong market signal, fostering investment in high-integrity, permanent CDR solutions like BECCS. This structured approach is the only way to achieve durable net zero—a state where carbon sources and sinks are balanced over appropriate time scales, ensuring the EU's long-term climate goals remain scientifically robust and environmentally effective.

4. Develop robust CO_2 transport and storage infrastructure

The EU must invest in the development of a robust CO_2 transport and storage infrastructure. This includes mapping geological (potential) storage sites, establishing cross-border CO_2 pipelines, and creating strategic reserves. A well-developed infrastructure is critical for the efficient deployment of BECCS projects across member states.

5. **Integrate BECCS into National Energy and Climate Plans (NECPs)**

The European Union should establish a comprehensive plan for the integration of Carbon Dioxide Removal (CDR) strategies, including Bioenergy with Carbon Capture and Storage (BECCS), into its climate policy framework. This should be supported by Member States through the incorporation of CDR measures into their National Energy and Climate Plans (NECPs). Such an approach would ensure that CDR solutions contribute effectively to defossilisation efforts, particularly in hard-to-abate sectors, while fostering a coordinated EU-wide strategy.

6. **Align corporate Green Claims with permanent carbon removals to support private investment**

The Green Claims Directive should encourage corporate investments in permanent carbon removals by allowing companies to make compensation claims for their acquisition of high-quality BECCS credits, not only for neutralizing residual emissions at the point of net-zero but also in the transition towards it. The EU must provide clear guidance on how companies can make compensation claims before reaching net-zero, ensuring that voluntary private sector funding can effectively support the early development of BECCS projects and contribute to the EU's climate objectives. With the absence of compliance markets for yet many years, it is essential that EU policy encourages and leverages the participation of the voluntary markets to enable the early build out of the permanent removals industry.

7. **Enhance public awareness and stakeholder engagement**

Raising public awareness about the benefits and safety of BECCS is essential for its acceptance and implementation. The EU should conduct educational campaigns and engage stakeholders, including local communities, to build trust and address concerns related to BECCS technologies.

8. **Need for increased EU Funding and Support**

EU funding for BECCS should be increased, with a focus on supporting the deployment of pre-commercial plants to enhance cost efficiency and accelerate market readiness. While BECCS technologies have reached high technology readiness levels (TRL), structural barriers—such as fragmented access to funding, administrative burdens, and restrictive eligibility criteria—continue to hinder large-scale implementation. Direct funding for Carbon Dioxide Removal (CDR) remains minimal, and existing R&D support does not sufficiently address the need for investment in near-commercial projects.

To bridge this gap, the EU should streamline funding mechanisms, simplify administrative processes, and establish targeted financial instruments to de-risk investments and facilitate the scale-up of BECCS across Member States. Additionally, enabling the stackability of different funding options—such as subsidies, EU ETS credits, and voluntary carbon market (VCM) revenues—can create more financial flexibility and security for CDR projects, making them more economically viable and attractive to investors. This should be done with appropriate accounting rules and state aid controls to prevent overcompensation while ensuring an effective and balanced support framework.

9. **Re-evaluating the Cascading Principle in light of BECCS/U**

Given the evolving role of Bioenergy with Carbon Capture and Storage/Utilization (BECCS/U) in achieving climate goals, we recommend considering the implications of BECCS/U when applying the cascading principle under the Renewable Energy Directive (REDIII). The current framework assumes that biogenic carbon is lost after combustion, positioning bioenergy at the lower end of the hierarchy. However, BECCS/U challenges this assumption by either enabling the reutilization of biogenic carbon, as in the case of BECCU, or delivering permanent climate benefits through carbon sequestration that outlasts harvested wood products, as in the case of BECCS.

10. **Strengthening Cross-Border Cooperation and International Carbon Markets for Effective Carbon Removal**

To ensure the effectiveness and scalability of Carbon Dioxide Removal (CDR) in the EU, it is essential to recognize the role of cross-border cooperation and international carbon markets. Given the limited availability of permanent CDR solutions within Europe, facilitating the use of high-integrity international credits is crucial for meeting demand while maintaining environmental integrity.

The EU should support transnational collaboration in CO_2 transport and storage infrastructure to optimize resource allocation and facilitate the deployment of large-scale CDR projects. This includes enabling joint initiatives between EU Member States and third countries, ensuring compatibility with the broader international carbon market framework.

11. **Accelerate the deployment of BECCS to reach the 2040 Climate targets**

By aiming for an implementation rate of 38% for BECCS deployment, aligned with a 95% carbon capture efficiency, 80 Mt of CO_2 could be captured and stored long-term, helping to meet industrial removal targets set in the 2040 impact assessment. To achieve this, the EU should further develop targeted incentives, financing mechanisms, and regulatory frameworks that prioritize BECCS integration in bioenergy-related industries. Additionally, increasing efforts beyond the 38% implementation rate would further enhance the mitigation potential of bioenergy, providing additional negative emissions crucial for achieving climate neutrality.

8 List of Figures and Tables

8.1 List of Figures

8.2 List of Tables

9 References

Anwar, M.N., Fayyaz, A., Sohail, N.F., Khokhar, M.F., Baqar, M., Khan, W.D., Rasool, K., Rehan, M., Nizami, A.S., 2018: CO_2 capture and storage: a way forward for sustainable environment. Journal of Environmental Management, https://doi.org/10.1016/j.jenvman.2018.08.009

Barlow, H., Shahi, S.S.M., Kearns, D.T., 2025: Advancements in CCS Technologies and Costs, Global CCS Institute, https://www.globalccsinstitute.com/resources/publications-reports-research/advancements-in-ccs-technologies-and-costs/

Ben-Mansour, R., Habib, M.A., Bamidele, O.E., Basha, M., Qasem, N.A.A., Peedikakkal, A., Laoui, T., Ali, M., 2016: Carbon capture by physical adsorption: materials, experimental investigations and numerical modeling and simulations–a review. Applied Energy 161, 225–255, https://doi.org/10.1016/j.apenergy.2015.10.011

Budinis, S., Krevor, S., Mac Dowell, N., Brandon, N., Hawkes, A., 2018: An assessment of CCS costs, barriers and potential, Energy Strategy Reviews, Volume 22, 2018, Pages 61-81, https://doi.org/10.1016/j.esr.2018.08.003.

Castellanos et al. 2022: Carbon dioxide removal taxonomy. in Castellanos, E., M.F. Lemos, L. Astigarraga, N. Chacón, N. Cuvi, C. Huggel, L. Miranda, M. Moncassim Vale, J.P. Ometto, P.L. Peri, J.C. Postigo, L. Ramajo, L. Roco, and M. Rusticucci, 2022: Central and South America. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1689–1816, doi:10.1017/9781009325844.014.

d´Amore, F., Romano, M., Bezzo, F., 2021: Carbon capture and storage from energy and industrial emission sources: A Europe-wide supply chain optimisation, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2020.125202

EBA, European Biogas Association, Statistical Report 2024, Tracking biogas and biomethane deployment across Europe, URL: https://www.europeanbiogas.eu/eba-statistical-report-2024/

EC, European Commission 2024, Commission staff working document, impact assessment report, Part 1, Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society, URL; https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52024SC0063

EEA, European Industrial Emission Portal, Industrial reporting dataset, URL: https://industry.eea.europa.eu/download

Fleiß, B., Priscak, J., Hammerschmid, M., Fuchs, J., Müller, S., Hofbauer, H., 2021: CO_2 capture costs of chemical looping combustion of biomass: A comparison of natural and synthetic oxygen carrier, Journal of Energy Chemistry, Volume 92, 2024, Pages 296-310, https://doi.org/10.1016/j.jechem.2024.01.048

Garðarsdóttir, S., De Lena, E., Romano, M., Roussanaly, S., Voldsund, M., et.al., 2019: Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis, Energies, https://doi.org/10.3390/en12030542

H2020 Project NEGEM: Quantifying and Deploying Responsible Negative Emissions, URL: https://www.negemproject.eu/ , https://www.negemproject.eu/wp-content/uploads/2024/05/DACCS.pdf

Hussin, F., Kheireddine Aroua, M., 2020: Recent trends in the development of adsorption technologies for carbon dioxide capture: A brief literature and patent reviews (2014–2018), Journal of Cleaner Production, Volume 253, 2020, 119707, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2019.119707

IEA, 2024: Bioenergy with Carbon Capture and Storage, Website, URL: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage#overview (visited on 13 March 2024)

IEA, 2010: CCS Technology Roadmap, URL: https://nachhaltigwirtschaften.at/resources/iea_pdf/ccs_technology_roadmap.pdf

IEAGHG, 2021: Global Assessment of Direct Air Capture Costs, URL: https://ieaghg.org/publications/global-assessment-of-direct-air-capture-costs/

Keith, D., Holmes, G., Angelo, D., Heidel, K., 2018: A Process for Capturing CO_2 from the Atmosphere, Joule, https://doi.org/10.1016/j.joule.2018.05.006

Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M., 2014: An overview of current status of carbon dioxide capture and storage technologies. Renewable Sustainable Energy Rev. 39, 426–443, https://doi.org/10.1016/j.rser.2014.07.093

Mannion, P., Parry, E., Patel, M., Ringvold, E., Scott, J., 2023: Carbon removals: How to scale a new gigaton industry by McKinsey, URL: https://www.mckinsey.com/capabilities/sustainability/our-insights/carbon-removals-how-to-scale-a-new-gigaton-industry

McDonagh, J.L., Zavitsanou, S., Harrison, A., Zubarev, D.,van Kessel, T., Wunsch, B.H.,Cipcigan, F. Chemical space analysis and property prediction for carbon capture solvent molecules. Digital Discovery, 2024, 3,528. DOI: 10.1039/d3dd00073g

Nessi, E., Papadopoulos, A.I., Seferlis, P., 2021: A review of research facilities, pilot and commercial plants for solvent-based post-combustion CO2 capture: Packed bed, phase-change and rotating processes, International Journal of Greenhouse Gas Control, Volume 111, 2021, 103474, ISSN 1750-5836, https://doi.org/10.1016/j.ijggc.2021.103474

Pröll, T., Zerobin F., 2019: Biomass-based negative emission technology options with combined heat and power generation, Mitigation and Adaptation Strategies for Global Change, https://doi.org/10.1007/s11027-019-9841-4

Raza, A., Gholami, R., Rezaee, R., Rasouli, V., Rabiei, M., 2019: Significant aspects of carbon capture and storage – A review, Petroleum, Volume 5, Issue 4, 2019, Pages 335-340, ISSN 2405-6561, https://doi.org/10.1016/j.petlm.2018.12.007

Rosa, L., Sanchez, D. L. and Mazzotti, M., 2021: Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe, Energy & Environmental Science, https://doi.org/10.1039/D1EE00642H

Samanta, A., Zhao, A., Shimizu, G.K.H., Sarkar, P., Gupta, R., 2012: Post-combustion CO_2 capture using solid sorbents: a review. Ind. Eng. Chem. Res. 51 (4), 1438–1463, https://doi.org/10.1021/ie200686q

Shahbaz M., AlNouss A., Ghiat I., Mckay G., Mackey H., Elkhalifa S., Al-Ansari T., 2021: A comprehensive review of biomass based thermochemical conversion technologies integrated with CO_2 capture and utilisation within BECCS networks, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2021.105734

Sievert, K., Schmidt, T., Steffen, B., 2024: Considering technology characteristics to project future costs of direct air capture, Joule, https://doi.org/10.1016/j.joule.2024.02.005

Slavin, B., Wang, R., Roy, D., Ling-Chin, J., Roskilly A., 2023: Techno-economic analysis of direct air carbon capture and hydrogen production integrated with a small modular reactor, Applied Energy, https://doi.org/10.1016/j.apenergy.2023.122407

Strengers, B., Matthews, R., Berndes, G., Cowie, A., Laganière, J., 2024: On the Science of Carbon Debt. PBL Netherlands Environmental Assessment Agency, https://www.pbl.nl/en/publications/on-the-science-of-carbon-debt#specifications

Sun, Y., Dong, B., Wang, L., Li, H., Thorin, E., 2022: Technology selection for capturing CO2 from wood pyrolysis, Energy Conversion and Management, https://doi.org/10.1016/j.enconman.2022.115835

Vega, Fernando & Cano, Mercedes & Camino, Sara & Gallego Fernández, Luz M. & Portillo, Esmeralda & Navarrete, Benito. (2018). Solvents for Carbon Dioxide Capture. 10.5772/intechopen.71443.

von Scheele, J., 2022: Oxyfuel Combustion with Hydrogen in the Steel, Non-Ferrous, and Glass Industries.

Wilk, V., Leibetseder, D., Zauner, C., Rath, A., & Schwaiger, M. (2024). Improving Energy Efficiency of Carbon Capture Processes with Heat Pumps. In *International Sustainable Energy Conference - Proceedings, 1* (International Sustainable Energy Conference - Proceedings). https://doi.org/10.52825/isec.v1i.1083

Zerobin, F., Pröll, T., 2020: Concentrated Carbon Dioxide (CO2) from Diluted Sources through Continuous Temperature Swing Adsorption (TSA), Industrial & Engineering Chemistry Research, https://doi.org/10.1021/acs.iecr.9b06177