Bioenergy with Carbon Capture and Storage (BECCS)

WBA Factsheet

SUMMARY

Bioenergy with Carbon Capture and Storage (BECCS) is an essential technology for reducing global greenhouse gas (GHG) emissions. BECCS is a multifaceted supply chain that has the advantage of enabling negative emissions whilst generating energy. Its versatility is illustrated by the possibility of using the full range of biomass feedstocks and many conversion pathways. BECCS is also a highly adaptable technology in that it can be applied to a variety of industries: power and heat plants, biofuel plants, waste-to-energy plants, biogas plants, and even heavy industry. Once the carbon dioxide (CO_2) has been captured, it must then be transported and stored, or even reused. However, reuse can sometimes result in no negative emissions, as the CO_2 is released into the atmosphere in the short term. This chain involves extensive logistics and costs, which is important to be considered in the entire value chain. Incentives and supportive policies are essential to the development and sustainability of this technology. In a context where limiting global warming has become a matter of urgency, BECCS projects need to be encouraged and supported to ensure that they can continue to meet the challenges of the future.

INTRODUCTION

Since the industrial revolution, with the exponential growth of human activities such as fossil fuel combustion and deforestation, there has been a significant increase in greenhouse gas emissions. This increase is the main contributor to climate change, encompassing global warming leading to extreme weather events, the displacement of living beings, rising seas, etc[1]. Responsible for 3/4th of emissions, CO_2 is the main contributor to climate change[2]. Since 1970, CO_2 emissions have risen by around 90%[3]. The Kyoto Protocol and Paris Climate Agreement (2015) aim to coordinate global action to reduce GHG emissions.[4] Technologies to reduce GHGs in the atmosphere already exist.

DEFINITION

Carbon Capture and Storage (CCS) includes technologies that capture CO_2 and then safely store it underground".[5] Thus, CCS applied to energy generation from biomass-based sources is called Bioenergy with Carbon Capture and Storage (BECCS). On the other hand, carbon dioxide can also be used (instead of storing underground), for example in aviation fuel or beverages, in which case it is referred to as CCU. The technologies deployed for capturing CO_2 and the infrastructure needed for transporting and storing CO_2 are the same for CCS and BECCS. The major difference between the two is that BECCS not only removes CO_2 but also generates electricity.[6] Since the Paris Agreement and the pressing need to limit global warming to below 1.5°C, interest in BECCS has been growing. It is a key technology[7] for reducing emissions already in the atmosphere, which will be required until there is a "balance between anthropogenic emissions by sources and removals by sinks".[8]

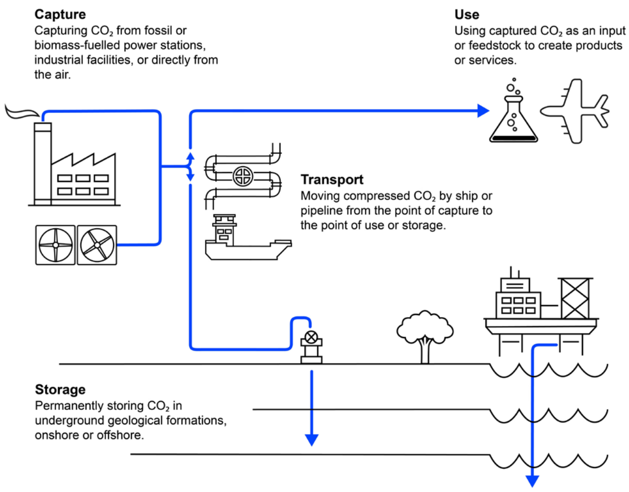

Figure 1 BECCS process. Source: IEA, link

PROJECTION SCENARIOS

The importance of BECCS is such that the technology is an integral part of most projected scenarios for limiting global warming. Projections have been provided by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC). In 2050, the IEA NZE scenario predicts that around 10% of total bioenergy will be equipped with CCS, which would represent 1.3 Gt of sequestered CO_2. Around 45% of this CO_2 is captured in biofuel production, 40% in the power sector, and the remainder in heavy industries, notably cement production. 18% of the 7.6 Gt of CO_2 to be captured would come from BECCS in 2050, and 95% of the total CO_2 captured would be stored, while the remainder would be used, notably to make fuels.[9]

The IPCC also publishes its projection scenarios. The two most recent scenarios are the IPPC 1.5 special report[10] and the Sixth Assessment Report.[11] SP1.5 forecasts a range of 0 to 10 Gt of CO_2 sequestered per year by BECCS for 2050, with a median of 5 Gt of CO_2. For AR6 WGIII, different pathways predict a CO_2 mitigation potential of between 0.5 and 11 Gt of CO_2.[12]

WHY A NEGATIVE EMISSION PROCESS?

The main advantage of BECCS and CCS in the fight against climate change is that they enable negative emissions to be achieved. This means that the process stores more CO_2 than is emitted.[13] Through photosynthesis, the plant captures carbon dioxide from the atmosphere. Then, when the biomass is transformed, by combustion or fermentation for example, the CO_2 emanating from the process is recovered and permanently stored underground instead of being released into the atmosphere.

1. Plants (organic matter) absorb CO_2 from the atmosphere as they grow through photosynthesis.
2. Biomass is transported to its combustion site. It is then converted into energy and other products through various processes. These may be power and/or heat production processes, liquid biofuels, or any other industrial process that produces high CO_2 streams from biomass feedstocks.
3. CO_2 is captured during the biomass conversion process.
4. Liquid CO_2 is transported to its destination for 2 conditions:
   - CO_2 is geologically stored, or
   - CO_2 is used. However, depending on the use, the climatic impact differs, and CO_2 is often emitted into the atmosphere with a delay. So, depending on use, zero emissions may be allowed rather than negative emissions.

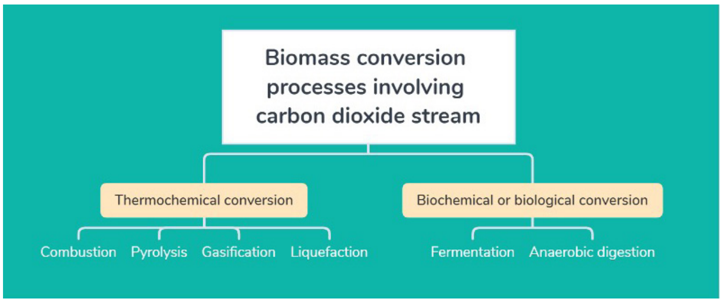

Figure 2 Summary of biomass conversion

BIOMASS CONVERSION

A variety of biomass feedstocks are available worldwide. Energy crops (corn, etc.), waste (used oil, municipal waste, food processing waste), and agricultural and forestry residues are all examples of biomass feedstocks. The conversion of these types of biomasses enables the production of biofuels, biogas, bioheat and bioelectricity.

Two main groups of biomass conversion processes involving a steady stream of carbon dioxide can be conventionally distinguished: the thermochemical conversion and the biological or biochemical conversion.

- **Thermochemical conversion** of biomass involves the creation of heat following a chemical reaction. Combustion, pyrolysis, gasification, and liquefaction allow the conversion of a wide variety of biomass.
  - ◊ **Combustion** allows the conversion of chemical energy contained in biomass into thermal energy directly for heating buildings and water or into electricity through moving turbines. This combustion takes place at temperatures between 800 and 1000°C, with devices such as ovens, stoves, boilers, steam turbines, etc, and biomass with low moisture content is preferred. The conversion also produces flue gases, including CO_2 which can be captured.
  - ◊ **Pyrolysis** consists in heating organic materials between 400 and 500°C, in the almost complete absence of free oxygen. The biomass can be converted into solid (biochar), liquid (bio-oil), or gaseous (biogas) products, and the CO_2 produced

Figure 3 POET and Navigator CO_2 Ventures BECCS project, USA. Source: POET, [link]

during conversion can be captured. The modulation of the process parameters creates three types of pyrolysis, fast pyrolysis, slow pyrolysis, and flash pyrolysis, for which it is possible to choose the type of biomass to adapt it to the final use.

◊ In the **gasification** process, biomass is thermally decomposed at high temperatures (between 800 and 900°C) with a controlled amount of gasification agents, such as steam, air, and O_2. The partial oxidation of biomass produces a gas mixture called syngas from which CO_2 can be isolated and captured. This syngas is rich in carbon monoxide (CO) and hydrogen (H_2) and is also composed of CO_2 (carbon dioxide), CH_4 (methane) and N_2 (nitrogen). Its composition depends on the use of gasification agents, the type of gasifier and other operating conditions (temperature, humidity level, etc.). It can be used directly as fuel, for heating or electricity (gas turbines). It can also be converted to produce certain chemicals as methanol, dimethyl ether, olefins, etc. Finally, it can be processed, by separating the hydrogen, by Fisher-Tropsch synthesis to create liquid fuels (gasoline, diesel, jet fuel, etc.), and by methanization to make synthetic natural gas (SNG).[14]

◊ During **liquefaction**, biomass is heated in a catalyst, usually in the presence of hydrogen, under conditions of low temperature (between 250 and 400°C) and high pressure. It leads to the production of oxygenated liquid fuels.[15]

- On the other hand, biochemical or biological conversion generally uses microorganisms and chemicals to produce or derive energy (ethanol and methane) and other products such as protein from organic biomass.

◊ **Fermentation** uses microorganisms to convert carbohydrates into alcohol. After crushing biomass (sugar cane, bagasse, sugar beet, crops, or lignocellulosic biomass), enzymes are used to convert the starch contained in this biomass into sugars. The sugar is then transformed into ethanol with the help of yeast. During the fermentation process, solid residues are created depending on the type of biomass used and can be used as animal feed, biomaterials, fuel for boilers or in the gasification or pyrolysis process, and gases, particularly the CO_2, can be extracted and captured.

Figure 4 Total Energies' Grandpuits site, France. Source : Total Energies, [link]

◊ **Anaerobic digestion** converts organic matter into biogas in an oxygen-free environment using bacteria. This biogas is composed mainly of methane, carbon dioxide (CO_2), and in smaller quantities of other gases such as hydrogen sulfide. By removing the CO_2, the resulting biomethane can be used for heating, in gas engines, in gas turbines to make electricity, or as fuel for natural gas vehicles.

CO2 CAPTURE FROM INDUSTRIAL EMISSIONS

Deploying BECCS to support keeping global warming below 1.5°C would, however, require a better understanding of the different capture technologies and their development. The scientific literature tends to distinguish several main approaches to carbon capture, such as pre-combustion, post-combustion, oxy-combustion, post-fermentation capture, and post-gasification capture. Within these approaches, different technologies are used to separate CO_2 from other elements and capture it, such as absorption or membrane separation. Some processes can be combined, and these techniques are adapted to specific parameters, such as the type of biomass or the type of production.

Indeed, capture technologies can be integrated into a wide range of industries.[16] Bioethanol production facilities are ideal because of the high concentration of CO_2 (about 99% purity) that can be captured. However, applications in pulp and paper mills are also favourable thanks to high CO_2 concentrations and the availability of excess heat that can be used in capture processes. Projects are also underway in power plants and waste-to-energy plants. Given that more than 2 billion tonnes of municipal solid waste are generated worldwide every yearvi, of which on average half is biogenic, this creates opportunities for the development of BECCS.[17] BECCS can also be an asset for decarbonizing heavy industry, in particular steel and cement plants, and the biochemicals industry, with hydrogen for example, or natural gas substitution (NGS) through methanization, which can incorporate a portion of biomass.[18]

CO2 CAPTURE DURING PROCESS

Carbon dioxide capture can appear in different ways in the bioenergy chain. Conventional ethanol currently represents the largest capacity of all biochemical production pathways where carbon capture is

Figure 5 KVA Linth WtE plant in Glarus, Switzerland. Source : KVA Linth, link

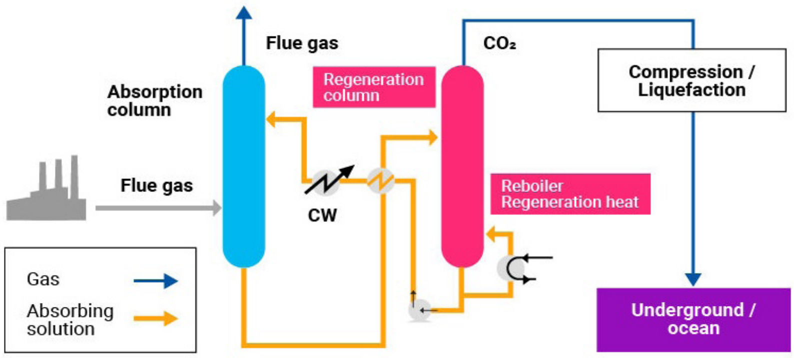

Figure 6 Absorption process. Source: link

Figure 7 Avedøre biomass cogeneration plant, Denmark. Source : Ørsted, link

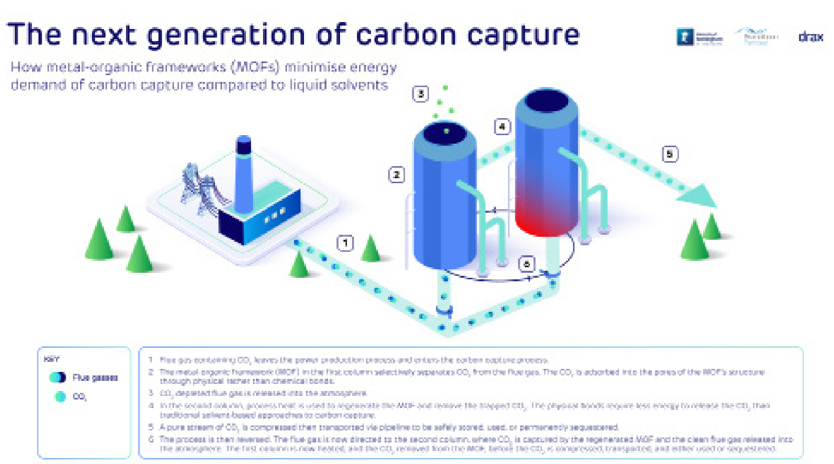

Figure 8 Adsorption process in the Drax power plant. Source : Drax, [link]

used, due to its low cost of capture, while efforts are underway to apply BECCS to thermochemical production pathways.[17]

Fermentation carbon dioxide capture (FCCS) occurs after the fermentation process of renewable biomass.[19] Carbon dioxide is formed as a by-product of the biomass fermentation process, alongside ethanol and other products such as protein. So once fermentation is complete, instead of being released into the atmosphere, the CO_2 is captured. Typically, the CO_2 stream from bioethanol plants is highly concentrated, so it can be captured at low cost.[20] The costs of capturing CO_2 from the fermentation process used in bioethanol production are among the lowest of all capture approaches in industry.[17] Today, around 25% of the bioethanol industry -in the US- captures CO_2 from its production process.[21]
The United States is showing leadership in the FCCS.[22] For example, POET, one of the world's largest biofuel producers, has embarked on a BECCS project with Navigator CO_2 Ventures, to join the Heartland Greenway System. Starting in 2025, the project will capture and store 5 million tonnes of CO_2 per year from 18 bioethanol plants. These facilities are in Iowa, Nebraska and South Dakota.[23] The project includes the development of new pipelines and several storage sites.[24]

While this approach is generally applied to bioethanol production plants, the same applies to certain biofuel chains[19] or to the conversion of biogas into biomethane, where CO_2 separation is already one of the process stages.[20]
The objective of pre-combustion is to pre-treat the fuel to obtain a synthesis gas rich in carbon monoxide and hydrogen with few impurities. In principle, the fuel is first gasified with a controlled amount of air, oxygen, or steam. The gasification process generates syngas mainly composed of carbon monoxide (CO) and hydrogen (H_2). This syngas is then introduced into a catalytic reactor with steam, in which a water-gas reaction takes place between CO and H_2O and produces CO_2 and H_2. Thus, CO_2 can be captured and H_2 can be used. A successful and widely used process for H_2/CO_2, particularly of fossil origin, is absorption by physical solvents[25].
Hydrogen can be used as a fuel to generate electricity[16] or as a motor fuel. In France, for example, a project involving Air Liquide and Total Energies aims to produce sustainable aviation fuel from biohydrogen, while capturing the CO_2 produced in the process. The biohydrogen produced by Air Liquide plans to use part of the biogas produced by Total Energies' biorefinery. This unit will be equipped with Air Liquide's Cryocap™ H_2 capture technology. This would capture more than 110 tonnes of CO_2 per year, which is planned to be reused.[26]

In the approach of the post-combustion, CO_2 is separated from ni-

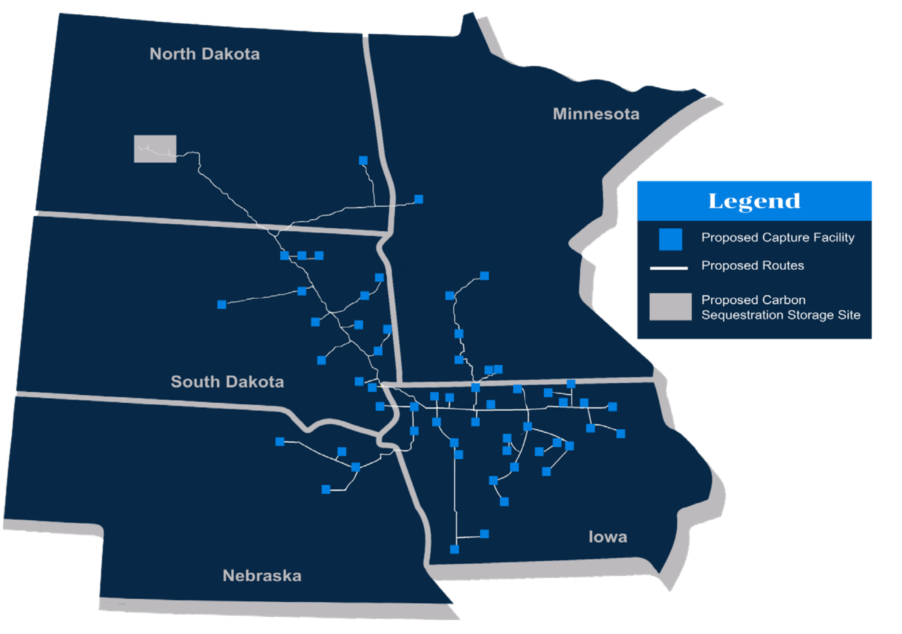

Figure 9 The Summit Carbon Solutions pipeline plan. Source: Summit Carbon Solutions, [link]

trogen, water vapor and other flue gases, then is captured after the flue gas is burned, and before the combustion, emissions are released to the atmosphere. Chemical absorption, especially with organic amines, is one of the most mature processes for post-combustion CO_2 capture.[27] Membrane separation is only compatible for higher CO_2 contents.
Post-combustion CO_2 capture, for example, can be used to generate heat and electricity.[16] In Switzerland, for example, the KVA Linth waste-to-energy plant plans to capture emissions from waste incineration, in collaboration with CO_2 Capsol, which will study the feasibility of the project. By 2025, more than 100,000 tonnes per year of CO_2 could be captured by amine absorption, half of which would be from biogenic sources.[28] Northern Lights is being discussed for carbon storage, but the question remains open as to its transport.[29]

Finally, **oxy-combustion** aims at burning biomass with pure oxygen. Before the combustion, an air separation unit allows to separate the N_2 from the O_2. Then, this oxygen will be placed in an oxy-combustion boiler with biomass to produce a synthesis gas. Due to the separation of nitrogen, this syngas

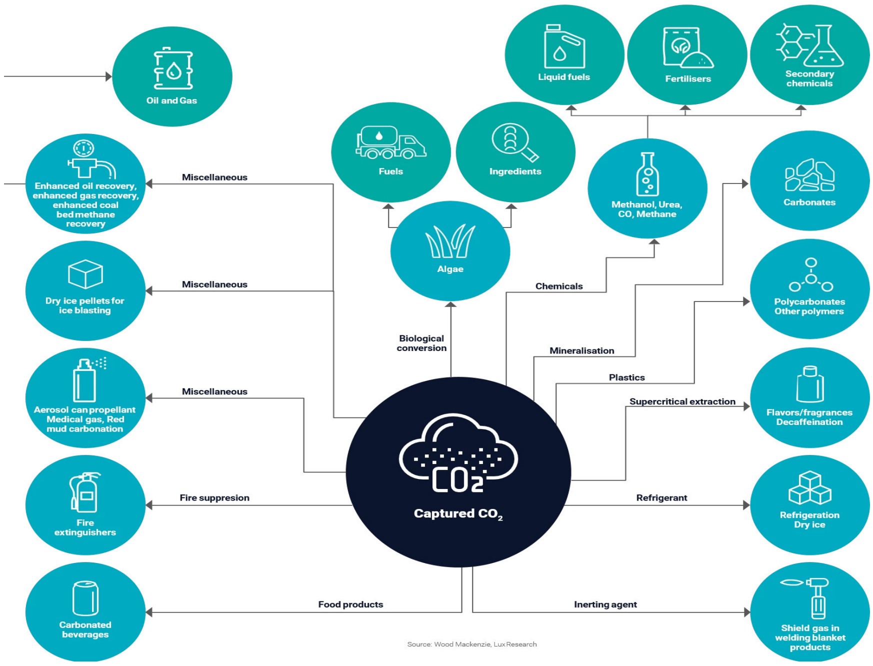

Figure 11 CO_2 utilization pathways. Source : Wood Mackenzie, link

is composed only of carbon dioxide and water (H_2O). The concentration of CO_2 varies according to the type of biomass used. Finally, the water is separated, condensed, and returned to the boiler. Potentially, this process could have the benefits of a flexible electricity load on the grid. For instance, a BECCS CHP Plant with oxy-combustion will enable more intermittent renewables on the grid because of the ability to drop load and continue oxy-combustion operations due to O_2 storage (or operate on air) in periods of low wind/solar generation[30]. In addition, if green hydrogen is produced, O_2 will be a natural co-product. This O_2 can be used for BECCS operations.

Currently, this technology still faces challenges, mainly due to the high energy cost required for oxygen separation[31], but CO_2 can easily be separated from the resulting flue gases[16]. Fidelis Project Cyclus[32] and Mendota BECCS power project[33] are two examples of projects in the USA using oxy-combustion carbon capture to create energy and/or heat.

Figure 10 CO_2 receiving terminal under construction in Øygarden, Norway. Source : Northern lights, link

CO2 CAPTURE TECHNOLOGIES

There is a vast array of technologies available for carbon capture. These include, but are not limited to, absorption, hydrate separation, cryogenic distillation, membrane separation and chemical looping combustion, etc. The level of maturity varies from one technology to another, and research is still ongoing to improve their efficiency. Within BECCS, absorption and adsorption are two technologies that stand out for their commercial rea-

Figure 12 Avedøre Power Station in Copenhagen, Denmark. Source : Ørsted, link

diness.

It must be noted that capture of CO_2 at ethanol plants is relatively straightforward, as a CO_2 stream is available in high purity (99%) often requiring only some minor dehydration.

Absorption technology allows CO_2 to be extracted from flue gas as it passes through a solvent. The CO_2 is then separated from the solvent and the depleted solvent is redirected to the beginning of the chain to be reused, after having been regenerated by an energy input. There are two types of absorption, physical absorption and chemical absorption. The latter is the most mature CO_2 capture method for BECCS[31]. The absorption of CO_2 by physical solvents consists of separating it by dissolution without chemical reaction, but according to the temperature of contact and the partial pressure of CO_2 in the fumes. Typical solvents are monoethanolamine (MEA), diethanolamine (DEA), potassium carbonate, amines, piperazine, ionic liquids, aqueous ammonium salts (ammonium carbonate). Absorption is also a commercial technique for BECCS.

The Avedøre biomass cogeneration plant is equipped with such technology. CO_2 is absorbed using amines, specifically monoethanolamine (MEA). Steam from the process is used to regenerate this amine. On leaving the capture plant, the CO_2 is compressed to a pressure of 110 bar, then transported by a pipeline and injected into a storage reservoir 1,300 metres below the surface. The Copenhagen-based plant, which runs on 100% wood pellets, has a capacity of 640 MWth.[34]
Adsorption works with a solid sorbent used to fix CO_2 on its surfaces. The CO_2 from the flue gas is thus absorbed by a sorbent which is regenerated by energy input (temperature swing adsorption, TSA) or by pressure drop (pressure swing adsorption, PSA). Thus, concerning the pressure variation, CO_2 is adsorbed on the surface of a sorbent at high pressure, which will switch to low pressure to desorb the sorbent and release the CO_2. Concerning the temperature variation, CO_2 is released by increasing the temperature using a hot air or steam injection system. Different sorbents exist, such as molecular sieves, activated carbon, zeolites, calcium oxides, hydrotalcite, or lithium zirconate. In the calcium cycle example, the carbon dioxide-rich flue gas is exposed to calcium oxide (CaO) in a carbonator. At high temperatures, a reaction between these elements forms calcium carbonate ($CaCO_3$). This element is then regenerated to form calcium oxide and carbon dioxide. The adsorption capacity of CO_2, the desorption and adsorption temperature as well as the kinetics are criteria for the selection of the sorbent. This technology is commercial for CSS, as well as for BECCS.

Drax Power Station is the focus of a pilot project using adsorption technology to capture CO_2, in partnership with the University of Nottingham and Promethean Particles. The capture process uses a solid sorbent called metal-organic frameworks (MOFs).[35] This requires less energy than solvent-based methods. Specifically, flue gas enters a first column, where the metal-organic framework separates the CO_2 which bonds physically to the MOF by adsorption into its pores. The depleted flue gas is exhausted into the atmosphere. In a second chamber, process heat is used to remove the trapped CO_2 and regenerate the MOF. The pure stream of CO_2 is then compressed and stored.[36]

For other capture technologies, such as Chemical-Looping-Combustion (CLC), membrane separation, hydrate-based separation, or cryogenic distillation, there are numerous R&D activities. Research is focused on process efficiency and on the most efficient way of integrating capture as a plant component.[20]

TRANSPORT

The captured and compressed

CO_2 must be transported to the storage site, which is not necessarily close to the place where it was captured. Emissions from the energy consumed to transport CO_2 are marginal and depend on the mode and distance of transport. These would be between 10 and 25 kg of CO_2 per tonne of CO_2 transported over distances of up to 1,000 km by pipeline or maritime transport.[20]Depending on the distance, CO_2 transport can be undertaken by pipeline, ship, train, or truck. The transport of CO2 from the BECCS chain benefits from the experience of carbon transport in general in the CCS chain.[17]

According to the IEA, among the existing transport modes, pipelines and ships are the most scalable options with the lowest cost per ton of CO_2. Transport by pipeline is a mature method [17], which is the most common method for transporting large quantities of CO_2. Millions of kilometres of pipelines transport various gases around the world, both onshore and offshore. 9,000 km of CO_2 pipelines have been identified (IEA), mainly in North America (6,500 km). Transportation by ship can be an alternative in many parts of the world. It is already used on a small scale in Europe. This type of transport, under pressure and at low temperatures, involves high preparation costs, in addition to storage and unloading costs, but this cost decreases with the transport distance. Nevertheless, some projects are working on the development of CO_2 terminals and ships able to transport CO_2 on a massive scale and barges for inland waterways are also being considered. Finally, transport by road or rail is complex and expensive for long distances but is still feasible for smaller quantities and when the capture and storage sites are close.

The magnitude of the transportation infrastructure needed to support the deployment of carbon capture to meet global warming targets is considerable. The USA has already developed several climate infrastructure projects for carbon transport. The Summit Carbon Solutions Pipeline project is an example of a large-scale construction project that illustrates the direction in which the USA is heading. The project aims to capture CO_2 from over 30 associated bioethanol plants and transport it to a common storage site in North Dakota. Once completed, this transportation network would have the capacity to transport and permanently store up to 18 million tonnes of CO_2 each year.[37]

STORAGE

Geological storage consists of injecting CO_2 at depths of at least 800 meters . These depths allow the CO_2 to be stored as a supercritical fluid with high temperature and pressure. There are different types of geological CO_2 storage, such as deep saline aquifers, depleted oil and gas fields, unexploitable coal seams, organic-rich shale, and basalt formations, etc. Sequestration in deep saline aquifers is the most successful of these methods[38]. Globally, the potential storage capacity is estimated to be far greater than what is needed to limit global warming to 1.5°C.[39]

Carbon storage projects are already operating on a commercial scale, having been used for many years to store CO_2 emissions from fossil industries. For e.g., Norway has a long history of operational experience, with the Sleipner site in the North Sea operating since 1996 and the Snøhvit site since 2008.[40] With these two sites, 1.7 million tons of CO_2 are stored per year after being separated from natural gas.[41] Thew new Northern Lights project involves the transport, reception, and permanent storage of CO_2 in a reservoir in the northern North Sea. Once the CO_2 has been captured, it will be transported by ship to the receiving terminal at Øygarden, pumped via a pipeline to a subsea structure on the seabed, and injected into a geological formation 2,600 meters below the seabed. The first phase of the project is part of the longship project and provides for a storage capacity of 1.5 million tonnes of CO_2 per year, with a future ambition of 5 million/t/CO_2/year.[42,43]

Canada and its Quest and Alberta Carbon Trunk Line (ACTL) projects have captured and stored more than 10.5 million tons of CO_2 since 2015[44]. Globally, large-scale efforts are underway around the world that demonstrate that CO_2 can be reliably stored, as stated by the IPCC in its special report on CSS.

UTILIZATION

The use of carbon in the BECCU chain is an alternative to its storage, which also provides important climate benefits. CO_2 utilization is a practice that allows to produce of an economically valuable product from CO_2 captured during biomass conversion, especially at concentrations above atmospheric levels.[45] This CO_2 can either be used directly, i.e. without chemical modification, or indirectly, by being transformed. Crucially, it can be used to replace CO_2 currently being produced from fossil fuels.

Today, no less than 230 Mt of CO_2 is recovered each year.[46] The CO_2 can be used directly in soft drinks and beer or in greenhouses or as dry ice for food preservation. For example, the Twence waste-to-energy plant in Hengelo in the Netherlands plans to use the "Just Catch" system to capture carbon. Once the CO_2 is captured and liquefied, it should be delivered by tanker to users such as nearby greenhouses, where it would increase plant and vegetable yields. This is intended to replace the emissions from the traditional method of CO_2 production for greenhouses using fossil fuel combustion. It is expected to capture and recycle about 100,000 tons of CO_2 annually.[47]

CO_2 can also be used as a working fluid or solvent, notably for enhanced oil recovery. This is one of the main uses, with 80 Mt of CO_2 used each year. [46] Today, the primary use of captured CO_2 is in the manufacture of urea, particularly for the fertilizer industry. This is a commercially established and viable use.[5]

New pathways are gaining momentum, where CO_2 can be used as a feedstock, thus promoting the circular economy.[5] Value-added products can be produced, such as polymers, chemicals, building materials, and synthetic fuels. However, they will likely require additional support to move into operation.[48] For instance, in Denmark, the Power-to-X project 'Green Fuels for Denmark' plans to capture CO_2 from a biomass power plant and turn it into fuels, especially for heavy transport. This combined heat and power plant has been judged to be the best sustainable CO_2 point source. The power plant's 100 MW straw unit could provide the amount of CO_2 needed to produce fuels for Denmark.[49]

The CO_2 recovered must come from biomass or air to expect to result in emission reductions. The additional climate change mitigation potential may also vary depending on the product or service that the CO_2 product replaces, the carbon intensity of the energy used in the conversion process, the length of time the CO_2 is retained in the product, and the size of the market for that particular use.[46] For example, only construction aggregates could qualify as permanent sequestration, as opposed to fuels and chemicals, which retain CO_2 for one to 10 years, and whose conversion process can be very energy intensive.[46] The use of low-carbon energy is a challenge for the industry to grow and BECCUS products should aim to replace similar products made from fossil feedstocks in the markets.[5]

Finally, the IEA argues that CO_2 use has a place in the projected scenarios for limiting global warming, but that storage should remain the primary objective of carbon capture.[48] Globally, one of the major challenges lies in the development of transport infrastructures to enable economies of scale. Especially since it could be interesting to combine the transport of CO_2 for its use and for its geological storage, especially in the context of CO_2 hubs and clusters in areas with high industrial emissions.[46]

LOGISTICS AND CARBON ACCOUNTING

The BECCS chain must be assessed to certify and account for negative emissions. How this evaluation is carried out, and the results it produces, will influence how BECCS contributes to climate change mitigation.[50] Assessing the process, however, is no easy task. The complex nature of the BECCS chain means that we need to analyze the system from its inception, when biomass is created, through all the intermediate phases of the transformation and the transport, to the storage or use of carbon. In fact, carbon accounting can depend on factors such as land use, carbon capture efficiency, and the duration of carbon storage, which varies greatly depending on the purpose for which it is stored or used.[17]

However, it is essential for this chain to be both sustainable and economically viable, which is another challenge for BECCS. Until a perfect balance can be found, the parties involved in the BECCS process must make choices.[51] A recent example is that of Sweden's Växjö Energi, that can illustrate the challenges associated with the choices BECCS companies can make. Växjö Energi aims to integrate carbon capture and storage from its combined heat and power plant by 2027. [52] As a result, transportation is already planned to be both cost-effective and climate friendly. The logical choice for them was rail transport, with a direct connection from Växjö to Goteborg.[52]

The origin of biomass can also be a decisive factor in carbon accounting and the quality of the BECCS chain. Consider, for example, the Danish company Ørsted, which estimates that by 2030, it will be able to feed its cogeneration plants with sustainable biomass sourced mainly from Denmark, and to a lesser extent from its Baltic neighbours to complete the supply chain. Speaking about the importance of reducing imports, Ole Thomsen, the Senior Vice President of Ørsted said "it makes a lot of sense to primarily use biomass from areas which are closer to home and thus get as close as possible to the supply chains to reduce the need for transport".[53]

The hubs model and concentration are useful for optimizing the BECCS chain. Indeed, CO_2 storage sites can accommodate CO_2 from different capture industries, whether of fossil or bioenergy origin. In this way, transport and storage infrastructures can also be shared to make them profitable, cut costs, and avoid unnecessary construction. [17] The UK is planning to create several clusters, which aim to be the world's first net-zero industrial region. They include the East Coast Cluster, Zero Carbon Humber, and Net Zero Teesside projects. These are expected to capture 10 Mt of CO_2 by 2030. Drax is expected to play a key role in The Zero Carbon Humber project. Infrastructure development is the key, so sharing carbon pipelines and storage sites, particularly under the North Sea enables companies to invest in them profitably. In this way, these projects are opportunities to create jobs and strengthen the UK's position as a world leader in green industries. [54,55]

The logistics chosen depend on the country and its geographical, economic, political, and legal context. In addition to the technological and technical issues of evaluation, the question of regulation and administrative supervision of negative emissions and the sustainability of BECCS is more widely raised. A unified approach is needed [17]. Before that, however, it would be useful to provide rules and a method for assessing the BECCS chain. Uniformity of regulations not only enables comparisons to be made but also avoids disincentives. An example of an existing measure that could be applied to BECCS is the use of scopes via the GHG balance of BECCS chains. Finally, the decisions taken by the parties involved in the BECCS chain are important. If chain emissions are low enough, there can be a net reduction in the amount of CO_2 in the atmosphere.[31]

ECONOMIC ANALYSIS

Cost of technology

To compare different BECCS technologies, the cost per tonne of CO_2 avoided is generally used.[56]

TABLE 1: BECCS COST

Sector	Cost per tonne of CO_2 avoided (USD/tCO_2)
Combustion	88 – 288 USD[59]
Bioethanol	20 – 175 USD[59]
Pulp mills	20 – 70 USD[59]
Biomass gasification	30 – 76 USD[59]/ 15 - 30 USD[27]
Power generation	56 – 64 USD[27, 60]
Industry	79 – 85 USD[60]
Other fuel transformation	15 – 30 USD[57]

This method can also be used to compare CDR technologies. At present, BECCS is the least expensive technological approach to carbon removal.[57] However, the cost of setting up a BECCS chain can vary widely, depending on the maturity of the technology used, the sector to which it is applied, and the scale of the chain. The Global CCS Institute estimates the cost per tonne of biogenic CO_2 avoided at between $15 and $400.[31] BECCS applied to bioethanol plants is considered the cheapest technology available today.

Decatur, Illinois (USA) is home to the largest BECCS installation at the Archer Daniels Midland (ADM) ethanol plant. The plant can capture up to one million tonnes of CO_2 per year in its corn fermentation process. This is equivalent to 3,000 t of CO_2 per day, which is then stored geologically. The project cost $207 million, 68% of which came from federal funds. The sequestration tax credit allows ADM to receive $23.82 per ton of geologically sequestered CO_2. So, if the bioethanol plant captures 1 Mt/ CO_2 per year, for 5 years, it can receive enough tax credit, i.e. $120 million, to exceed its initial investment. The total investment and operating cost of the plant have been estimated at $28.35 per tonne of CO_2.[58]

In general, the biofuel and biogas[20] industries appear to be well suited to the development of BECCS, since the industrial process often includes a CO_2 separation stage, which results in concentrated CO_2 streams.[17] While BECCS applied to ethanol plants is the most mature technology, other promising applications are under development. Pulp and paper mills, for example, have the same advantage in terms of high CO_2 concentration, but also offer surplus heat that can be used for the capture process, thereby reducing costs.[17]
For new biomass-fired power plants, in so far as a modification of the main process is required, capture technologies using chemical loop or calcium loop combustion are promising.[17] For existing or cogeneration ones, it is preferable to use post-combustion technology instead, being commercially available and widely used for fossil-source CCS.[17] Similarly, these processes can be introduced in waste-to-energy plants.

In addition, it is important to emphasize that R&D is active in the development of more efficient CO_2 capture methods. Research and practice have shown that certain elements can directly influence the cost of CO_2 capture. Firstly, in the biomass transformation process, it is preferable to have a concentrated CO_2 flow, to enable less energy-intensive and therefore less costly CO_2 capture. Secondly, to reduce costs, it's preferable for the CO_2 captured in the plant to come from one large point source, rather than several small point sources. Finally, the presence of excess heat in the biomass conversion process could be used for CO_2 capture, to lower energy costs.[17]

Since BECCS involves several stages (biomass harvesting, transport, and conversion; carbon capture, compression, transport, and storage), the total cost per tonne of CO_2 may increase as a function of each of these variables. Studies have also estimated that adding carbon capture to a bioenergy plant would double the facility's capital cost.[61]

CURRENT INITIATIVES

Today, the various costs associated with BECCS technologies can still be significant.[57] Moreover, few BECCS projects have reached large-scale development.[62] If Drax's BECCS project at its Power Station in Selby goes ahead, it will be the largest BECCs project in the world and sequester 8 million tonnes of CO_2 per year, based on two BECCS units.

BECCS, faces several challenges in its initial scaling-up phase.[57] This is why policies have an essential role to play in resolving these issues. However, these policies are also intricate and constantly evolving.[62] The role of an effective policy is multifaceted, and it must stimulate investment that makes these projects attractive. It must ensure that costs are not prohibitive to the creation of new projects and that existing uncertainties are overcome. There is, therefore, a need for financing to reduce risks and co-finance industrial investment in large-scale demonstration facilities.[17]

Because the effective deployment of BECCS is crucial for the years to come, public policy interventions need to take place at several levelslx and in a coordinated fashion. These include financial support, operating subsidies, carbon pricing, demand-side measures, innovation, and R&D. These direct and indirect incentives can be combined to support this emerging sector, which contributes to net zero emissions.[57]

The current policy landscape is quite varied and, in many cases, is being actively shaped.[62] However, most policies concern CCS in general and can be extended to BECCS, but there are few or no incentives exclusively for BECCS.

The recent update on CCS tax credits in the USA has initiated a new wave of interest in operating subsidies and highlights the importance of this type of climate policy to support projects. Initially, Section 45 Q of the U.S Internal Revenue Code on the CO_2 storage tax credit was introduced in 2008. Its framework was extended, and its duration extended, with the Inflation Reduction Act (2022). A seven-year extension has been adopted, capacity requirements have been reduced, and the BECCS chain has been included in the scope of application[63]. Today, a BECCS facility can receive up to $85 per ton of CO_2 sequestered, and up to $60 per ton of CO_2 used for enhanced oil recovery (EOR) or other industrial uses.[63,64]

Other countries, such as the Netherlands and the UK, have introduced operating support policies. For example, the SDE++ scheme in the Netherlands was launched at the end of 2020 to subsidize the use of renewable energy production and CO_2 reduction techniques.[65] It provides a "15-year CfD-like subsidy support covering the 'uncommercial' cost of CCS operation, i.e. The cost above the EU ETS price".[66] To illustrate its characteristic as a transitional technology, no industrial CCS subsidies will be granted after 2035.[66] The UK has also launched contracts for different programs to support low-carbon electricity generation.[67]

To improve the performance and development of the BECCS chain, financial support is essential, and two funds are exemplary in this respect. On the one hand, the UK CCS infrastructure fund represents £1 billion of investment in BECCS in the UK to support this emerging sector. The fund has been confirmed since November 2020 and includes a commitment to deploy CCUS in four clusters by 2030 at the latest with the ambition of capturing 10 $MtCO_2$/year by 2030.[68] On the other hand, the European fund has earmarked a total of over 1.1 billion euros in support for seven innovative projects aimed at bringing to market cutting-edge technologies in energy-intensive industries, hydrogen, carbon capture, utilization and storage, and renewable energies.[69] This is the European Innovation Fund's second call for projects, and to date, 11 projects with a CCS or CCU component have received funding.[70] For example, 180 million euros have been awarded to Stockholm Exergi's BECCS projectl,[71] for its bioenergy carbon capture and storage facility at its combined heat and power plant in Stockholm. The third call plans to invest 3 billion euros in projects providing solutions to reduce CO_2 emissions on the market by 2030.[70]

To make BECCS technologies available in the long term, another well-known incentive is carbon pricing. A forerunner in this field, Norway introduced its first CO_2 tax in 1991. This made the CCUS Sleipner and Snøhvit projects commercially viable since capture allows operators to avoid paying the tax.[72] This type of measure can be combined with sub-territorial measures such as the European ETS. The EU ETS is a cap-and-trade system that sets a ceiling on total

GHG emissions within the system, which is reduced from year to year. GHG allowances are seen as commodities that can be traded on the market. Companies can be allocated allowances free of charge, particularly for sectors considered to be at risk of carbon leakage, but they can also acquire them on the market or via auctions. Introduced in 2005, the EU ETS is now in its fourth phase, until 2030. In 2022, the average cost of an emission allowance to emit one tonne of CO_2 was around 80.32 euros and reached a record high of 100.34 euros per metric ton of CO_2 in February 2023. This covers around 45% of the EU's GHG emissions.[73,74] More recently, China has also introduced its own Emissions Trading Scheme (ETS), making it the world's largest carbon market. It became operational in 2021 and is set to expand to include new industrial sectors soon.[75,76]

Furthermore, more indirectly, innovation and R&D constitute another essential incentive channel. For example, the Carbon Removal Xprize is a multi-year competition funded by the Musk Foundation that “aims to reward novel methods to ‘pull carbon dioxide directly from the atmosphere or oceans and lock it away permanently in an environmentally benign way’.”[77] Start-ups that meet these criteria and have been selected will share a total of $100 million. At the European Union level, Horizon Europe is the funding program for research and innovation until 2027. It replaced the Horizon 2020 program and has a total budget of 95.5 billion euros.[78] Approximately 6 million euros could be allocated to DACCS and BECCS.[79] The US Department of Energy also has a major R&D program, including the Carbon-Negative Shot.[80]

Finally, incentives can be complemented by demand-side measures. For example, the use of low-carbon materials in construction projects can be encouraged by legislation, as in the Netherlands and Canada. Similar incentives exist for aviation fuel in other European countries.[46] Another measure, the Carbon Border Adjustment Mechanism (CBAM) and would help avoid the risk of "carbon leakage". This mechanism entered its transitional phase in October 2023, with a permanent entry into force in 2026. It aims to set a fair price on the carbon emitted during the production of carbon-intensive goods entering the EU, and to encourage cleaner industrial production in non-EU countries. Its introduction comes at the same time as the phasing-out of free allowances in the Emissions Trading Scheme (ETS).[81]

The various measures outlined are merely illustrations, and by no means represent an exhaustive list of what exists in this field. However, while other countries or regions have announced projects or taken steps toward deployment, their policies remain underdeveloped and will require further intervention to support wider deployment.[82]

In general, the choice of incentives, based on local institutional and market conditions, is not sufficient. The absence of a mechanism that rewards negative emissions seems to weigh on the system, as does the lack of policies that specifically address the BECCS chain. For incentive policies to work, they need to be anchored in a general framework that supports the creation of a sustainable and viable market for BECCS.[83]

FOCUS ON THE US IRA AND ITS IMPACT ON BECCS

On August 16, 2022, in the United States, the Inflation Reduction Act (IRA) was promulgated by President Biden.[84] This provided $500 billion in spending and tax credits to encourage renewable energies, increase tax revenues and reduce healthcare costslxv. According to the United States Environmental Protection Agency (EPA), this climate legislation is "the most significant climate legislation in U.S. history, offering funding, programs, and incentives to accelerate the transition to a clean energy economy”.[85] The legislation provides for an extension of eligibility for the Q45 tax credit, extending the deadline for the start of project development to January 2023, and reduces the minimum amount of CO_2 that must be captured per year, to make it easier for projects to obtain financing and qualify for the subsidy.[86] In addition, a BECCS facility can now receive $85/tonne of CO_2 permanently sequestered in geological formations, up from $50/tonne previously.[64] The amount allocated for the use of CO_2, generally for enhanced oil recovery (EOR), has also been increased from $35/tonne CO_2 to $60/tonne CO_2.

This is the third piece of legislation passed since the end of 2021, following the Bipartisan Infrastructure Bill (BIL) and the CHIPS & Science Act, aimed at improving US economic competitiveness, innovation, and industrial productivity.[87] With these larger BECCS subsidies, companies in certain sectors could break even or even benefit from the addition of necessary equipment and the resulting carbon management.[86] For example, the expanded tax credit could encourage the use of wood pellets in US coal-fired facilities as part of BECCS projects.[88]

OPINION OF WORLD BIOENERGY ASSOCIATION

Climate change is a critical challenge for humanity. Apart from efforts to mitigate and adapt to climate change, it is important to capture the emitted CO_2 already existing in the atmosphere. Though technologies that capture GHG directly from the atmosphere exist in some regions, capture and storage of emissions from bioenergy operations hold significant promise. A variety of conversion processes from biomass to energy and related emission capture systems are already deployed on various levels in different countries. Capture of CO_2 from ethanol fermentation seems to be a low-cost and commercially viable option today already while focus on post-combustion capture in thermal power plants holds significant promise.

Bioenergy with CCS is one of the only renewable technologies that can offer significant negative emissions in the process. Although some regions (e.g. USA, EU) are putting together policies for incentivizing the deployment of CCS technologies in bioenergy systems, the incentives must be more attractive, long-term, and more widespread to increase the confidence in the investor community. Technologies exist already and with the right signals, it is possible for BECCS to play an important role in the global fight against climate change.

For all references, please visit: Endnotes

Acknowledgments

This document was prepared by Lea Bernardin, with the support of the Secretariat, and has greatly benefited-from the expert contributions provided during the review process earlier this year. We would like to extend our gratitude to Andrew White from Drax Group, Jamie Stephen from Torchlight Bioresources, and Zoltan Szabo from Ethanol Europe for their invaluable input. For further queries or comments, please contact us at info@worldbioenergy.org.

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