Deployment of BECCS/U value chains

Technological pathways, policy options and business models

IEA Bioenergy: Task 40

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Executive summary

It is becoming increasingly clear that substantial amounts of negative emissions – essentially, the removal of carbon dioxide from the atmosphere – will likely be required if global climate change is to be limited to 2°C above pre-industrial levels. In order to limit warming to 1.5° and thereby substantially reduce the risks associated with global climate change, negative emissions will be a crucial part of the mitigation toolbox. Among the different negative emissions options, bioenergy with carbon capture and storage, or BECCS, is arguably one of the most commonly discussed in climate policy debates.

BECCS is very often discussed in terms of its potential and drawbacks over a very long timeframe, e.g., 2050 and beyond. In this report, however, we focus on the potential and challenges associated with deploying BECCS systems and value chains in the near to medium term. We provide a brief overview of different technological options for capture, transport and storage of CO_2, and offer insights into how BECCS business models could be set up. We further discuss the role of public policy in this setting and how bioenergy with carbon capture and utilization (BECCU) could play a role in enabling BECCS deployment.

An important starting point for any discussion on BECCS is to see it as a subset of a broader group of options for carbon capture and storage (CCS), because from a technological perspective the general principles are largely the same. When it comes to sectors where capture of biogenic CO_2 would be feasible, bioethanol production facilities are a particularly low-hanging fruit because of the high concentrations of CO_2 available for capture. However, applications in pulp and paper mills also show promise thanks to substantial CO_2 concentrations and availability of excess heat that can be used in the capture processes. In addition, there are BECCS pilot and demonstration projects under development in both power stations (using wood pellets) and in waste-to-energy facilities. When it comes to transportation and storage infrastructure, these will most likely have to be shared among CCS systems irrespective of whether the source of CO_2 is fossil or biogenic.

Regardless of the area of application, actual deployment of BECCS will require public policy interventions at several levels. To begin with, there is a need for financing to de-risk and/or co-finance industrial investments in large-scale demonstration facilities. In addition, there needs to be a policy mechanism in place that rewards negative emissions. For example, no such mechanism is possible under the EU emissions trading system (ETS) and although there are other possible means of implementing such systems, the discussions on how this could be done are so far quite immature. In terms of the *utilization* of biogenic CO_2 (BECCU), this could help drive innovation and enable cost reductions that help to unlock BECCS potential, because BECCS/U shares similar needs for CO_2 capture technologies and infrastructure. In terms of the mitigation potential of BECCU in itself, this will vary a lot because BECCU includes a wide range of applications from enhanced oil recovery (EOR) to production of synthetic fuels via so-called power-to-X (PtX).

In conclusion, the technological obstacles to near to medium-term deployment of BECCS systems are likely not prohibitive. However, the policy measures required to incentivize the demonstration, deployment and operation of BECCS value chains are currently largely absent. It is imperative that policymakers begin an earnest discussion about this as soon as possible if the potential of BECCS as a negative emissions technology is to be realized.

Contents

1 Introduction

1.1 NEGATIVE EMISSIONS AND BECCS AS PIECES IN THE CLIMATE CHANGE MITIGATION PUZZLE

Negative emissions technologies (NETs) have gained increasing attention in recent years. The main reason for this is the realization that without negative emissions – sometimes also referred to as carbon dioxide removal (CDR) - achieving the goals of the 2015 Paris Agreement would require very steep emission reduction curves up to 2050. For example, if the 2° C target is to be achieved without NETs, the share of low-carbon sources in the global electricity generation mix would have to increase from 30 to 80% between 2016 and 2030 (van Vuuren et al. 2017). This would require a pace of transformation in the global electricity sector that may not be feasible, despite rapid and promising developments in growing deployment of renewables.

At the same time, emission reduction strategies that place excessive emphasis on NETs come with significant risks. Relying too much on negative emissions technologies as a means to meet emission targets may create a moral hazard problem, i.e., "why should we go through the effort to reduce emissions now, when we can deal with the problem later by using NETs"? (Anderson and Peters 2016). The potential dilemmas pertaining to NETs notwithstanding, global GHG emissions continue to grow despite expanding renewable electricity generation. This means the world is approaching a situation where drastic emissions reductions and deployment of NETs is not an either/or question. Rather, both will likely be needed to approach a realistic chance of meeting the Paris Agreement target of well below 2°C, not to mention 1.5°C.

While there is an active research debate on how to implement different low-carbon solutions for electricity generation and vehicle transport, the climate change mitigation discussion has hitherto paid relatively little attention to the factors that influence the prospects of deploying NETs in the near- to medium term. Notably, the debate on bioenergy with carbon capture and storage, or BECCS, has mostly focused on issues related to long-term global opportunities and challenges. There has been much less focus on different technological solutions, the feasibility of BECCS in different sectors, or on how policy frameworks and business models could be designed to enable BECCS deployment. This is a gap that needs to be filled, because negative missions can come to be an important piece in the overall decarbonization puzzle, even at relatively low levels of deployment (Bellamy and Geden 2019).

1.2 BECCS – CONCEPTUAL OVERVIEW

Although largely similar from a technological perspective, the key difference between BECCS and CCS based on fossil fuels is that because the CO_2 being captured is biogenic, in effect BECCS can be used to contribute to a net reduction of CO_2 in the atmosphere (see Figure 1).

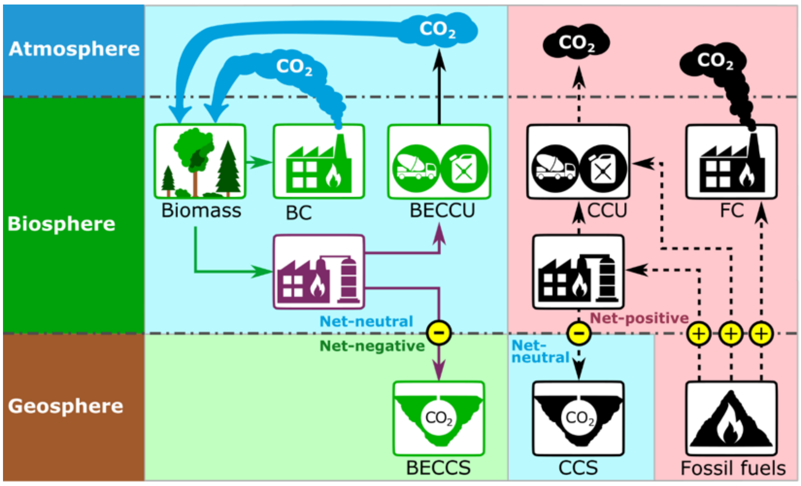

Figure 1. Schematic diagram of carbon dioxide cycles in different bioenergy utilization routes. Sustainable biomass conversion (BC) and biomass with carbon capture and utilization (BECCU) can be considered close to carbon neutral. Biomass conversion with carbon capture and storage (BECCS) can lead to negative emissions.

The potential of BECCS for climate change mitigation will be a function of a host of factors across the life cycle, from land use and biomass procurement to how efficiently CO_2 is captured and transported, as well as duration of carbon storage. Having said this, issues pertaining to the procurement of biomass are comprehensively discussed in many other IEA Bioenergy publications, so in this report we focus on factors crucial for deployment of the remaining components of BECCS supply chains.

As in discussion on deployment of BECCS, the discussion on carbon capture in general (and including bio-carbon capture) tends to include the potential to *utilize* captured CO_2 for various purposes (so called carbon capture and utilization, or CCU). These purposes include enhanced oil recovery (EOR), carbonation of beverages, CO_2 fertilization in greenhouses, or use as raw material in industrial processes for production of fuels, chemicals and plastics (Naims et al. 2015). Whereas implementing CO_2 storage requires public policy incentives that reward the avoided emissions, the utilization of CO_2 could be more appealing from a commercial perspective. At the same time, in most envisioned CCU applications, the CO_2 is released into the atmosphere within fairly short time spans and, consequently, its potential in terms of climate change mitigation is far below that of CCS. However, because parts of the CCS and CCU supply chains overlap, CCU could act as an enabling factor in the development of technology necessary for CCS.

1.3 REPORT OBJECTIVE AND OUTLINE

In this report, we outline the prospects for near to medium-term implementation of technologies for bioenergy with carbon capture and storage or utilization (BECCS/U).

Key questions that we cover include:

- What are the technological options for BECCS/U implementation in different sectors?
- What business models could be set up to enable either storage or utilization of captured biogenic CO_2?
- What kinds of policy instruments would be needed to enable deployment of BECCS/U supply chains?

2 BECCS overview

2.1 BECCS – A SUBSET OF CCS

From a technological perspective, BECCS should be viewed as a sub-category of CCS more broadly. CCS technologies have been in use in various forms for decades and can be considered rather mature. This applies not only to the capture part of the supply chain, but also transportation and storage, although there are variations depending on the source of CO_2, the transportation system and the geological features of the storage site (Bui et al. 2018).

Because existing CCS technologies to a large extent have been developed around combustion of fossil fuels, these may need to be adapted in order to be applicable to systems based on biomass. Biomass-based fuels are quite different from, for example, coal and natural gas when it comes to fuel properties and the composition of flue gas, especially concerning trace elements in the biomass (Finney et al. 2019). Having said this, it is important to note that the breadth of possible CCS applications in energy generation and various industry sectors means that there are variations that go well beyond the question of whether the CO_2 to be captured is of fossil or biogenic in origin. For example, even though in both cases the CO_2 is from fossil sources, deployment of CCS in a coal power station – that has one large point source of CO_2 – will be distinctly different from deployment in a steel mill, where CO_2 emissions are distributed among several different point sources (Mandova et al. 2019). Similarly, capturing the highly concentrated CO_2 stream from a fermentation process in a bioethanol production facility (Sanchez et al. 2018) is quite different in terms of energy requirements and cost compared to capturing CO_2 from a combustion process in a biomass power station (Arasto et al. 2014; Bui et al. 2018). Below we provide an overview of the characteristics of different BECCS applications.

2.2 CAPTURE OF BIOGENIC CO_2 – AN OVERVIEW OF DIFFERENT APPLICATIONS

As a general introduction, a few selected parameters can be highlighted that are particularly important for determining the feasibility and cost of CO_2 capture. To begin with, a highly *concentrated CO_2 stream* enables CO_2 capture that is less energy-demanding and less costly. Another important parameter is whether the CO_2 emissions at a facility originate primarily *from one large point source* or from several smaller point sources: the former is preferable, because capturing CO_2 at several different places within a facility will drive up costs. A third factor worth mentioning is whether the facility in question has *excess heat* available on-site, as this heat can then be utilized in the capture process, thereby helping to reduce energy costs (Gardarsdottir et al. 2019).

2.2.1 Combustion for energy generation purposes

Until fairly recently, CCS as a climate change mitigation measure was mainly discussed in relation to combustion of fossil fuels for electricity generation. However, as the costs of electricity generated from wind and solar have fallen dramatically, there is now less interest in this application. While the bioelectricity generation sector is also struggling somewhat in the competition with wind and solar (on a purely EUR/kWh basis) it does have potential as a flexible and grid-balancing renewable resource for electricity generation, which possibly also can be operated synergistically with BECCS (Levihn et al. 2019).

For newly built plants, some emerging technologies, such as chemical looping combustion, are promising low-cost technologies for CO2 capture (Mendiara et al. 2018). However, when it comes to technologies for integrating CCS with existing bioelectricity or biomass-based combined heat and power (bio-CHP), the most preferable alternative is clearly post-combustion separation of CO_2, because it is currently commercially available (Bui et al. 2018), However, it has been developed around coal, and would have to be adapted to accommodate the biomass fuels and their different fuel properties and flue gas composition. And there are also systemic differences between capturing CO2 from biomass compared with coal: for example, bioenergy facilities tend to be smaller and less geographically concentrated than coal power stations (Thrän et al 2019), which is worth noting because in the CCS value chain the transportation of CO2 involves substantial economies of scale.

One application of CCS that is increasingly being discussed is implementation in waste-to-energy (WtE) facilities. Every year the world generates over 2 billion tons of municipal solid waste (MSW), a large part of which is not properly managed (Kaza et al. 2018). On average more than 50% of MSW is biogenic in origin. Even though materials recycling is increasing, there will remain a large potential for waste incinerators in which waste can be disposed of in a controlled way, thereby reducing emissions that otherwise result from leakage of greenhouse gases from landfills sites into the atmosphere. Moreover, if CCS technologies are applied to waste incinerators, it is possible to reach negative CO_2 emissions. In principle, the same CCS technologies can be applied to waste incinerators as for other point sources. Currently, there is a large scale piloting of waste-to-energy CCS planned for Norway's Klemetsrud power plant operated by Fortum Oslo Värme AS (Stuen 2019).

2.2.2 Heavy industry

Recent years have seen increasing focus and discussion on deep decarbonization of heavy industry sectors such as steel, cement, and pulp and paper. The prospects of eliminating GHG emissions from these sectors have traditionally been considered rather bleak, but several recent studies have shown that for most sectors there are technologically feasible decarbonization pathways at costs that need not be prohibitive (E.T.C. 2018; Material Economics 2019). Bataille et al. (2018) highlight two main pathways for decarbonization of heavy industry: one radically transformative, based on electrification (directly or via hydrogen), and one more gradual, based on processes currently in use. Although utilization of biomass for energy and/or as a carbon source will likely be important in both pathways, the second pathway draws particularly heavily on implementation of CCS.

Currently, most heavy industry sectors (with the exception of the pulp and paper sector, which we discuss in more detail below) are highly reliant on fossil fuels as input energy and/or as chemical reactants. For example, although there is large variation within the sector, the global cement industry currently on average uses only around 6% biomass for process heat (Consoli 2019). In the steel industry, the use of biomass is mainly limited to wood-based charcoal in small blast furnaces in Brazil (Machado et al. 2010). For reasons mainly related to the different physical properties of coke and charcoal, it is unlikely that biomass has much potential when it comes to replacing coke as the reduction agent in blast furnaces (Suopajärvi et al. 2017). When it comes to CCS, one problem in the steel industry is that in steel mills which use the dominant blast furnace-basic oxygen furnace (BF-BOF) process, CO_2 emissions are distributed across several point sources, which increases the cost of capture. Having said this, Mandova et al. (2019) find that a combination of partial introduction of biomass and CCS could technically enable net zero emission steel production.

The pulp and paper sector stands out among heavy industries in that it derives a large portion of its process energy from biomass. Pulp mills are globally the largest users of wooden biomass and consequently are large emitters of bio-based CO_2 emissions. It is estimated that roughly 2.5 tonnes of (primarily biogenic) CO_2 is produced per dry ton of pulp (Kuparinen et al. 2019). Figure 2 presents the development of global chemical pulp production (FAO 2019), estimates of resulting emissions of CO_2 (fossil and biogenic).

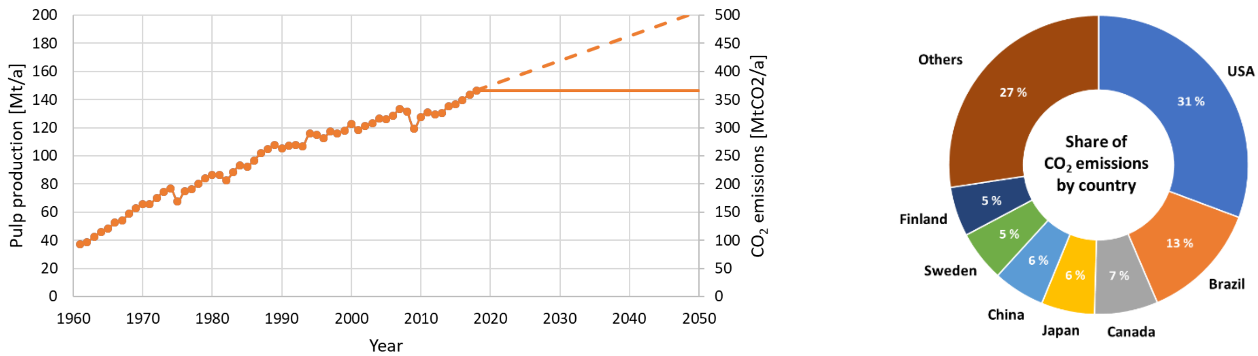

Figure 2. Left pane: Historical development of global chemical pulp production (FAO 2019), estimated (fossil & biogenic) CO_2 emissions. 2020-2050 data illustrates two scenarios for pulp & paper CO_2 emissions: flat emissions 2020-2050 (solid line) and a trend extrapolation (dashed line). Right pane illustrates CO_2 emissions from pulp & paper sectors in different countries (Kuparinen et al. 2019)

CO_2 emissions from kraft[1] pulp mills come mainly from the recovery boiler (75–90%), as well as the lime kiln (5-10%) and the biomass boiler (10–20%, optional). Except for the lime kiln, the emissions are mainly biogenic. Standard post-combustion CO_2 capture processes are applicable to all flue gas streams and can be applied without disturbing the main production process. Recent estimates of the cost of CO_2 avoidance in kraft pulp mills, using currently available amine-based post-combustion processes, vary from €52–66 per ton of CO_2 (Onarheim et al. 2017). In a pulp mill environment, excess heat, electricity and oxygen are usually available on-site, which together with a high number of full-load hours and stable operation are good prerequisites for CCS. More advanced CO_2 capture processes, such as Chemical Looping Combustion (CLC) or Calcium Looping (CaL), could lead to further decreases in costs but are more difficult to retrofit and/or require changes to the main process.

In the IPCC 1.5° special report (IPCC 2018), the role of BECCS varies between 0–16 $GtCO_2$ per year by the mid of this century. Current CO_2 emissions from chemical pulp production are roughly 350 $MtCO_2$ per year. By 2050, the BECCS potential in pulp mills could be in the range of 200–400 $MtCO_2$ per year and could play an important role in reaching the required negative emission targets. In terms of CO_2 storage capacity, there are good opportunities in the vicinity of large pulp producers in countries like USA, Canada, Brazil and China (IPCC, 2005). For countries like Sweden and Finland, where the bedrock is not suitable for permanent CO_2 storage, transportation via ship to storage sites in other countries could be an alternative option (see section 2.3).

2.2.3 Biofuel production

When it comes to implementing BECCS, it has been suggested that the inclusion of CO_2 capture in facilities that produce liquid biofuels is a low-hanging fruit, because in several biofuel production pathways, CO_2 is already separated as part of the process (Arasto et al. 2014; Sanchez et al. 2018). This means that there are concentrated CO_2 streams available, thereby reducing the costs of capture. In fact, the costs of CO_2 capture from the fermentation process used in bioethanol production are among the lowest of all CO_2 point sources (Sanchez et al. 2018). One of the few commercial-scale BECCS facilities currently in operation is based on capture and sequestration of CO_2 from ADM's bioethanol production facility in Decatur, Illinois.

CO_2 separation is also a part of the process when upgrading biogas to biomethane. It is estimated that in 2016 there was 1.5 Mt CO_2 available from biogas upgrading plants in Germany (Billig et al. 2019). However, the CO_2 streams from upgrading are not yet captured and stored. At a global level, though, biomethane production in combination with CCS has the technical potential to remove up to 3.5 Gt greenhouse gas emissions in 2050 (IEAGHG 2013).

2.3 TRANSPORTATION OF CO2

2.3.1 Onshore transport

For small-scale and pilot projects, CO_2 can be transported by tanker (by rail or truck), while pipelines are the most cost-effective method for large-scale onshore transport of CO_2. This is a well-known and mature technology: CO_2 pipelines have been in commercial use since the 1970s, the vast majority of these in the US.

2.3.2 Offshore transport

The two offshore options for transport of CO_2 are via ship or pipeline, and which option is the most cost-effective will depend on project-specific factors. For example, the cost of transporting CO_2 via pipelines depends on the terrain that the pipeline will cross, the diameter of the pipeline, the length of the pipeline, whether the CO_2 is piped in its gaseous or liquid form[2], and, often most importantly, the capacity of the pipeline. Kjärstad et al. (2016) investigated the costs of transporting CO_2 in the Nordic countries,

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[1] Also known as the sulfate process.

[2] It is generally less costly to transport CO_2 as a dense liquid. However, this also requires more energy.

and one of the main findings was an estimated break-even point between shipping and pipelines, depending on many of the factors outlined above. The findings are summarized in Figure 3.

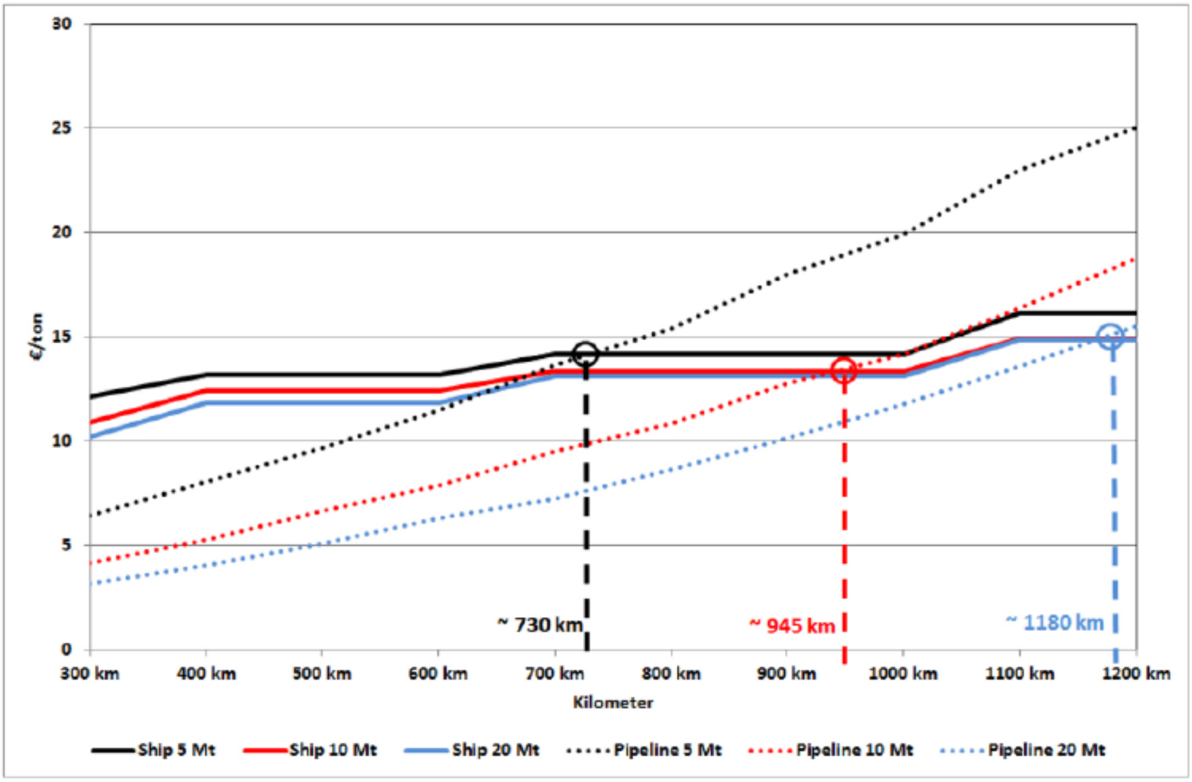

Figure 3: Comparison of ship and pipeline transport cost, in Euros per ton of CO_2, as a function of yearly transport volume and distance, for transport volumes between 5 and 20 million metric tons per year. Image from Kjärstad et al (2016)[3].

The figure illustrates that in general shorter transport distances and greater volumes favour pipelines, while with lower volumes and greater distances shipping becomes more cost-effective.

There are a few elements that are not incorporated into the above costs. In terms of flexibility, ships are favourable because they can act as a CO_2 buffer, and thereby smooth out short-term deficits in supply and demand. Reliance on ships also allows for long-term flexibility, because CO_2 from additional and/or alternative sources could be added. Likewise, establishing pipelines with surplus capacity could also provide much of the same short-term and long-term flexibility regarding the timing and sourcing of additional CO_2 sources.

In terms of stability, ships may be less reliable for transporting CO_2, because bad weather could lead to delays; a potential drawback that could pose ongoing logistical challenges. Lastly, the energy demand required to transport a ton of CO_2 is higher for ships compared with a pipeline.

2.4 OPTIONS FOR GEOLOGICAL STORAGE

2.4.1 Deep saline aquifers

The largest potential for CO_2 storage is in deep saline aquifers, which are favourable because they are plentiful throughout much of the globe. The process involves pumping CO_2 deep underground into a layer of porous rock that is saturated with brine. The brine and CO_2 will both move to the surface as they flow

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[3] Reprinted from *International Journal of Greenhouse Gas Control*, Vol 54, p 168-184, Jan Kjärstad, Ragnhild Skagestad, Nils Henrik Eldrup, Filip Johnsson, "Ship transport—A low cost and low risk CO2 transport option in the Nordic countries", Copyright (2016), with permission from Elsevier

through the porous rock. However, the water is attracted to the rock surface and therefore will cling to the pores which will eventually restrict the flow of CO_2, thus trapping it within the pores. While not yet a mature technology, studies indicate that the CO_2 can be safely stored in these tiny pores for centuries. The CO_2 will eventually dissolve in the brine, and a small portion of the CO_2 will react with the rock to produce minerals such as iron and magnesium carbonates (Bang 2008)

2.4.2 Depleted oil and gas reservoirs

Abandoned oil and gas fields are prime locations for injecting CO_2 because the pore space that was once occupied by oil or gas can now be filled with the CO_2. Relative to other non-value-added options, depleted oil and gas reservoirs are favourable because geologists are familiar with the sites and they have already proven that they can contain oil or gas for millions of years. Gas reservoirs are generally preferable to oil reservoirs because they are larger and more plentiful. Storage sites with a capacity greater than 1 Mt are more cost-effective, as are those with depths of between 900 and 3500 meters, because it is at depths below 800 metres that the pressure and temperature will result in CO_2 taking its desired liquid or supercritical state (Bang 2008).

3 Options for utilization of CO_2

Carbon capture and utilization (CCU) is a concept that is commonly discussed in conjunction with CCS. This is warranted to a certain extent, because the supply chains and processes of CCS and CCU partly overlap. At the same time, there are substantial differences in terms of the potential of the two when it comes to climate change mitigation. In most CCU applications, CO_2 is released back into the atmosphere within a fairly short time span (Bui et al. 2018), thereby limiting its usefulness as a climate change mitigation measure relative to CCS. Whereas the ultimate aim of biogenic CCS, then, is to create net negative emissions, the primary focus of BECCU is to enhance resource efficiency and substitute fossil fuels.

The global CCU potential is estimated to be around 300 Mt CO_2 in the near future (Aresta et al. 2016; Naims 2016) with a maximum potential in the longer term of 2000–4600 Mt CO_2 (Chauvy et al. 2019; von der Assen et al. 2016). While estimates do not exist for the available global potential of biogenic CO_2 sources for CCU purposes, CO_2 captured as a by-product of bioenergy plants is nevertheless a versatile resource for a broad range of potential CCU applications.

CCU pathways can be divided into three categories: physical, material and energetic utilization.

Physical utilization includes direct use of CO_2 in liquid or gaseous form, e.g. in production of carbonated beverages or in greenhouses. Enhanced oil recovery (EOR) or Enhanced gas recovery (EGR) also fall under the scope of this CCU pathway, with CO_2 being used as a fluid to extract additional fossil resources.

Material utilization includes various uses of CO_2 as a chemical building block that can be combined with hydrogen (H_2) into synthetic hydrocarbons, which can ultimately be transformed into platform chemicals and plastics (Palm et al. 2016).

Energetic utilization also builds on the use of CO_2 as a chemical building block, but instead for production of synthetic hydrocarbon fuels.

3.1 ENHANCED OIL RECOVERY

The injection of CO_2 into an oil well to increase recovery rates is referred to as enhanced oil recovery (EOR) and it can increase yields for two reasons. Firstly, when the CO_2 is injected it can mix and dissolve into the oil (often referred to as miscible EOR), thereby reducing its viscosity and making it easier to extract. Secondly, the injecting of CO_2 also increases the pressure within the reservoir, which again results in more oil being recovered (immiscible EOR). Both types are often used in combination with water injection. At appropriate sites, CO_2 EOR can boost rates of extraction from recoverable reserves by an average of 50% (this average is based on an expected 8–15% extraction increase of the total resources in place).

The IEA has a global database that includes EOR projects, which includes data on how much oil these projects produced in 2017. Table 1 shows the number of CO_2 EOR projects and oil production in eight countries in 2017.

Table 1: CO2 EOR projects and oil production according to country in 2017 (IEA 2018b).

Country	Number of CO_2 EOR projects	Daily oil production (bbl/day)
Brazil	3	100 400
Canada	4	20 700
China	4	3700
Croatia	1	200
Saudi Arabia	1	20 000
Turkey	1	9000
UAE	1	10 000
United States	83	310 300
Total	**98**	**474 300**

While figures can vary greatly from oilfield to oilfield, EOR processes currently result in roughly half of the CO_2 remaining in the ground, with the other half returning to the surface where it is captured and reused. According to the IEA, in the US roughly 300-600 kg of CO_2 is injected per barrel of oil produced (IEA, 2018). Oil has a CO_2 content of between 400 and 450 kg per barrel, and the IEA estimates that an additional 100 kg of CO_2 are emitted during the production and processing of oil, giving a total of 500-550 kg CO_2 emitted per barrel.

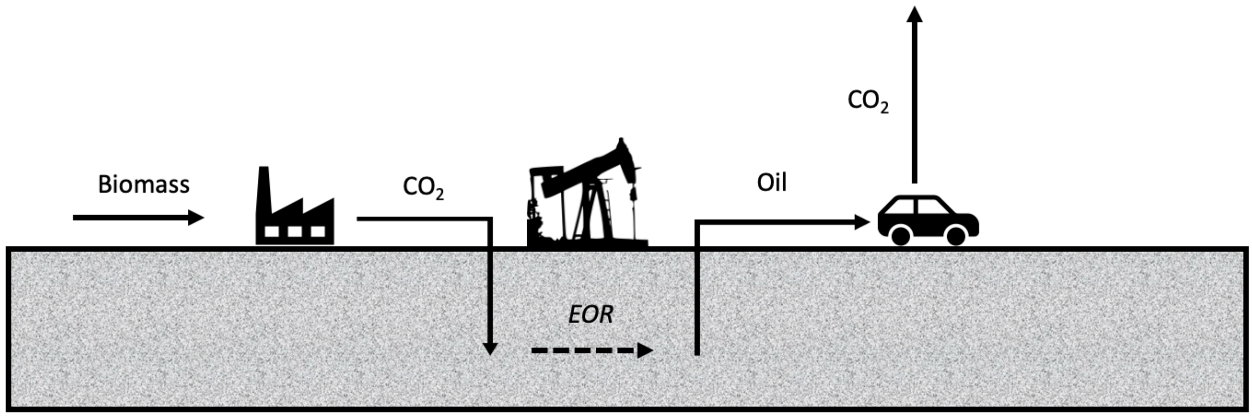

Figure 4: Conceptualization of a Bio-CCU EOR setup.

However, EOR facilities in general must pay for the CO_2 they use, and therefore the focus is on recycling as much CO_2 as possible. With a growing emphasis on both reducing CO_2 emissions, and producing "green" transport fuels, the objective can now become to trap as much CO_2 in the ground as possible. This can be done by adjusting the technology, as well as injecting CO_2 into the well when it is depleted and/or injecting CO_2 into nearby depleted wells. If the CO_2 used in this process comes from biomass, then this can result in producing "green oil", i.e. oil that has a negative CO_2 footprint (McGlade 2019), that can likely be sold at a higher price than conventional oil. Although the long-term effects of this in terms of climate change mitigation ambitions can certainly be discussed, there are already policy frameworks that incentivize this setup, as we discuss in section 4.2.

3.2 CCU AND POWER-TO-X

Both the material utilization and energetic utilization approaches to CO_2 depend on hydrogen, which in a zero-carbon future is typically assumed to be produced via electrolysis using renewable electricity. For this reason, these two CCU pathways are also referred to as power-to-gas (PtG), power-to-liquid (PtL) or, generically, as power-to-x (PtX). The CO_2 needed for all these applications can be obtained either directly through the air (direct air capture, DAC), from fossil or bioenergy plants, as well as from industrial point sources (such as the steel or cement industry). The advantage of using biogenic CO_2 sources is that there are capture technologies that are already mature and widely used, e.g. for biogas upgrading or bioethanol production. As noted in section 2, these processes also yield relatively pure streams of CO_2, so that costly purification procedures are not necessary. However, large CO_2 volume flows are required for a cost-efficient CCU process. In this respect, large biomass (co-)firing plants are particularly well suited, whereas widely scattered biogas plants in rural and agricultural areas cannot provide sufficient CO_2, unless their CO_2 streams can somehow be pooled.

No matter the source of CO_2, CCU can be seen as a form of waste treatment that contributes to a circular economy, provided that the CO_2 is of non-fossil origin. For reasons of energy and supply security, this may be of particular interest to countries with limited available fossil and biogenic resources. CCU also generates additional value and can drive innovative business cases, e.g. by opening new market segments and revenue streams for bioenergy and industrial plants. However, while CCU can contribute to improved resource efficiency, the outlook on its potential for GHG mitigation is rather mixed. Even under optimistic long-term assumptions, CCU could only contribute to a 6% reduction of anthropogenic emissions (Naims et al. 2015). This is partly because many CCU applications retain the carbon only for a few weeks or months before releasing it back to the atmosphere, resulting in a low rate of long-term CO_2 fixation. For example, synthetic fuels only store carbon for as long as they are not used (although the retention time can be longer – up to several decades – for plastics and building materials).

4 Policy options and business models to enable BECCS deployment

Taking BECCS to a commercial stage where it can actively begin to remove CO_2 from the atmosphere involves a host of different direct and indirect administrative challenges linked to carbon accounting, standardization, and governance of supply chain sustainability (Vivid Economics 2019). In addition, because the economies of scale in the transportation and storage part of the CO_2 supply chain are substantial (Finney et al. 2019), it is not feasible that each and every CO_2 capture project will develop its own storage supply chain. Instead, a realistic approach would be to gather CO_2 from several different sources to a joint storage site (Vivid Economics 2019).

Setting up of infrastructure for transportation and storage of CO_2 is an absolutely crucial component in enabling CCS, be it fossil-based or bio-based. This is not only a techno-economic challenge; it also requires societal acceptance, and there is still substantial debate around the desirability and deployment of CCS as a means of climate change mitigation (acatech/Leopoldina/Akademienunion 2019). With this in mind, we focus on two basic economic challenges that we deem especially relevant for market actors aiming to set up BECCS facilities (cf. Hellsmark et al. 2016).

The **first** challenge is largely a matter of innovation and how to drive BECCS along the technological development pathway, from the laboratory scale, via pilot and demonstration facilities to commercial readiness.

The **second** challenge concerns the business model of a BECCS facility and how the operational costs of capturing, transporting and storing CO_2 should be covered.

In the following, we will discuss these two aspects in more detail, including the role of public policy in resolving both challenges.

4.1 BECCS PILOT & DEMONSTRATION PLANTS – NECESSARY BUT DIFFICULT

As has been noted throughout this report, there are carbon capture and storage projects that have been commercially operated for decades, indicating that the technological obstacles to BECCS should not be unsurmountable. However, within the BECCS subset, there are large variations in terms of technological readiness. CCS integrated in bioethanol production can be considered commercial, whereas BECCS applied to power stations, CHP plants and industrial facilities (i.e. outside the bioethanol sector) reside further down the technological readiness level (TRL) scale (Bui et al. 2018; Vivid Economics 2019).

Regardless of the technology characteristics, however, taking innovations from lab-scale to commercial application tends to be risky and uncertain, both when it comes to technological performance and in terms of financing, permitting and business model viability (Jacobsson and Bergek 2004; Mossberg et al. 2018). Several of these issues become especially challenging for BECCS, where the technology in question is highly capital intensive, highly exposed to regulatory uncertainties and untested in large-scale settings. The scale issue becomes important because although successful tests at a lab indicate that a technology could be viable at full-scale, it is by no means guaranteed. The phase from lab-scale success to commercialization is so characterized by obstacles, in the form of high capital requirements, technical risk and exposure to market uncertainties, that it is commonly referred to as the "valley of death" (Nemet et al. 2016).

In order to cross the valley of death, a common approach is to gradually deploy a technology at sequentially larger scales in settings that in one way or another are shielded from full market competition, typically in pilot and demonstration plants (Frishammar et al. 2015; Nemet et al. 2018; Tolio et al. 2019). The latter especially tend to be associated with challenges, with the main reason being that they are highly capital intensive but still very risky from a technological perspective. This puts demonstration facilities in a difficult position from the perspective of investors, because the risk level is so high that it would suit a venture capital firm, but the capital volumes required are such they are typically only accommodated by very large commercial financial institutions, which are a lot more risk-averse.

Perhaps not surprisingly, then, Rootzén et al. (2018) identify the lack of capital needed to finance development and upscaling of carbon capture technologies as a key challenge to BECCS deployment. Here, public actors need to step in to help de-risk uncertain and highly capital-intensive pilot and demonstration facilities. It is important to note, though, that this is also a challenge and a risk for the public actors in question. Not only do they expose themselves to criticism for squandering taxpayers' money on high-tech adventures (Kelly 2018), but there could also be legal obstacles, for example EU rules that govern state aid (Myhre 2012).

4.2 BECCS BUSINESS MODELS – WHO WILL PAY?

Regardless of how successful the process of innovation and scale-up of BECCS technology becomes, it is – all else being equal – inevitable that the costs of facilities and infrastructure that captures, transports and stores CO_2 will be higher than if the CO_2 was just emitted into the atmosphere. Innovation and scale-up successes have little value if there is not market demand for the service being provided (Burke et al. 2019; Zetterberg et al. 2019), with the service in this case being carbon dioxide removal.[4] In terms of where this market demand could come from, there are a couple of different options that have been discussed in the research literature.

A basic problem is that current climate change mitigation policy schemes generally do not include any function to account for negative emissions (Fuss et al. 2016; Torvanger 2019). For example, while the EU Emissions Trading Scheme (EU-ETS) could potentially[5] drive implementation of CCS schemes aimed at capturing and storing fossil CO_2, its current structure means that this is not even conceptually possible (Torvanger 2019). It might be possible to reform the EU-ETS so as to include negative emissions in some form, but the administrative and political effort of doing so could make this a very time-consuming process that would not support deployment of BECCS in the near-term – i.e. before 2030 (Zetterberg et al. 2019).

In this context, alternative approaches would be needed to reward carbon dioxide removal. The following two options have been discussed in the literature (Burke et al. 2019; Vivid Economics 2019; Zetterberg et al. 2019) and are inspired by policy measures used in programmes aimed at support for renewable energy. Both of these options would be project-based programmes, i.e. where each individual project is assessed for validity and eligibility in terms of its CDR potential (Kemper 2015).

The *first* approach would be to introduce a tradeable certificate programme for negative emissions, as with programmes used to support renewable electricity generation. Under such a programme, actors who perform the function of removing CO_2 from the atmosphere would be rewarded a negative emissions certificate. At the same time, some economic actors would be mandated to purchase a certain volume of negative emissions certificates, thereby creating a demand for the certificates. If these certificates are traded in an open market and are available in smaller packages (e.g. 1 tonne CO_2 at a time), they could also attract interest from individuals and businesses interested in carbon offsets. It is worth noting here some early activity in voluntary platforms that market negative emissions (e.g., Nori.com, Puro.earth or Compensate.com). In addition, there are examples of businesses who have already committed internal funds specifically to carbon dioxide removal to offset their internal emissions (Anderson 2019; Microsoft 2020; Shopify.com 2019).

A *second* option would be to set up a system based on reverse auctions, wherein governments commit to procurement of a certain volume of negative emissions over an extended period and where potential providers of this service can submit bids with prices at which they could accomplish this. The lowest bidder that fulfils the criteria stipulated by the government in question would then win the auction and be rewarded the contract. This approach was suggested by a recent Swedish governmental investigation

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[4] Another crucial factor is public acceptance of CCS.

[5] Potentially, because current prices of EUA are too low to incentivize deployment of CCS. In addition, heavy industries active in globally competitive markets receive large amounts of freely allocated EUAs.

analysing different policy measures to incentivize negative emissions (SOU 2020:4 2020).

In addition to the options above, CCS business models could also be based on combinations of policy measures. One example worth mentioning here is already in operation in California. If CO_2 is used for EOR, this can make the fuel produced from this oil eligible for inclusion under California's Low Carbon Fuel Standard. In addition to this, there is a US federal tax credit available for companies who capture and either sequester or utilize CO_2. As it turns out, revenue from these two policy programmes can be "stacked" and combined to a possible total of around US$ 200 per ton CO_2, which clearly could incentivize a substantial amount of activity in the EOR/CCS space (Global CCS Institute 2019; Rathi 2019). While this may be questionable from the perspective of fossil fuel phase out, it is nonetheless interesting from a policy design perspective.

From a business perspective, deploying BECCU can drive innovation and enable cost reductions that help to unlock the BECCS potential, because BECCS/U shares similar needs for CO_2 capture technologies and infrastructure (IEA 2018a). Similarly, implementing on-site BECCU in a first step, before moving to BECCS in a second step, can be instrumental in identifying commonalities and synergies between the two (Collodi et al. 2017), potentially making investment decisions more robust. However, Mac Dowell et al. (2017) warn that CCU is a "costly distraction" from the mitigation challenge, claiming that – even if CCU might make commercial sense – it takes away the focus and financing from much needed negative emission options such as BECCS.

Finally, a driver of demand for negative emissions could be that businesses will be able to charge a premium for their products because they have carbon-negative supply chains. This would require some coordination across the value chain, however, because even though the additional cost of adding BECCS technology to a pulp and paper mill would add a significant cost to the production of pulp, the price increase of the final product, such as a hardcover book or beverage, would be in the order of 0.1–0.2% (Klement 2019).

5 Discussion

This report has provided an overview of the current technological options for capture, transportation and storage of biogenic CO_2 from different sources and discussed different policy and business models that could be used to support deployment of BECCS. In this concluding section, we close with a few key points that need to be addressed in further discussions on BECCS as a negative emissions technology that can be deployed in the near- to medium term.

To begin with, much of the controversy around the long-term effects of deploying BECCS on a massive scale relates to the amount of land needed to grow the feedstock for the large expansion of BECCS facilities. While there certainly are valid concerns about the effects that this would have on ecosystems and potential for land-use conflicts, these hypothetical long-term issues should not be seen as an obstacle to investigating the deployment of BECCS in the nearer term. The lowest hanging fruit for BECCS is likely to be integration with already existing facilities, as this would largely remove many of the concerns about increased land use.

We have noted that it is important to see BECCS as a subset of CCS. In this respect, it is worth emphasizing that the lowest cost deployment of CCS is not necessarily in fossil applications (Garðarsdóttir et al. 2018). In terms of capture costs, it will in several cases be more economical to capture biogenic CO_2, because the costs of capture are more a function of the specific conditions of a facility and not directly related to whether the CO_2 is of biogenic or fossil origin. However, from a policy perspective, the question of whether the CO_2 is fossil based or biogenic is of central importance, as there are policy tools in place that incentivize the capture and storage of fossil CO_2, but very few – if any – that also incentivize capture and storage of biogenic CO2 (Cox and Edwards 2019). So, a key question moving forward is: given that negative emissions in all likelihood will be necessary to achieve political targets for climate change mitigation, is there a need for more serious discussions on how negative emissions should be incentivized (Burke et al. 2019; Fajardy et al. 2019; Haszeldine et al. 2018)?

In terms of discussions around deployment of BECCS in different contexts, questions of scale are crucial but have not yet been discussed in satisfactory detail. While there may sometimes be diseconomies of scale in the capture component of the BECCS supply chain, the transportation component is another issue, especially in the case of pipeline transport. This means that it may not be feasible to transport and store CO_2 from smaller bioenergy facilities. So, one possible setup could be that smaller facilities could be more suitable for BECCU than for BECCS. It is also important to think about the operation conditions surrounding BECCS and its integration in the electricity sector. A BECCS facility would ideally operate for 24 hours a day, 365 days a year, to maximize the sequestration of atmospheric CO_2 – as well as any revenue received from society for this service. However, this means of operation contrasts with the role that bioelectricity is likely to play in the future electricity system, where capabilities of load-following and grid stabilization can become highly valued in grids dominated by variable renewables in the form of solar and wind. Finding a way to combine these two operational models will be an important component of BECCS and biopower business models.

Finally, it is worth contemplating how BECCS compares to DACCS (i.e., direct air capture and storage of atmospheric CO_2). DACCS has for some time been discussed at a conceptual level, but is garnering increasing interest from researchers and policymakers. For example, Nemet (2019) argues that DAC shares some of the technological characteristics of solar PV in that it is a technology that is modular and potentially amenable to steep cost reductions from technological learning. This could lead to substantial reductions in capital cost, although operational costs could also be substantial given the high energy requirements of DACCS. One possibility is that BECCS and DACCS will turn out to be complementary solutions. For example, implementing BECCS in existing facilities is a different matter than mass deployment of BECCS facilities on greenfield sites – which would be needed for the vast amounts of negative emissions envisioned in some climate change mitigation pathways (IPCC 2018). In summary, though, it is important to emphasize that in order to answer these questions, negative emissions technologies must move from academic discussions to full value-chain deployment.

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