IEA Bioenergy
Technology Collaboration Programme

Deployment of BECCUS value chains

From concept to commercialization

Synthesis Report

IEA Bioenergy: Task 40, 36, 44 & 45

November 2022

image: free image from pixabay.com

Deployment of BECCUS value chains

From concept to commercialization

Synthesis Report

Olle Olsson, Michaël Becidan, Christian Bang, Nabil Abdalla, Silvana Bürck, Horst Fehrenbach, Zoe M. Harris, Daniela Thrän, Otavio Cavalett, Francesco Cherubini, Christiane Hennig

IEA Bioenergy: Task 40, 36, 44 & 45

November 2022

ISBN 979-12-80907-22-6

Published by IEA Bioenergy

Executive Summary

Over the duration of the 2019-2021 IEA Bioenergy triennium, a consortium of IEA Bioenergy Tasks – Task 36, Task 40, Task 44 and Task 45 – collaborated on an inter-task project called *Deployment of BECCUS value chains*. The objective of the project was to improve the understanding of the opportunities for, and obstacles to, deployment of bioenergy combined with carbon capture and utilization or permanent storage (BECCUS).

The ambition of the project was to cut across a broad set of factors that together determine successful deployment. This has included analysis of techno-economic fundamentals and technology readiness, but also business model viability as well as design of appropriate policy and regulatory frameworks. Project components can be classified as belonging to one of two categories, with studies on the one hand looking into cross-industrial and conceptual aspects (system studies) and the on the other hand being industry case studies or deep-dives. All in all, seven publications have been produced as project outputs. This report includes a summary and a synthesis of these individual studies, as well as a discussion and an outlook into questions to be further explored in future research.

The project findings show that, while much of the technology necessary is proven to a great extent, more research and development is needed to find business models for on-the-ground deployment that make the most sense from a techno-economic standpoint when applying CCS (carbon capture and storage) and CCU (carbon capture and utilization) respectively. This includes aspects such as specific designs and technology selection (for example, for CO_2 capture), deployment scales, and site location selection. Furthermore, there are still unanswered questions related to policy design and business models. While some of these issues are evaluated and discussed in this report, several additional questions have arisen during the project and need to be addressed.

Some particularly important aspects for further inquiry can be mentioned. To begin with, despite there being technologies for CO_2 capture that are rather mature and that could be deployed in the near time without much further development, there are emerging approaches that can come with important advantages in the form of improved efficiency and lower costs. Another important conclusion from this project is that conditions for deployment of BECCS and BECCU will vary markedly between the different heavy industries of the secondary industrial sector and national contexts. Varying suitability of different CO_2 capture technologies for existing bioenergy generation concepts is an example of one such condition. But these also include system-wide aspects such as how to integrate it into full supply chains. In terms of national context the governance support for BECCS and BECCUS applications among different countries and regions is very heterogeneous. In some countries and regions first deployment activities with first implemented business models can be observed e.g. in the Scandinavian region. In other countries, on the contrary, there are still mainly research activities in order to address the question if BECCS and BECCU should be applied at all. Furthermore, although this report discusses bio-CCS and bio-CCU jointly and in parallel, there are large differences between the two concepts. These differences partly relate to how the two play fairly distinct roles in terms of climate change mitigation. This also spills over into how policy frameworks and business models are set up.

These emerging questions are presented and discussed in the conclusion section of this report. Moreover, many of these issues will be analyzed and discussed in more detail in a second phase of the inter-task project that will run throughout the 2022-2024 triennium. Next to case studies covering further industries of the secondary industry sector, the core question when to utilize

or to store will be further explored addressing the distinct roles of bio-CCS and bio-CCU. Hence, BECCUS 1.0 and BECCUS 2.0 combined will allow for a complete picture of technology options and a broader systemic view. Information and updates on this can be found at the project website through https://task40.ieabioenergy.org.

Acknowledgments

Funding for this report and the underlying project has been provided by IEA Bioenergy Executive Committee and the individual IEA Bioenergy Tasks (36, 40, 44 and 45).

1 Introduction

Bioenergy combined with carbon capture and utilization or storage, also known as BECCS/U, bio-CCUS or BECCUS (see Text box 1), is a concept that has been discussed in climate change mitigation research for quite some time. However, it is only in the last five-year period that actual implementation has become the subject of serious consideration. For bio-CCS, this increase in interest is largely a result of how technical carbon dioxide removal (CDR), also sometimes referred to as "negative emissions" will be necessary for the world to have any chance at reaching the ambition of the Paris Agreement to limit global warming to 1.5°C above pre-industrial levels (IPCC 2022). Bio-CCU, on the other hand is a concept that thus far has received less attention but one that has become more interesting as an approach to make use of otherwise wasted CO_2 to produce valuable products (Koytsoumpa et al. 2021). While the potential benefits of the two approaches in terms of potential to contribute to climate change mitigation thus differ somewhat in nature, they can both play important roles in the increasingly urgent effort to drastically reduce global greenhouse gas (GHG) emissions. In light of this, identifying and implementing approaches for how bio-CCUS systems can be deployed and integrated in ways that maximize their utility in terms of climate change mitigation, as well as in terms of energy system integration and sustainability ambitions more broadly, is highly important.

Text box 1. Note on abbreviations related to capture of biogenic CO_2

Note on abbreviations

Capture and storage or utilization of biogenic CO_2 is sometimes abbreviated as "BECCS/U", as "BECCUS" and sometimes as "Bio-CCUS". There is not yet real consensus as to which is preferred. However, the latter has the advantage that it does not exclude capture of biogenic CO_2 that originates from processes where energy generation is not the primary goal. Examples of this include fermentation in the production of bioethanol or upgrading of biogas to biomethane.

Over the duration of the 2019-2021 IEA Bioenergy triennium, a consortium of IEA Bioenergy Tasks – Task 36[1], Task 40[2], Task 44[3] and Task 45[4] – collaborated on an inter-task project called *Deployment of BECCUS value chains* under the leadership of Task 40. The objective of the project was to improve the understanding of the opportunities for, and obstacles to, deployment of BECCUS in different industries. The ambition was to get a broad assessment by cutting across the full set of factors that determine successful deployment, including technology readiness, business model viability and design of appropriate policy and regulatory frameworks.

The project elements can be classified as belonging to either of two categories, the first being cross-industrial and conceptual aspects and the second being industry case studies or deep-dives, as illustrated below.

- Conceptual and cross-cutting analyses
    - Overview of technological pathways, policy options and business models (Olsson et al. 2020)
    - Carbon accounting in bio-CCUS supply chains (Olsson et al. 2022)
    - Bio-CCUS and bioenergy flexibility (Hennig et al. 2022)

[1] Task 36 – *Material and energy valorisation of waste in a circular economy*
[2] Task 40 – *Deployment of biobased value chains*
[3] Task 44 – *Flexible bioenergy and system integration*
[4] Task 45 – *Climate and sustainability effects of bioenergy within the broader bioeconomy*

- Industry case studies & deep-dives
    - Bio-CCUS and biomass-based combined heat & power (Bang 2021)
    - Bio-CCS and bioelectricity (Harris 2021)
    - Bio-CCS and waste-to-energy in Oslo (Becidan 2021)
    - Deployment of bio-CCS in the cement industry (Cavalett et al. 2021)

In this report, we summarize and synthesize the work done in the inter-task project. We provide a concise presentation of the overall results and put these into a broader context and discuss further research needs. The structure of the report largely follows a thematic categorization of the project as described above. In section 2, we present the results from the cross-cutting project components, followed by a summary of the industry-focused work in section 3. Section 4 concludes with a forward-looking discussion into issues in need of further research.

2 Cross-cutting aspects of bio-CCUS deployment: system integration and carbon counting

2.1 SCOPING KEY ISSUES[5]

The first component of the project was a scoping report (Olsson et al. 2020) that aimed to review the current status of the bio-CCUS landscape from a scientific and technological perspective as well as from a broader perspective taking into account potential business models and public policy frameworks. In other words, the objective was to collect, synthesize and present an overview of a range of aspects that are of importance to take bio-CCUS value chains from concept to actual on-the-ground commercial operation.

From a technological perspective, an important starting point for any discussion on bio-CCUS is to see it as a subset of a broader group of options for carbon capture and utilization or storage (CCUS). The reason is simply that technology-wise the general principles for capture, processing and storage are the same regardless of whether the CO_2 to be captured is of fossil or biogenic origin. The key difference is primarily related to aspects having to do with the climate impact. CCS based on fossil CO_2 can, even with a (in practice impossible) 100% capture rate, only at best prevent CO_2 from being transferred from geological deposits to the atmosphere, whereas bio-CCS can enable actual net removals of CO_2 from the atmosphere. Similarly, a CCU product – say, a fuel or a chemical - based on fossil CO_2 will only delay the transfer of fossil CO_2 to the atmosphere for the duration of the lifetime of the product in question. In contrast, a CCU product based on biogenic CO_2 will act as a removal of CO_2 from the atmosphere during the product lifetime, changing back to a net zero CO_2 balance once the product has reached its end-of-life. These aspects, which we further elaborate on in section 2.2, are not always fully recognized but are of central importance when it comes to the roles that can be played by CCU, CCS, bio-CCU and bio-CCS in climate change mitigation.

An important aspect to be aware of when discussing bio-CCUS is that it can be implemented in a wide range of industries that are very different but have a common denominator in that they include processes that generate biogenic CO_2. In most contexts under more serious discussion for bio-CCUS deployment, the CO_2 is generated through some sort of combustion process. However, e.g., in the bioethanol production wherein very pure streams of CO_2 are already generated from fermentation processes before the actual conversion. Similarly, for processes wherein biogas is upgraded to biomethane, CO_2 comes out as a by-product in a form that can be very pure.

When it comes to aspects that are worth considering for assessing the techno-economic feasibility of CO_2 capture in different contexts, the CO_2 concentration in the gas stream in question is important in that a higher concentration typically means a more energy efficient CO_2 capture process. Other important aspects include the size of the facility in question, where economies of scale means that bigger tend to be better – and whether there is excess process heat available onsite. So, for example bioethanol production facilities are typically considered as a low-hanging fruit because of the highly concentrated CO_2 available for capture. Applications in pulp and paper mills also show promise thanks to good CO_2 concentrations and availability of process heat that can be used in the capture processes. 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.

From a policy perspective, regardless of the area of application, taking bio-CCS to commercial deployment will require public policy interventions at several levels. To begin with, there is a need for supporting financing to de-risk and/or to co-finance industrial investments in large-scale demonstration facilities. In addition, there needs to be a policy mechanism in place that rewards negative emissions. Currently, 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 quite immature so far.

[5] This section is based on the report by Olsson et al (2020)

In conclusion, the technological obstacles to near to medium-term deployment of bio-CCUS systems are likely not prohibitive. However, the policy measures required to incentivize the demonstration, deployment and operation of bio-CCUS value chains are essential but currently largely absent. In addition, there are key issues to resolve pertaining to carbon accounting, especially when it comes to bio-CCU. We cover these issues further in section 2.2.

2.2 COUNTING CARBON & UNDERSTANDING CLIMATE IMPACT IS ESSENTIAL[6]

As noted in section 2.1, while most of the individual technologies necessary to enable bio-CCUS are at, or close to, commercial readiness, there are still substantial gaps when it comes to the non-technological pieces needed to make value chains fully functioning. When it comes to enabling this, public policy measures will be crucial. Here, there is still substantial progress needed. A particularly important aspect to resolve for development and design of bio-CCUS policies is appropriate carbon accounting and quantification of the climate impact of bio-CCUS systems. The challenges here lie both in developing standardized methodologies and to integrate these into policy frameworks[7]. The report by Olsson et al (2022) aimed at identifying key issues to focus on and discussed different options for how this could be addressed from a scientific as well as from a policy perspective.

While it is common for CCU and CCS systems – be they based on biogenic or fossil CO_2 - to be jointly discussed as (bio-) CCUS, there are important differences between the two. This pertains to post-capture CO_2 accounting, as well as public policy systems and business models. For bio-CCS, analysis of post-capture CO_2 flows should be fairly straightforward, as the CO_2 is to be permanently stored and immobilized in geological formations. This is assuming avoidance of e.g., leakages in transport and storage. The major policy challenge around bio-CCS concerns how to design policy frameworks to incentivize carbon dioxide removal (CDR), also referred to as negative emissions. A key question is if, or to what extent, policy frameworks for CO_2 removal should be integrated into existing systems for emission reductions – such as the EU ETS– or whether there should be specific ring-fenced systems for CDR.

Analysis of the post-capture CO_2 flows for bio-CCU is more complicated than for bio-CCS. CO_2 can be utilized for a wide range of purposes, including as feedstock for many different products, which means that there are great many cases to analyze in order to understand the net climate impact in detail. This concerns aspects such as the process efficiency, the kinds of energy used and what existing product the bio-CCU product could be replacing. In addition, a very important issue that has thus far not received sufficient attention is how to factor in the variation in CO_2 storage durability between different CCU products – i.e., for how long time CO_2 used in a product stays away from the atmosphere. This can vary from less than a year for a fuel or a chemical, via decades for non-packaging plastics and up to possibly centuries in the case of some building materials.

[6] This section is based on the report by Olsson et al (2022).

[7] An important note is that although upstream feedstock supply chains are a key factor in total life cycle emissions accounting, there is already a large literature on carbon accounting in biomass supply chains in general. Furthermore, we do not expect feedstock supply chains for bio-CCUS to differ from biomass supply chains in general, and thus we here only touch briefly upon upstream aspects.

Given the growing interest in (bio-)CCU projects, it is essential to find approaches to *a)* quantify how the climate impact of CCU products depends on inherent CO_2 storage permanence and *b)* how these aspects can be integrated into policy frameworks. To this end, one approach could be to draw inspiration from existing similar frameworks, such as the UNFCCC accounting framework for Harvested Wood Products. However, there is a clear and urgent need for more research into this.

To ensure that bio-CCUS systems can fulfil their potential to mitigate climate change, it is key to strike a balance between properly understanding the full picture of their climate impacts and finding reasonably straightforward means how to include these aspects in policy frameworks. Table 1 summarizes key issues identified in terms of thinking around carbon accounting across bio-CCUS supply chains.

	All Bio-CCUS	Bio-CCS	All Bio-CCU	Short-lived Bio-CCU (e.g., fuels)	Mid to long lived Bio-CCU (e.g., plastics)	Long-lived Bio-CCU (e.g., construction materials)
Key aspects for CO_2 counting	Energy input, Upstream feedstock emissions	Distance between biomass plant and geological storage?	Carbon retention over time (e.g. decay); potential second life stage / handling; Accounting principles (e.g. avoidance of double counting); LC performance in comparison to conventional products (systems); iLUC / aLUC and sustainability aspects of the supply chain;	Movement between industries, tracking across supply chains; LC performance in comparison to conventional products (systems); accounting principles (e.g. avoidance of double counting)	Second life Carbon retention over time Decay function	Carbon retention over time (e.g. decay)
Key aspects for public policy	Consideration of concentration and purity of CO_2 in recommendations (avoid further purification steps where possible for environmental and economic reasons); consideration of energy and upstream feedstock in recommendations	Moral hazard problem? Emission reductions vs negative emissions: equivalence or ring-fencing?	Accounting principles; LC performance; Sustainability of the whole supply chain; iLUC / aLUC;	Consideration of end-use emissions	Adaptation to recyclability	Incentivise long-lived Bio-CCU rather than short-lived
Key open questions	Type of biomass involved	Storage permanence/geological security	Cut-off point(s) for long-lived vs. short-lived (HWP vs 0/500 vs…); Accounting principles in specific cases, e.g. sector coupling, CO_2 as a resource	Type of hydrogen provided	Type of hydrogen provided Supply of additional feedstock?	Market situation/access; supply of additional feedstock (calcium-rich minerals …)

Table 1. Summary of key issues around carbon accounting in bio-CCUS supply chains. (Olsson et al. 2022)

2.3 BIO-CCUS AS A COMPONENT OF FLEXIBLE BIOENERGY SYSTEMS[8]

When implementing climate mitigation scenarios or pathways and their respective measures in order to keep global warming well below 2 degrees Celsius, decarbonizing the global energy system is a core aspect. Main pillars of decarbonizing of the energy system are seen in energy efficiency, behavioural changes, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy and carbon capture and storage (The IEA's seven key pillars of decarbonization (IEA 2021)). To make this transformation work and implement the two pillars renewables and electrification flexibility measures are required. One flexible energy source is thermal power plants like flexible bioenergy plants.

One significant aspect to explore is how the pillars on the energy supply side – namely electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy - are affecting the energy system design and how they interact with each other. Bio-CCUS and flexibility (in the form of flexible bioenergy) are expected to be two of the more important characteristics for the future bioenergy systems and thus low-carbon energy system as such. Therefore, in the area of bioenergy an essential question that arises is how bio-CCUS and Flexible Bioenergy interact when becoming part of the energy system. And from there, to understand how to actually implement and bring these two in a (broader and faster) deployment.

Thereby it is important to see how these two characteristics can come rather in the form of synergies, and finally find strategies for this synergetic implementation. Initial considerations have been presented in this first system study.

In order to support the implementation of both measures the following questions have been identified and discussed:

1. Where and how do bio-CCUS and flexibility interact in biobased value chains and what are the implications for the (bio)energy system?
2. How can the implementation of bio-CCUS solutions in different sectors can be combined with flexible bioenergy in terms of existing modi operandi, technologically, business models and value chain configurations? And how does it look for the different specifications of flexible bioenergy (flexibility of inputs, shifting between different outputs and varying outputs over time)?

The system study shows bio-CCUS and flexible bioenergy are implemented at different speed. Flexible Bioenergy is already in place for grid stability in some regions of the world (Schipfer et al. (2022), IEA Bioenergy Task 44 (2021)). The actual implementation of bio-CCUS has become the subject of serious consideration only in the last five years (Rodriguez et al. (2021), Klement et al. (2021)). This has been also revealed by the case studies presented within the scope of this project (compare section 3). Many concepts are demonstration plants to become full-scale projects or still concepts to become pilots.

Combining CCU and CCS and a flexible operation is possible from a technological point of view. From a modi of operandi point of view a flexible operation may lead to a lower level of total CO_2 captured per installation when ramping up and down is taking place. The current business model for a flexible operation is based on the electricity market prices and/or a possible incentive schemes supporting a flexible operation. As the business models for the provision of flexible bioenergy and bio-CCS are of different nature, it has to be governed which measure is preferable at different times and scales. The currently core business model for operating CCU is the market price realized for selling the carbon. Here, a constant CO_2 capture rate could be required to run reliable CO_2-utilization concepts and business models. A business model for BECCS does not exist per se, potentially it is a revenue generated due to carbon dioxide removal – one could think of a mechanism that rewards CO_2 removal, i.e. negative emissions, like a premium payment (financial instrument) or emission certificates.

[8] This section is based on the report by Hennig et al (2022)

3 Context matters: learning from bio-CCUS projects in different industries

As noted in section 1, bio-CCUS is an umbrella term that includes a great variety and it can be implemented in basically any setting where there are biogenic emissions of CO_2 available in sizeable quantities. The specifics related to implementation can vary quite substantially depending on the sector, jurisdiction and political contexts. Variations can include easily quantifiable differences in technological factors such as CO_2 concentrations in the gas stream to be captured, but also differences in how different sectors operate under varying commercial and regulatory conditions.

In this section, we present results from a series of case studies carried out under this project. The aim of the case studies was to investigate and illuminate such sector-specific characteristics. The ambition was to provide deeper insights into the key aspects that come into play in the process of practically setting up value chains for capture, transportation and sequestration or utilization of biogenic CO_2.

3.1 BIO-CHP AND BIO-CCUS IN COPENHAGEN[9]

Across the Baltic Sea region, biomass-based combined heat and power (CHP) in district heating systems has over the last three-four decades become an important component in the phase-out of fossil fuels for space heating. CHP combines decentralized electricity generation with heat recovery for distribution to residences and commercial buildings alike across metropolitan areas.

With the increased interest in negative emissions as a climate change mitigation strategy, numerous Baltic Sea utilities that operate CHP systems are now looking into adding carbon capture and utilization/storage, or CCUS, to their facilities. HOFOR is a Danish utility owned by the City of Copenhagen, which has set a goal of becoming a carbon-neutral city by 2025, with bio-CCS being one technique under consideration. The city is about to start piloting carbon capture and storage (CCS) at one of its waste-to-energy (WtE) plants. The WtE facility is situated next to the site where HOFOR's biomass-based CHP operations are located, and HOFOR has begun to look into different CCS deployment alternatives also for the latter.

Despite the fact that HOFOR is still in the early stages of its bio-CCUS endeavor, they are convinced that the remaining technological obstacles associated with the CO_2 collection component of the value chain will be manageable. However, there are still some unanswered questions. One of these is the integration of the heat requirement for the capture systems into the heat and power production regime, as well as whether or not there can be synergies between HOFOR's CCS project and other similar regional initiatives. Another question is what will happen to the CO_2 captured, and whether it will be permanently stored or used to make e.g., transportation fuels. This might be one approach to generate revenue to cover the additional costs of the CO_2 capture system's investment and operation. However, financial policy support tied to national Danish mitigation targets could also be used.

3.2 WASTE-TO-ENERGY AND BIO-CCS IN OSLO[10]

Despite increased global objectives for more material recycling, waste-to-energy (WtE) will likely continue to play a role in coming decades as a means of managing waste streams that are challenging to treat in other ways. In advanced economies, 40-60% of municipal solid waste (MSW) utilized as input in WtE facilities tends to be biogenic, implying that WtE implementation of CCS can be at least partially categorized as bio-CCS with the potential to enable negative CO_2 emissions. There are currently several active initiatives investigating CCS in WtE settings across different geographies, with the project originally initiated by FOV

[9] This section is based on the report by Bang (2021).
[10] This section is based on the report by Becidan (2021).

(Fortum Oslo Varme) at its Klemetsrud WtE plant in Oslo, Norway, among the more advanced.

As context, it is worth noting that there is currently a lot of CCS activity in Norway, both in the form of point source capture initiatives – notably the Norcem cement CCS project - and the development of a transport and offshore storage infrastructure project called *Northern Lights*. The FOV project was launched as part of the city of Oslo's larger goal of reducing GHG emissions by 95 percent between 2009 and 2030. With the FOV plant being the city's largest single emission source, finding a mitigation solution is imperative.

The FOV project's initial pilot phase began in 2015, and since then a number of pilot campaigns and feasibility studies on an amine-based CO_2 collection system have been completed. In parallel, the Norwegian government has examined various ideas for facilities that may be used in a full-scale CCS supply chain demonstration. In autumn 2020, it was revealed that the FOV project would be one of two facilities to receive government funding, the other being the Norcem cement plant operated by Heidelberg Cement.

Unlike the Norcem plant (and Northern Lights) however, the original plan for the funding of the FOV WtE project was contingent on it being able to deliver 50% co-funding (300 million €) from own funds or other external sources, with the EU Innovation Fund seen as the best opportunity. In the end, the FOV project was not among those who received funding in the first innovation fund round, as communicated in November 2021. However, the project will still go ahead after the Klemetsrud plant was sold by Fortum in May 2022 to an investor consortium called Hafslund Oslo Celsio (Norwegian Government 2022). This consortium is led by Hafslund Eco (100% owned by the City of Oslo), Infranode and HiltecVision which with governmental support continued to develop the project. The demolition of this plant started in summer 2022 and begin of operation is expected in 2026.[11]

3.3 BIO-POWER AND BIO-CCS AT DRAX[12]

Partially or completely substituting biomass for coal in power plants designed for the latter has over recent decades proven a cost-effective and quick strategy for utilities to reduce their use of fossil fuels while avoiding asset stranding. However, with declining biopower subsidies and rapidly falling costs of solar and wind, bioelectricity faces an increasingly difficult time competing in power markets. However, the growing interest in negative emissions in the form of bio-CCS could create a new market opportunity for biomass power plants, among whom Drax Power Station in northern England is the largest currently in operation. Here, Drax has more than 2.5 GW of biomass-based power capacity based on wood pellets. The company is currently studying and piloting the establishment of a bio-CCS value chain based on absorbing CO_2 from its four biomass-fired units, with the declared goal of being a carbon-negative corporation by 2030. Drax has invested in two pilot projects aimed at better understanding how the capture process will be conducted in practice. One project is utilizing bespoke technology developed by C-Capture and the other is based on an "off-the-shelf" solution provided by Mitsubishi Heavy Industries.

Drax does not envisage any substantial technological impediments to full-scale deployment of the CO_2 collection phase of the whole value chain, despite the fact that the scale of implementation at Drax would be far beyond what has been done previously with these technologies. However, there are a few critical components that must be in place before moving on. First, a transportation and storage infrastructure must be established. Drax is working toward this goal as part of the Zero Carbon Humber initiative, which intends to establish a CCUS cluster in the Humber region (an industrial region on the east coast of northern England). Second, a policy framework must be in place that allows enterprises that produce negative emissions to generate revenue. While Drax believes that negative emissions will be incentivized through some sort of international emissions trading scheme in the long run, complementary interim solutions - such as contracts

[11] https://www.projectaccsess.eu/2022/05/25/fortum-oslo-varme-is-now-hafslund-oslo-celsio/

[12] This section is based on the report by Harris (2021).

for difference - will be required to get projects off the ground in the near to medium term.

3.4 THE ROLE OF BIO-CCS IN THE HARD-TO-ABATE CEMENT SECTOR[13]

Cement is the central component of concrete, the most frequently used construction material in the world and the literal foundation of many modern activities. At the same time, cement manufacture is one of the single most important economic activities in terms of greenhouse gas emissions. According to the International Energy Agency's 2021 Net-Zero study, emissions from cement production must decrease by about 95% between 2020 and 2050 if global climate change mitigation goals are to be met (IEA 2021).

To achieve this, a wide range of measures will be required, including enhanced energy efficiency, reduced cement use, and increased use of alternative binder materials. However, major emission reductions in the cement sector will almost certainly be unattainable without the use of CCS technologies. This study examined the potential for CCS deployment in the cement industry, with focus on the possibilities for integrating this with the use of biogenic fuels for process heat, thereby enabling bio-CCS. This could be a critical instrument for achieving net-zero CO_2 emissions in cement manufacturing, as well as possibly enabling negative emissions.

Bio-CCS can be implemented in the cement industry in a variety of ways, depending on the technology used. When it comes to operational aspects and the level of investment required, their characteristics differ. One thing they all have in common is that, even with the cost savings that come with increased technological maturity, their deployment will result in significant rises in cement production costs.

How these costs should be covered is a crucial question for cement decarbonization. Given that public procurement affects a big amount of societal cement consumption in some way, modifying procurement criteria to enforce low-CO_2 emission cement in publicly funded projects could be a promising policy approach.

[13] This section is based on the report by Cavalett et al (2021)

4 Discussion

4.1 TURBULENT TIMES, BECCUS INCREASINGLY RELEVANT

The *Deployment of BECCS/U value chains* inter-task project ran from 2019 to 2021, with this synthesis report being completed in 2022. It has only been three years since the inception of the project in early 2019, but these years have been truly eventful for global energy and climate aspects in general as well as for BECCS/U developments more specifically. The outbreak of the covid-19 pandemic led to a substantial slowdown in the global economy which resulted in a record drop in GHG emissions in 2020, but already in 2021 emissions had bounced back to above pre-pandemic 2019 levels (IEA 2022). As the pandemic was beginning to recede in early 2022, Russia's invasion of Ukraine let loose another set of shockwaves across global markets and supply chains. The war has had very direct effects on European energy markets, and with emerging ripple effects – the extent of which can only be seen in the years to come – in global markets for energy as well as other commodities like grains and minerals.

However, neither the covid-19 pandemic nor the war in Ukraine takes away the urgency of climate action. When it comes to CDR approaches in general and BECCUS in particular, these become ever more important with every year that the world fails to achieve substantial emission reductions. Having said that, while there is broad agreement on the general importance of CDR and BECCS as mitigation tools, specifics vary broadly. The IPCC AR6 WG3 report (IPCC 2022), covering mitigation of climate change, was released in April 2022. All 1.5°C scenarios modelled by the IPCC include CDR to some extent, although this extent certainly does vary markedly between scenarios. Notably, the cumulative amount of CO_2 removed from the atmosphere by use of BECCS covers a range of 30-780 Gton CO_2 in the time span 2020-2100, with an average of 2.75 Gton per annum in 2050. For reference, the IEAs Net-Zero (IEA 2021), released one year prior to IPCC AR6 WG3, has its BECCS deployment annual removals in 2050 of 1.3 Gton CO_2.

4.2 CONVERGENCE NEEDED BETWEEN SCENARIOS AND ON-THE-GROUND REALITIES

While there is general agreement from both the IPCC and the IEA analysis on the importance of BECCS, there is less information **how** these BECCS volumes are to be achieved. The IEA Net-Zero report (p.78) sees BECCS deployment distributed as 45% in biofuels production, 40% in electricity generation and the remaining 15% in heavy industry, cement in particular. The IPCC AR6 WG3 report mentions different ways of implementing BECCS - including as part of bioelectricity generation and different biofuel production methods. Notably, the illustrative mitigation pathways (IMPs) presented in the report see BECCS-based electricity generation providing 1-5% of global electricity generation in 1.5°C scenarios. In these, BECCS-equipped production systems make up 9-21% of global production of liquid fuels (Ch.6-109).

Given that the 2050 target year is now less than 28 years away, it is becoming increasingly pertinent to find approaches that see a convergence between the role of BECCS, as portrayed in long-term scenarios, and the current situation in terms of deployment. This report, and the project upon which the report is based, has largely focused on mapping and analyzing today's status when it comes to deployment of BECCS systems. However, in an effort to zoom out and bring the findings into a larger context, we have in Table 2 summarized some more general key takeaways from the industry analyses. Taken together with the overview of important carbon accounting aspects in Table 1, this set of factors can form a starting point for continuing discussion on how to accelerate deployment of sustainable BECCUS systems.

Industry	Techno-economic issues	Negative emissions possible with BECCS?	BECCUS or BECCU?	Factors for creating business models	Main other decarbonisation options
Electricity	Optimize on CO_2 capture or electricity value?	Yes	Both possible	Policy incentives for negative emissions such as ETS, carbon pricing	Solar, wind, nuclear…
Heat	Optimize on CO_2 capture or heat value? Scale of heat plants?	Yes	Both possible	Policy incentives for negative emissions such as ETS, carbon pricing	Heat pumps, electricity
Cement	Biomass or electricity for process heat? High CAPEX needed for high % capture and low OPEX	Possibly	BECCS could be preferable because CO_2 stream is partially fossil	Policy incentives for negative emissions such as ETS, carbon pricing, or downstream procurement demands	Other binder materials, material efficiency, though zero emissions needs CCS.
Waste-to-energy (WtE)	High CAPEX needed for high % capture and low OPEX	Probably	BECCS could be preferable because CO_2 stream is partially fossil	Policy incentives for negative emissions such as ETS, carbon pricing (+ downstream procurement criteria?)	Material recycling, though some portion of WtE likely to be needed long-term

Table 2. Overview of different aspects pertaining to implementation of BECCUS in different industries (series of case studies presented in this study)

4.3 CONCLUSIONS AND FURTHER RESEARCH

The focus of the first phase of the *Deployment of BECCS/U value chains* inter-task project has been on trying to review and discuss a broad set of factors that determine successful deployment. These factors include technology readiness, business model viability, upstream supply chain set up and design of public policy and regulatory frameworks.

Our results indicate that while much of the technology required to a large extent can be considered proven, there is still research and development needed into finding models of on-the-ground deployment that make the most sense from a techno-economic perspective. This includes aspects such as specific designs and technology choice (e.g., for CO_2 captures), deployment scales and choice of site locations. Furthermore as the case studies reveal many concepts are looking for (right) business models for the captured carbon. The business models show that in many cases the carbon is utilized rather than stored and often actually lack a business model for implementing CCS. This is mainly due to missing knowledge and concepts for storage and above all missing political will and governance with corresponding support measures and regulations for storing the carbon and thus creating demand for negative emissions. Also the supply chain set up and possibly alterations of existing supply chain concepts bring challenges. This might be due to the scale of the facilities and the economic feasibility of related investments when integrating capture processes or connecting to a storage site (mainly the case with smaller single point capture project). While some of these issues have been reviewed and discussed herein, many new questions have emerged over the course of the project and that remain to be addressed for a (broader) deployment of BECCUS. Particularly important factors that remain to be investigated further pertain to:

- Shedding more light on the different types of capture processes
- Supply chain integration approaches for integrating the capture and the storage or utilization in the existing infrastructure. For some cases it might be feasible and beneficial to develop an own storage or utilization infrastructure and in some cases to connect to a cluster.
- Analysis of the important differences *between* BECCS and BECCU, not least from the perspective of potential business models and public policy development In order to better understand when it is preferred to store or utilize the captured carbon.
- Shedding light on deployment options for small-scale BECCS, so the perspective of carbon capture in small-to-medium biomass installations (with a removal capacity less than 100 kton CO_2 per year), of which there are many in Europe
- Synergies and/or trade-offs with other energy system services (e.g. flexibility) and other CDR technologies when integrating CCUS into biobased value chains and thus the broader energy and climate systems
- Detailed analysis of design and implementation approaches for policies incentivizing BECCUS systems
- Sustainability aspects and risks related to the implementation of the CDR option BECCS[14]

[14] The latest IPCC WG3 publication the sixth assessment report as of April 2022 has acknowledged that (IPCC 2022): *"The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO2 or GHG emissions are to be achieved. The scale and timing of deployment will depend on the trajectories of gross emission reductions in different sectors. Upscaling the deployment of CDR depends on developing effective approaches to address feasibility and sustainability constraints especially at large scales. (high confidence) {3.4, 7.4, 12.3, Cross-Chapter Box 8 in Chapter 12}"* (in Climate Change 2022, Mitigation of Climate Change, C.11).

CDR is perceived as an important addition to all 1.5 degrees scenarios. This shows how fast climate change is progressing and also that nations worldwide have been doing so far too little in recent years to actually combat climate change. This makes the application of CDR technologies vital and asks for their deployment. While doing so, it is underlined that the "how" ,i.e., the appropriate implementation is key in order to avoid negative environmental and social impacts. (IPCC 2022. Climate Change 2022, Mitigation of Climate Change, C.11.2)

Some of the presented issues are further in more detail in a second phase of the project. During the IEA Bioenergy triennium 2022-2024, a second phase of the inter-task project will run. This is part of the work of the IEA Bioenergy Task 40 group on deployment of biobased value chains and understood as an inter-task activity with other IEA Bioenergy Tasks. For the actual deployment of BECCUS there is still a way to go. In order to move to deployment we need to understand which conditions are required and which concepts can contribute to a broader deployment and how the design of public policy instruments and measures shall look like to make their deployment effective. Crucial and guiding for further research into the deployment of BECCUS are the results and of the ITP BECCUS phase 1.0 project. Information and updates on this can be found at the project website through https://task40.ieabioenergy.org .

References

Bang, C. (2021). *Deployment of Bio-CCS: Case Studyon Bio-Combined Heat and Power*. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2021/05/Bang-FINAL-2021-IEA-Bio-BECCUS-HOFOR.pdf

Becidan, M. (2021). *Deployment of Bio-CCS:Case Study on Waste-to-Energy*. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2021/05/Becidan-2021-FINAL-IEA-Bio-BECCS-FOV-Case-study.pdf

Cavalett, O., Cherubini, F. and Olsson, O. (2021). *Deployment of Bio-CCS in the Cement Sector: An Overview of Technology Options and Policy Tools*. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2022/03/bio-CCS-in-the-cement-sector.pdf

Harris, Z. (2021). *Deployment of Bio-CCS: Case Study on Bioelectricity*. https://www.ieabioenergy.com/wp-content/uploads/2021/05/Harris-2021-FINAL-IEA-Bio-BECCS-Drax-Case-study.pdf

Hennig, C., Olsson, O., Thrän, D. (2022). *Bio-CCUS and Bioenergy Flexibility - Finding the Balance*. IEA Bioenergy (tbp)

IEA (2021). *Net Zero by 2050 - a Roadmap for the Energy Sector*. https://www.iea.org/reports/net-zero-by-2050

IEA (2022). *Global CO2 Emissions Rebounded to Their Highest Level in History in 2021 - News - IEA*. International Energy Agency. https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021

IEA Bioenergy Task 44 (2021). Expectation and implementation of flexible bioenergy in different countries.

IPCC (2022). Climate Change 2022. *Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*

Klement, J., Rootzén, J., Normann, F., Johnsson, F. (2021). Supply Chain Driven Commercialisation of Bio Energy Carbon Capture and Storage. *Frontiers in Climate. Sec. Negative Emission Technologies*. DOI: https://doi.org/10.3389/fclim.2021.615578

Koytsoumpa, E. I., Magiri – Skouloudi, D., Karellas, S. and Kakaras, E. (2021). Bioenergy with carbon capture and utilization: A review on the potential deployment towards a European circular bioeconomy. *Renewable and Sustainable Energy Reviews*, 152. 111641. DOI: 10.1016/j.rser.2021.111641

Norwegian Government (2022). *Sikrar Finansiering for CO2-Fangst På Klemetsrud - Regjeringen.No*. https://www.regjeringen.no/no/aktuelt/sikrar-finansiering-for-co2-fangst-pa-klemetsrud/id2912399/

Olsson, O., Abdalla, N., Bürck, S. and Fehrenbach, H. (2022). *Carbon Accounting in Bio-CCUS Supply Chains – Identifying Key Issues for Science and Policy*. IEA Bioenergy

Olsson, O., Bang, N. C., Bolchers, M., Hahn, A., Karjunen, H., Thrän, D. and Tynjälä, T. (2020). *Deployment of BECCS/U Value Chains*. IEA Bioenergy Task 40. https://www.ieabioenergy.com/wp-content/uploads/2020/06/Deployment-of-BECCS-Value-Chains-IEA-Bioenergy-Task-40.pdf

Rodriguez, E., Lefvert, A., Fridahl, M., Grönkvist, S., Haikola, S., Hansson, A. (2021). Tensions in the energy transition: Swedish and Finnish company perspectives on bioenergy with carbon capture and storage. *Journal of Cleaner Production*, 280. 124527. DOI: https://doi.org/10.1016/j.jclepro.2020.124527

Schipfer, F., Mäki, E., Schmieder, U., Lange, N., Schildhauer, T., Thrän, D., Hennig, C. (2021). Status of and expectations for flexible bioenergy to support resource efficiency and to accelerate the energy transition. *Renewable and Sustainable Energy Reviews*, 158. 112094. DOI: https://doi.org/10.1016/j.rser.2022.112094

IEA Bioenergy
Technology Collaboration Programme