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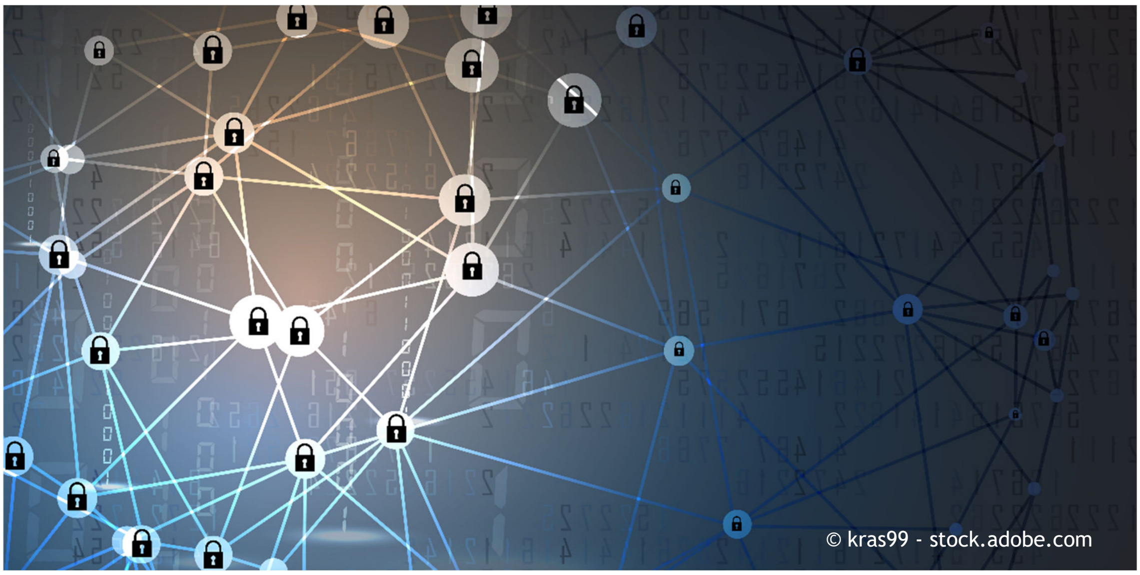
BECCUS and flexible bioenergy – finding the balance

Contribution of IEA Bioenergy Task 44 & Task 40 to the Inter-task project *Deployment of BECCUS value chains*

IEA Bioenergy: Task 44

August 2023



BECCUS and flexible bioenergy – finding the balance

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Preface

Next to accelerating the reduction of greenhouse gas emissions, substantial amounts of negative carbon dioxide emissions may be required if global climate change is to be limited to well-below 2°C above pre-industrial levels, as is the ambition of the 2015 Paris Climate Agreement. Among the different negative emissions technology options available, bioenergy with carbon capture and storage, also referred to as bio-CCS or BECCS, is arguably one of the most commonly discussed in climate policy debates.

Up until recently, BECCS was primarily discussed in terms of its potential and drawbacks over very long timeframes, e.g., 2050 and beyond, but there is now growing focus on more near-term aspects. The IEA Bioenergy inter-task project *Deployment of BECCUS value chains* ran 2019-2022 and strives to provide insights about the opportunities and challenges pertaining to taking BECCS and also BECCU from pilots to full-scale projects. To this end, the project puts focus not only on technological aspects but also on how BECCU/S business models could be set up and the role that public policy could play in enabling sustainable deployment of BECCU/S. It should though be noted that the focus in the project is on the CO_2 capture, transportation and storage or utilization phases of the supply chain. Upstream biomass feedstock supply systems are only touched upon very briefly in this study as these issues have been analysed to great detail in other IEA Bioenergy work[1].

An important characteristic of BECCU/S is that it can be implemented in a broad range of sectors - basically any setting where there are biogenic emissions of CO_2 available in sizeable quantities. This includes generation of heat and power from biomass in various contexts, but also industrial facilities like cement production, pulp & paper mills or ethanol plants. The specifics related to BECCU/S implementation can however vary quite substantially from sector to sector. This is partly because of differences in technological factors like CO_2 concentrations and volumes, but also a result of how different sectors operate under widely varying commercial and regulatory conditions.

A key aspect of integration of CCS/CCU in already operating systems is how the addition of carbon capture and storage or utilization interacts with existing modi of operandi, technologically as well as when it comes to business models and value chain configurations. In this report, we focus on one particular aspect of this, namely how implementation of BECCU/S solutions in different sectors can be combined with different forms of flexibility as it pertains to bioenergy, including flexibility in terms of inputs, shifting between different outputs and varying outputs over time and place. Thereby it is the objective to identify if their combined implementation within a certain technology can come rather in the form of benefits and which trade-offs might exist. Widely speaking what the implications for the energy system design are. For the analysis available case studies on the application of BECCS and BECCU were taken into account. Thereby mainly combustion technologies for renewable energy generation were looked into, with a focus on the post-combustion technology to capture the carbon. This system study is part of a series of studies carried out under the IEA Bioenergy inter-task project Deployment of BECCUS value chains with the aim to highlight these system-specific characteristics.

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[1] Compare IEA Bioenergy Task 43 “Biomass Supply in Sustainable and Circular Economics” https://task43.ieabioenergy.com/

Executive Summary

Flexible bioenergy and BECCS (bioenergy with carbon capture and storage) are two important technologies that are expected to play a crucial role in mitigating climate change (compare IEA Net Zero by 2050 roadmap, IEA 2021). Flexible bioenergy involves the use of biomass to produce energy, such as heat and electricity, and can be used to replace fossil fuels in various applications. The flexibility of this technology lies in its ability to adjust its output according to the demand for energy, inter alia, making it a valuable complement to intermittent renewable energy sources like wind and solar power (operational flexibility) and also allowing the use of different feedstocks and intermediates (flexibility in input) as well as providing different energy carriers and products and services (flexibility in output).

On the other hand, BECCS is a negative emissions technology (NET) that involves the use of bioenergy to produce electricity or other forms of energy while capturing and storing the resulting carbon dioxide (CO_2) emissions underground and thus preventing it from entering the atmosphere. This process not only reduces emissions from the energy sector but can also remove CO_2 from the atmosphere, thus contributing to negative emissions. With BECCU the resulting carbon dioxide emissions are captured and further utilised and thus kept for some longer time in use. However, CO_2 emissions are not permanently stored and prevented from entering the atmosphere. Negative emissions won't result from this technology.

Combining CCU and CCS with a flexible operation of bioenergy facilities is possible from a technological point of view. With respect to modi of operandi a flexible operation of a bioenergy installation can lead to a lower level of total CO_2 captured per unit when ramping up and down is taking place. The current business models for a flexible operation is mainly based on the electricity market prices and/or a possible incentive schemes supporting a flexible operation. Broader climate policy instruments and corresponding incentive schemes, however, are not in place (yet). The currently core business model for operating CCU is the market price realised for selling the carbon for use in other applications. Here, a constant CO_2 capture rate could be required to run reliable CO_2-utilization concepts and business models. For developing a business model for BECCS a reward system needs yet to be established first, 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. As the business models for the provision of flexible bioenergy and BECCS/U are of different nature, it has to be governed which role each of the technologies are going to play within the energy system and further within climate policy making. In particular, the implications of the interaction of both technologies should be considered and taken into account.

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1 Introduction

1.1 THE ROLE OF BECCUS IN REACHING NET-ZERO EMISSIONS

The discussion on bioenergy with carbon capture and storage or utilization (bio-CCUS, BECCS/U or BECCUS) has for quite some time focused on the long-term opportunities and challenges of these technologies to mitigate climate change. However, it is really only in the last five-year period that their actual implementation has become the subject of serious consideration and first projects being launched (for example the Danish energy company Ørsted awarded a 20-year contract for its carbon capture and storage (CCS) project with adding a carbon capture unit to the biomass based combined heat and power plants in the greater Copenhagen area and in Kalundborg with a total capture and storage rate of approx. 430,000 tonnes of biogenic CO_2 every year[2], and RWE to the power plants in Eemshaven and Amer with prospective 11 to 14 megatons of negative emissions[3].) The reasons for this are largely related to two factors: *a)* an emerging awareness of the need for BECCS and other negative emissions technologies if there is to be any chance to stay well below a 2°C increase in the global temperature and *b)* the rapidly decreasing costs of solar & wind (and expectations of similar developments for electrolysers) that have made BECCUS options based on power-to-X technologies more interesting.

Technologies for capturing the biogenic CO_2 from bioenergy generation are the same that are used for capturing the carbon from fossil origin. Overall three main types can be differentiated 1) the oxy-fuel combustion process, the pre-combustion process and the post-combustion process. When it comes to adding carbon capture to biomass based electricity or combined heat and power installations post-combustion is the most promising technology as a retrofitting will allow its integration.

While the term "BECCUS" is useful as an umbrella term to cover all aspects related to capture of CO_2, it is important to be aware that apart from the CO_2 capture component, BECCU and BECCS do not have very much in common. BECCS can be highly valuable to generate negative emissions but does not make sense without a market - created through policy and/or voluntary purchases - that specifically values removal of CO_2 from the atmosphere. BECCU on the other hand will in most cases **not** generate negative emissions but can be valuable as a means of producing fuels and other hydrocarbon-based products with close-to-zero emissions footprint. One way to see this is that BECCS is important for the climate system to generate negative emissions and just adds problems for the energy system in the absence of a mechanism that rewards carbon dioxide removal (CDR), whereas BECCU may not generate negative emissions but is still important for the climate system in its potential of allowing substitution of fossil products and can also be supportive to the energy system.

In light of this, identifying and implementing approaches for how BECCUS systems can be deployed and integrated in ways that maximise benefits in terms of climate change mitigation - as well as in terms of energy system integration and sustainability ambitions more broadly - is highly important.

1.2 FLEXIBLE BIOENERGY

Flexibility is a phrase that has become increasingly common in energy and climate discussions over the last decade, predominantly pertaining to find and implement approaches by which the intermittent power generation patterns of wind and solar can be handled in electricity systems where they are increasingly dominant (see e.g., IEA 2021). This definition is highlighting the importance of flexibility for an electricity system based on renewable resources. Hence, it is rather narrow and only covers one aspect of flexibility, that in the electricity system.

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[2] https://orsted.com/en/media/newsroom/news/2023/05/20230515676011

[3] https://benelux.rwe.com/en/press/2022-12-12-rwe-launches-project-beccus-for-large-scale-capture-and-storage-of-co/

For bioenergy, which tends to be generated in biobased value chains where energy is only one of several different outputs, products and services, the discussion on flexibility needs to be broadened. In other words, in bioenergy systems, flexibility can come in a wide variety of forms, some of which are connected to electricity system operations but others that are not. If we want to understand flexibility at a more granular level and in specific sectors, a thorough analysis is needed. The energy transition requires flexibility measures in different sectors - including industrial and space heating, provision of transportation services – and across sectors, and also e.g. in the broader circular economy.

2019 saw the launch of a new IEA Bioenergy Task specifically focused on flexibility in bioenergy systems also referred to as flexible bioenergy. This Task, **IEA Bioenergy Task 44 - Flexible bioenergy and system integration**, defines flexible bioenergy in general as "*…a bioenergy system that can provide multiple services and benefits to the energy system under varying operating conditions and/or loads*" (IEA Bioenergy Task 44). In other words, this goes beyond balancing variable renewable energy (VRE) in the electricity system and "cover(s) multiple dimensions of flexibility, including temporal and spatial flexibility, as well as flexibility with respect to feedstock, operation, and end-products." (Schildhauer et al. 2021).

When applying this broader definition and understanding to the scope of the biobased value chain then flexibility comes with the input (downstream), the output (upstream) and conversion process. As illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**, flexibility within biobased value chains can be seen in inputs (feedstocks and intermediates) and outputs (energy carriers and products) and the flexibility in operations (with the respective temporal and spatial occurrence).

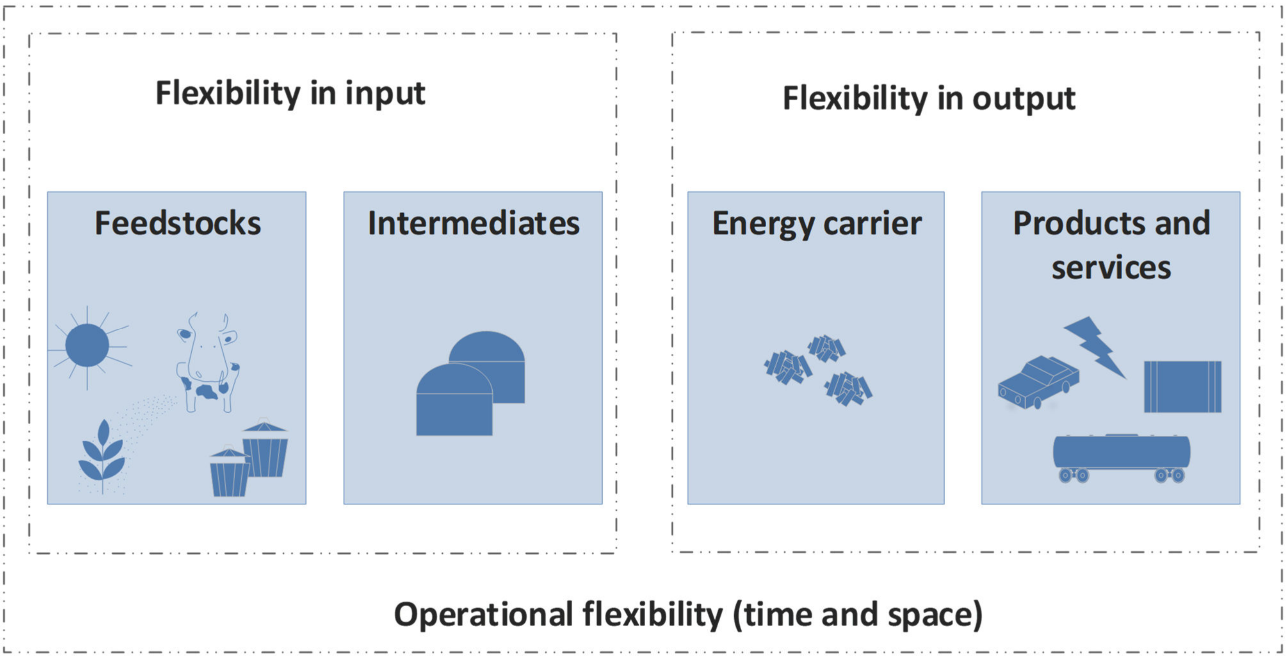

Figure 1 Dimensions of Flexible Bioenergy in biobased value chains (based on IEA Bioenergy Task 44 and Schildhauer et al. 2021)

Flexibility in input refers to the ability of a bioenergy system to use various types and qualities of a) biomass feedstock or b) intermediates, providing a broader feedstock base. This aspect increases the flexibility of a bioenergy system or a system using biogenic feedstocks as fuel by being able to respond to changes in the feedstock supply chain – both in quantity and quality terms – and also to market price disruptions.

Flexibility in output refers to the ability of a bioenergy system to produce and provide multiple products and services. These can be (a) different energy carriers and (b) different products (electricity, heat, fuels, biochemical) and thus energy system services e.g., long-term (energy) storage[4]. This ability of flexible bioenergy systems to provide multiple products and services supports the energy system as well as the establishment of a circular biobased economy.

Flexibility in operation:

The **time dimension of operational flexibility** describes when the feedstock or intermediates is applied in order to achieve a market demand-oriented energy and/or (bio)energy system service supply (compare also Lauer et al. 2017) and when the respective energy carrier or application is available. This can be categorised in "**short-term flexibility** to balance and stabilise the electricity grid by both positive and negative ancillary services and **long-term flexibility** by biomass-based energy carriers that can be (seasonally) stored and transported within existing infrastructure" (compare also Schildhauer et al. 2021).

The **space dimension of operational flexibility** addresses where the feedstock can be sourced or intermediates can be produced and where the product and/or system service can be applied. Implying that a feedstock or bioenergy product, respectively, can be easily stored, handled and transported (compare also Schildhauer et al. 2021) and/or on the output side that a system service can be easily applied to various energy sectors.

1.3 REPORT OBJECTIVE AND RESEARCH QUESTIONS

Given that BECCUS and flexibility measures for example in the form of flexible bioenergy are expected to be two of the more important characteristics for bioenergy systems of the future and thus services for a low-carbon energy system, it is important to see how these two aspects interact and find strategies for how these interactions can come in the form of benefits rather than trade-offs. In this brief, we discuss how flexible bioenergy and BECCUS interact across a series of different sectors and contexts and outline some key areas that merit particular attention for researchers, policy makers and practitioners alike.

Our key research questions are:

- How could a more flexible operation of the BECCUS value chains of the various sectors look like?
- Where and how do BECCUS and flexible bioenergy interact in biobased value chains and what are the implications for the (bio)energy system?
- How can the implementation of BECCUS solutions in different sectors be combined with flexible bioenergy in terms of existing modi of operandi, technologically, business models and value chain configurations?

For shedding some light on these questions different case studies on technologies and sectors which have been carried out under this project are used as examples. These case studies represent two main industry sectors – the heavy industry sector as the cement industry as hard-to-abate sector, and the secondary industrial sector with energy generation facilities based on biomass. By means of these case studies it has been explored how flexibility measures may affect the carbon capture of these (bioenergy) technology concepts.

A general overview on the characteristics and development of different technologies for flexible bioenergy is presented and discussed in the IEA Bioenergy Task 44 publication "Technologies for Flexible Bioenergy" (Schildhauer et al. 2021). This report gives a broad overview on the different bioenergy technologies and their implications when operated flexibly as well as the need for further research and development on flexible bioenergy. The information and findings of the report in the area of biomass combustion technologies are used here to describe and discuss how flexibility measures look like with the individual technologies.

[4] Also compare definition of Flexible Bioenergy by IEA Bioenergy Task 44

2 BECCUS and flexible bioenergy in different sectors

An important starting point for any discussion on BECCUS is that it can be implemented in a wide variety of sectors – essentially anywhere there are biogenic CO_2 emissions. Consequently, there is a substantial amount of heterogeneity attributable to the diversity in applications available. This pertains partly to technological issues – e.g., CO_2 concentrations, a key aspect for costs of capture – but to market and policy aspects as well. Throughout the course of the IEA Bioenergy inter-task project on deployment of BECCUS value chains, a series of case studies on the application of the post-combustion technology has been carried out that each illuminate the factors that are particularly important for implementing carbon dioxide capture. The sectors of interest for bioenergy combustion are the energy industry and the manufacturing industry, especially heavy industries where fossil fuels can be potentially replaced by biobased fuels. Below we build upon these case studies and specifically discuss how the issue of flexible bioenergy comes into play in each context and how a more flexible operation of the BECCUS concepts could look like. Moreover, this analysis will give insights where and how BECCUS and flexible bioenergy interact in biobased value chains. Finally, general conclusions are derived.

The examined BECCUS case studies for the different sectors are namely[5]:

1. Biomass-based electricity generation and bio-CCS (Drax Power Station, United Kingdom),
2. Biomass-based combined heat and power and bio-CCS (HOFOR Amager CHP, Copenhagen, Denmark),
3. Waste-to-energy and bio-CCS (Fortum Oslo Varme (FOV), Oslo, Norway),
4. Bio-CCS implementation in the cement industry.

2.1 DRAX (ELECTRICITY FROM BIOMASS COMBUSTION)

Power plants based on biofuels are well suited for implementing carbon capture technologies. The CCS/U technologies can be rather easily integrated within the existing facilities and corresponding infrastructure. Large power plants (> 100 MW installed electric capacity), like the DRAX power plant in the UK, reveal a high level of removal of CO_2 as large CO_2 single point emitter. Even more important during the post combustion process a high level of CO_2 capture can be realised (Olsson et al. 2020). At the same time biomass power plants can be managed flexibly in terms of input – various types of feedstock like woody and agricultural residues and waste materials also of different qualities are conceivable. In the current deployment woody residues and wastes are mainly used due to economic reasons linked to feedstock costs. Also, agricultural residues and waste materials are still available on the market to a limited extent. Also, a flexible operation i.e. ramping up and down is a flexibility that can be provided by biomass power plants. The larger the plant the more the benefits need to be evaluated. Combining CCS/U and a flexible operation is possible from a technological point of view. However, it may represent a trade-off with respect to operational flexibility. A more flexible operation would mean a lower level of CO_2 captured due to ramping up and down, when e.g. contributing to more grid stability. In this case a constant CO_2 capture rate cannot be assured what could be specifically a drawback for certain CO_2-utilization concepts and business models where a constant level of CO_2 supply may be a requirement (Harris 2021).

The decision for the type of operation would be guided by electricity market prices or other incentive schemes for providing flexibility services and by the potential revenue generated from carbon dioxide removal and the penalty to be paid from having to buy emissions rights or pay a carbon tax. Overall, it is subject to climate policy and energy security goals to either prioritise one of these services or to demand both. Here further research would be required addressing among others the question if a CCS operation would result in a higher level of carbon emissions savings due to negative emissions and thus compensating for the amount of variable renewable energy sources that could not be used as flexibility measures were not provided in that case. Here it would be important to look into other flexibility measures than flexible

[5] More details on the respective case studies can be found here: https://www.ieabioenergy.com/blog/task/deployment-of-beccus-value-chains/

bioenergy and their potential availability. At the same time one could also consider to have dedicated biomass-based power plants in place either operating fully in base load with carbon capture or focusing on a flexible operation without BECCUS.

2.2 HOFOR AMAGER (BIOMASS-FIRED COMBINED HEAT AND POWER (CHP))

Biomass-fired combined heat and power plants (CHPs) can be highly important and valuable resources in energy systems. This is not just because they enable highly efficient energy generation through the co-production of both electricity and heat, but also due to their decentralised nature and their operational patterns they can act as an important source for flexibility. The fact that CHP plants tend to be located in, or close to, urban centers means that they can act as a form of firm decentralised generation of renewable electricity, a property which is rare among power generation technologies. In addition, in high latitude regions with cold winters, the electricity generation of CHP plants tend to be the highest at times when e.g., solar PV produce the least, thereby providing important seasonal balancing capacity. Next to this operational and output flexibility offered, various types of feedstocks of different qualities can be used (flexibility in input).

CHP plants based on biofuels are well suited for implementing carbon capture technologies. Hence, it is important to raise the question around how this balancing role can be best combined with generation of negative emissions through the addition of BECCS. As described earlier bio-CCS facility should ideally run with as high a capacity as possible to maximise the amount of CO_2 captured, as capturing of CO_2 will consume energy which otherwise could have been used for electricity generation. One way to integrate BECCS in CHP plants without having to do too much of a trade-off against the role of dispatchable decentralised generation is to design the facility so that it is possible to by-pass the CO_2 capture unit as described by e.g., Levihn et al. (2019). This concept would allow the plant to avoid the energy penalty from the CO_2 capture during hours of the year with highest peak load, say around 5% of the total annual runtime. In other words, it would be a question of “flexing from the top”, i.e., where the plant runs at full capacity for most of the year in order to generate as much negative emissions as possible but then prioritises electricity generation at specific times when this is needed the most.

2.3 FORTUM OSLO VARME (WASTE-TO-ENERGY)

Waste-to-energy facilities can be operated flexibly in terms of types of fuels used. A wider spectrum of fuel qualities can be considered. Moreover, multiple energy products can be provided. These facilities can provide heat and/or electricity directly through combustion. One common application of the heat produced is the supply to the local district heating network.

On the user end when supplying heat to the local district heating network a constant supply during the heating season has to be assured what limits a flexible operation during this time of the year. Moreover, energy supply can be limited to a certain area that is the local district heating network. Hence, waste-to-energy plants might be not the preferred facilities for balancing VRE in the electricity system.

Combining CCS/U and a flexible operation at waste-to-energy facilities would be in general possible from a technological point of view. Carbon capture can be integrated into the established production process. The decision for the type of operation would be guided by the described heat demand pattern. For the heating period of the year a constant carbon capture can take place what would be a favourable condition for CCS and CCU. During the summer period a constant CO_2 capture rate may not be assured what could be specifically a drawback for certain CO_2-utilization concepts and business models where a constant level of CO_2 supply may be a requirement.

An important aspect of CCS in waste incineration plants is that only roughly 50% of the input material is on average from biogenic origin by global comparison (Babu et al. 2021). This varies between geographies and also over time as waste management practices evolve. Thus, only the organic fraction of municipal solid waste (OFMSW) can be attributed to bio-CO_2 streams.

2.4 BECCUS IMPLEMENTATION IN THE CEMENT INDUSTRY

Compared to the previously described concepts the cement industry belongs to the heavy industry sector. According to the IEA Net Zero by 2050 roadmap, 15% of the BECCUS applications are estimated to happen in the heavy industry mainly in the cement industry (IEA 2021). For cement facilities especially flexibility with respect to the input can be under main consideration. Cement facilities are quite flexible in terms of different types of fuel used from a technology perspective because high combustion temperatures allow also the use of fuels with lower quality, although energy-dense fuels are required to reach these high temperatures. Today, biogenic wastes are already looked into and tested. The tests show that from the physical and chemical properties perspective organic wastes can act as alternative fuels. The main challenge lies within the requirement to reach higher temperatures which cannot be achieved when solely using biogenic waste fuels. Thus, only a certain share of replacing conventional fuels can be considered in the future (Kusuma et al. 2022; Rahman et al. 2016). Flexibility in operation is rather unlikely since a constant fuel supply might be required for the production process. Production interruptions would be rather troublesome from a process perspective prevailing the benefit of a flexible operation for balancing power.

An important aspect of carbon capture in cement industry is that it is not given that carbon capture and storage results in negative emissions at site level because the majority of CO_2 emissions in cement comes not from fuel combustion but from the limestone used as raw material. Maximization of the organic share in the fuel mix can result in negative emissions, but this is not a given. Thus, a cement production facility with a varying fuel mix could potentially shift between different types of fuels, on some occasions being rewarded for carbon dioxide removal (CDR) and on other occasions being forced to buy emission rights. This makes for an interesting case in terms of flexibility in input as there would be potential to balance the relative cost of fuels -e.g., biomass vs coal - against the potential revenue generated from carbon dioxide removal and the penalty to be paid from having to buy emissions rights or pay a carbon tax. A key question here pertains to the exact policy design of CDR rewards and if these are directly linked to penalties of emitting fossil CO_2. On the policy design first debates and research happen.

3 Lessons and conclusions from the case studies

From the BECCS deployment case studies the following conclusions can be drawn when considering a flexible operation:

- Combining CCS/U and a flexible operation at the presented facilities would be in general possible from a technological point of view.
- Different types and levels of flexibility measures (flexibility in input, operations and output) can be applied to the various BECCS/U case studies with post-combustion.
- All presented case studies allow for the flexible input of materials.
- However, not all of the BECCS/U case studies and thus (bioenergy) facilities are suitable for flexible operation
- A flexible operation does not allow for a constant CO_2 capture rate what could be specifically a drawback for certain CO_2-utilization concepts and business models where this is a requirement. Here a trade-off exists.
- Also a flexible operation leads to a lower level of carbon captured what in turn results in a lower level of negative emissions per point source.
- Three of the cases are purely energy related and one is in an industry setting. Hence there are operation requirements resulting in different drivers for providing flexibility measures. As an energy provider it is more common to ramp up and down as the focus is on an energy market. As a heavy industry company, the process and consumer product is the main business. In the latter case other incentives are presumably required for ramping up and down.
- Due to the lack of policy instruments on rewarding carbon capture and storage, most of the business models will currently look into utilization for using the captured carbon.

The lessons learned are summarised in the Table 1 below. There, an overview on the specifics on implementing flexibility measures in post-combustion BECCU/S concepts in each of the energy generation and heavy industry sectors is presented. . This conceptualisation has been named “FlexBECCUS” implying benefits and/or trade-offs when applying both flexible bioenergy measures and CCS/U to bioenergy technologies in different sectors (here with particular focus on biomass combustion technologies). The discussion of the possible implications of FlexBECCUS are presented in the last column of the table.

	Role of CCU/S in biomass combustion in different sectors "BECCSability"					Role of flexibility in biomass combustion in different sector	Flexibility measures and BECCUS "FLEXBECCUS"
Sector	**Techno-economic issues**	**Negative emissions possible with BECCS?**	**BECCS or BECCU?**	**Factors for creating business models**	**Main other decarbonisation options**	**Key flexibility aspects (Flexibility in input, output and operation)**	**Benefits and/or trade-offs when applying flexible bioenergy and CCS/U to the different sectors**
Electricity	Trade-off: Optimize on CO_2 capture or electricity value?	Yes	Both possible	Policy incentives for negative emissions such as ETS, carbon pricing	Solar, wind, nuclear	Flexibility in input (different types and qualities of feedstocks) and in operation (ramping up and down).	When operated flexibly especially the question to maximise CDR or electricity generation is relevant. A constant CO_2 capture rate can not be assured what can be a challenge for utilization concepts and related business model. Trade-off providing flexible electricity or using (share of) electricity to capture carbon.
CHP	Trade-off: 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, renewable electricity	Flexibility in input (different feedstocks), in operation (ramping up and down) and in multiple outputs (heat and electricity).	When operated flexibly especially the question to maximise CDR or heat generation is relevant. A constant CO_2 capture rate can not be assured what can be a challenge for utilization concepts and related business model. Trade-off providing flexible electricity or using (share of) electricity to capture carbon.
Waste-to energy (WtE)	Trade-off: Optimize on CO_2 capture or heat value? High CAPEX needed for high % capture and low OPEX	Probably	BECCS preferable because the CO_2 stream partially fossil	Policy incentives for negative emissions such as ETS, carbon pricing and possibly downstream procurement demands	Material recycling, though some portion of WtE likely to be needed long-term	Flexibility in input (particularly in qualities of feedstocks), in operation (ramping up and down) and in multiple outputs (heat and electricity). Limited operational flexibility in case of supply to district heating.	When operated flexibly especially the question to maximise CDR or heat generation is relevant. A constant CO_2 capture rate may not be assured what could be specifically a drawback for certain CO_2-utilization concepts and related business model. When supplying heat to the local district heating networks a constant supply during the heating season has to be assured what limits a flexible operation
Cement	Biomass or electricity for process heat? High CAPEX needed for high % capture and low OPEX	Possibly	BECCS preferable because the CO_2 stream partially fossil, BECCU through mineralization could be an option	Policy incentives for negative emissions such as ETS, carbon pricing, or downstream procurement demands	Other binder materials, material efficiency, though zero emissions needs CCS.	Limited number of flexibility options due to type of operations i.e. production process. Mainly flexibility in type of input given, as a broad feedstock base and qualities can be considered from a technological point-of-view (not necessarily economic point of view).	Potential to balance the relative cost of fuels -e.g., biomass vs coal - against the potential revenue generated from carbon dioxide removal and the penalty to be paid from having to buy emissions rights or pay a carbon tax

Table 1 overview on BECCUS and Flexible Bioenergy (FlexBECCUS) in the case of biomass combustion technologies

4 Discussion and outlook

The combination of CCU/CCS and flexibility measures in biomass combustion plants is generally technologically possible. When looking at the modi of operandi a flexible operation can 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. The currently core business model for operating CCU is the market price realised for selling the carbon for use in other applications. 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 yet, 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. As the business models for the provision of flexible bioenergy and BECCS/U are of different nature, it has to be governed which measure is preferable at different times and scales.

How the integration of CCS/U in existing facilities and related business models is done depends on the exact policy design of the CDR support. If the CDR revenue is fixed e.g. through a feed-in tariff, then this leads to different market behaviour than if the CDR revenue varies with time, which would be the case if the CDR reward is linked to the Emissions Trading System (ETS). On EU level so far carbon removals are not tradeable within the EU ETS. In general carbon dioxide removals can be integrated into such a system what would require an adaptation of the EU Emissions Trading System as it is designed today (Schenuit and Geden 2023). The idea and concept on incentivizing CDR by integrating it in an ETS is currently strongly discussed and studied among experts and researchers and has already reached the policy agenda. Of course also other climate policy instruments can be thought of to govern CDR implementation (compare Schenuit and Geden 2023). From a deployment perspective incentivising CDR allows for a broader implementation of BECCS concepts as it especially will bring in "new" business models for BECCS.

Currently we think of CDR (in particular BECCS) and Flexible Bioenergy as two services that to a certain extent are trade-offs. A key question is if the current energy and climate policy design can be adapted to minimise potential trade-offs. Furthermore, the development of the demand for these two services BECCS and Flexible Bioenergy over time in the long-term is relevant. For example, that we see very rapid technological developments in non-biomass approaches to provide flexibility, to the point where the biomass-based flexibility options might be unable to compete. Then there would no longer be a trade-off. Conversely, we could see a very rapid development in other forms of CDR e.g., direct air capture - especially in terms of costs and scalability - then there would be little demand for BECCS and the Flexible Bioenergy option would be of higher priority. Of course, which of these two developments is more likely - or both, or neither - is very difficult to prognosticate and actual decisions in terms of policy and business strategy will have to be taken under uncertainty.

The decision for the type of operation would be guided by electricity market prices or other incentive schemes for providing flexibility services and by the potential revenue generated from carbon dioxide removal and the penalty to be paid from having to buy emissions rights or pay a carbon tax. Overall, it is subject to climate policy and energy security goals to either prioritise one of these services or to demand both. Here further research would be required addressing among others the question if a CCS operation would result in a higher level of carbon emissions savings due to negative emissions and thus compensating for the amount of variable renewable energy sources that could not be used as flexibility measures were not provided in that case.

Within this study we highlighted and identified characteristics of different flexibility options when linked to BECCU/S concepts with post-combustion. The assessment was based on case studies that have been elaborated within the scope of the inter-task project "Deployment of BECCUS value chains". Biomass combustion technologies have been chosen as case studies within the scope of this inter-task project as these are currently the bioenergy applications with the most promising realisation of carbon capture in the near-term. Naturally, also other bioenergy technologies can be considered for biogenic carbon dioxide capture. For a complete overview and understanding also these technologies need to be assessed in terms of FlexBECCUS. The follow-up inter-task project "Management of Biogenic CO_2: BECCUS Inter-task Phase 2" builds on this inter-task project at hand and considers complementary carbon capture from biomass gasification as well as biogas production technologies, and also looks into direct thermal liquefaction technology options. Combined the two inter-task projects will allow for a complete picture of bioenergy technology options and hard-to-abate industrial sectors for carbon capture and storage and/or utilisation.

Summarizing, this study has developed an initial understanding of linking flexibility measures to BECCU/S concepts. For further analysis and evaluation of the two services flexible bioenergy and carbon capture and use or storage, also shedding some light on the various other bioenergy technologies and their different carbon capture technologies is necessary. For better describing the implications of FlexBECCUS for the energy system we see a need for a profound energy system modelling, and thereby raising the awareness among energy system modellers and policy makers that possible trade-offs for the energy system may occur when bioenergy installations provide flexibility and CCS/U at the same time. This will also support the understanding on the level of carbon dioxide removals from the atmosphere when a bioenergy installation provides flexibility and carbon capture and storage at the same time.

5 References

Babu, R., Prieto Veramendi, P., M., Rene, E., R. (2021). Strategies for resource recovery from the organic fraction of municipal solid waste, Case Studies in Chemical and Environmental Engineering, Volume 3, 2021, 100098, ISSN 2666-0164, https://doi.org/10.1016/j.cscee.2021.100098.

Bang, C. (2021). *Deployment of Bio-CCS: Case Study on 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

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

IEA Bioenergy Task 44 (2021). Flexible Bioenergy. https://task44.ieabioenergy.com/flexible-bioenergy/

Kusuma, R., T., Hiremath, R., B., Rajesh, P., Kumar, B., Renukappa, S. (2022). Sustainable transition towards biomass-based cement industry: A review. Renewable and Sustainable Energy Reviews, Volume 163, 2022, 112503, https://doi.org/10.1016/j.rser.2022.112503.

Levihn, F. et al. (2019). Introducing BECCS through HPC to the research agenda: The case of combined heat and power in Stockholm. Energy Reports, 5, 1381-1389. https://doi.org/10.1016/j.egyr.2019.09.018.

Lauer, M., Dotzauer, M., Hennig, C., Lehmann, M., Nebel, E., Postel, J., Szarka, N., and Thrän, D. (2017) Flexible power generation scenarios for biogas plants operated in Germany: impacts on economic viability and GHG emissions. Int. J. Energy Res., 41: 63- 80. doi: 10.1002/er.3592. https://onlinelibrary.wiley.com/doi/full/10.1002/er.3592

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

Rahman, A., Rasul, M., Khan, M., M., K., Sharma, S. (2016). Chapter 9 - Cement Kiln Process Modeling to Achieve Energy Efficiency by Utilizing Agricultural Biomass as Alternative Fuels, Editor(s): M. Masud K. Khan, Nur M.S. Hassan, Thermofluid Modeling for Energy Efficiency Applications, Academic Press, 2016, Pages 197-225, https://doi.org/10.1016/B978-0-12-802397-6.00009-9.

Schenuit, F., Geden, O. (2023). Carbon dioxide removal: climbing up the EU climate policy agenda. In Rayner, T., Szulecki, K., Jordan, A. J., Oberthür, S. (Eds.), Handbook on European Union Climate Change Policy and Politics. https://doi.org/10.4337/9781789906981.

Schildhauer, T. et al. (2021). Technologies for Flexible Bioenergy. IEA Bioenergy Task 44. https://task44.ieabioenergy.com/wp-content/uploads/sites/12/2021/08/IEA-Task-44-report-Technologies-for-Flexible-Bioenergy.pdf

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