On the deployment of Bio-CCS in the EU: Barriers and policy requirements for a 2 °C pathway

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Summary

For the European Union to be consistent with a 2 °C emission pathway, a considerable amount of negative emissions will need to be generated up to 2050 with carbon dioxide removal methods. One of these methods is bioenergy with carbon capture and storage (BECCS), which plays a dominant role in integrated assessments models due to its upscaling potential and relative technology maturity. However, very few successful efforts have been made to generate negative emissions with BECCS and failing to do so in the first half of this century will severely reduce the chance of achieving global climate targets.

Complying with a 2 °C consistent pathway implies that the EU needs to deploy 56—64 GW_e of solid biomass BECCS. Upscaling can fundamentally be realised by either (i) increasing the level of co-firing in fossil CCS plants, (ii) retrofitting existing bioelectricity plants or (iii) constructing dedicated BECCS plants. However, only 20 GW_e of additional capacity would be required, as there is a considerable retrofitting and co-firing potential in Europe. Furthermore, the identified methods vary in technological readiness and even more so in costs. However, at €86/tCO_2, method (iii) is the most cot-efficient in storing a tonne of biogenic CO_2, i.e. negative emissions while being the most expensive in terms of support per unit electricity generated.

Expert interviews and literature analysis yielded barriers of varying natures, although the most prominent barriers where those of a political or regulatory nature. One of these barriers is the absence of recognition and remuneration for negative emissions, which has so far led to an insufficient incentive for key actors to engage in BECCS. Interestingly, the presence of these barriers in different Member States can vary considerably—generic EU wide policy will therefore not be effective. For some barriers, the development of country-specific policy is recommended.

Indeed, most of the identified barriers can be mitigated through existing domestic and EU policy. However, for some barriers it was found that existing policy will not be sufficient. The EU ETS, even when amended, would still not be capable of sufficiently incentivising negative emissions from BECCS. Additional funding mechanisms are therefore essential. The window of time to introduce amendments and new policy is tightening, since deploying BECCS at levels consistent with the 2 °C target requires ambitious upscaling from 2025. Initiating discussions and raising awareness on BECCS and negative emissions is therefore fundamental to ensure well-informed decisions are made in the short-term.

Chapter 1 – Introduction

1.1 Background

In December 2015, nearly 200 nations worldwide decided that we should pursue efforts to limit global warming to at least 2 °C above pre-industrial levels by the end of this century to avoid the most dangerous climate change impacts, while striving for 1.5 °C. This decision was formalised into the Paris Agreement, which passed the threshold for entry into force on 5 October 2016 (UNFCCC, 2016). However, the voluntary pledges that were made in the Agreement by countries in their Nationally Determined Contributions (NDCs) currently amount up to emissions that correspond with 2.3—3.5 °C of warming by 2100 (Climate Action Tracker, 2016). Hence, complying with the Agreement will require more drastic reductions in global greenhouse gas emissions (GHGs).

The most important GHG in the Earth's atmosphere to anthropogenic global warming is carbon dioxide (CO_2) (IPCC, 2007). The relationship between cumulative global CO_2 emissions and global mean temperature change has been proven to be robust and shows near-linear behaviour (Allen et al., 2009; Matthews et al., 2009). Reasoning from that near-linear relationship, scientists argue that a quota—i.e. 'carbon budget'—of no more than 1,200 billion metric tonnes (Gt) CO_2 is necessary to limit global forcing to levels that are consistent with a 2 °C pathway (Friedlingstein et al., 2014). This should be in combination with efforts to reduce forcing from non-CO_2 greenhouse gases. One of the determining factors of this carbon budget is the probability that global mean temperature change will actually stay below this 2 °C threshold. Often, the term *likely* is used to describe that this threshold will be met with a likelihood of more than 66% and applies to the 1,200 Gt carbon budget (IPCC, 2007). A higher carbon budget of e.g. 1,500 Gt CO_2 would decrease the chance of staying below 2 °C warming to 50%. In 2014, global CO_2 emissions amounted up to 35.7 Gt (PBL, 2015), and a quick calculation points out that this 2 °C budget will be consumed in 30 years' time if countries worldwide continue to emit greenhouse gases at present rate. This indicates that the window of opportunity to stay below 2 °C is closing rapidly. Scientists worldwide therefore call for 'deep decarbonisation', which refers to rapid and structural mitigation efforts across all sectors (P. Smith et al., 2016). At the same time, doubts exist as to whether achieving net-zero emissions is achievable with conventional mitigation options alone, as carbon intensive sectors such as the aviation and shipping sector are particularly difficult to decarbonise (Gasser et al., 2015).

Meta studies of integrated assessment model (IAM) scenarios have pointed out that the vast majority of the scenarios that are consistent with a 2 °C pathway assume a successful and large-scale deployment of carbon dioxide removal (CDR) technologies at least in the second half of this century (Figure 1) (Fuss et al., 2014; Anderson, 2015). CDR refers to technologies or methods of which their application results in the net removal of CO_2 from the atmosphere (van Vuuren et al., 2013). In scientific literature, approximately 30 of these prospective technologies or methods come forward

(McLaren, 2012), including among others direct air capture (DAC), afforestation and reforestation (AR), bioenergy with carbon capture and storage (BECCS), biochar, enhanced weathering and ocean alkalinity enhancement (Lomax, et al., 2015a). Although many of these options have not reached maturity yet and carry considerable uncertainties with regard to their impacts, three options consistently appear to have the largest potential to generate 'negative emissions', taking into account economic and environmental constraints: BECCS, AR and DAC (Keith et al., 2006; Azar et al., 2010; Smith & Torn, 2013; van Vuuren et al., 2013; Smith et al., 2016).

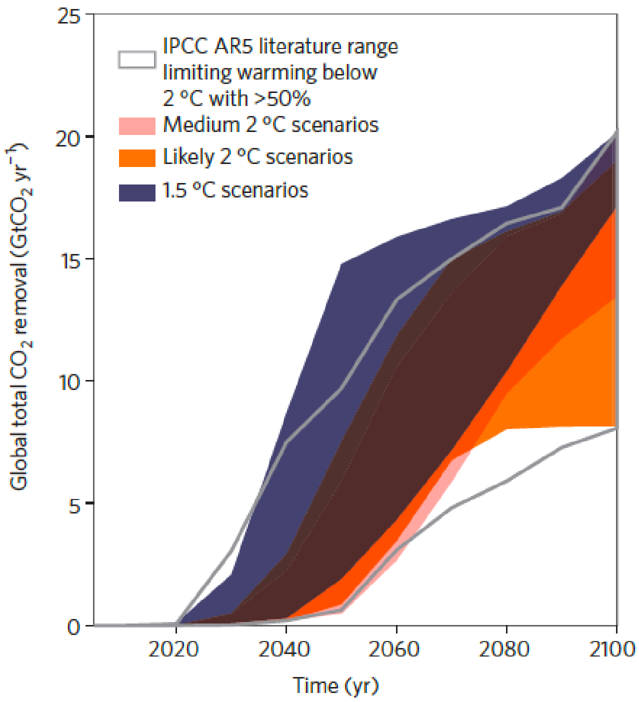

Figure 1: Global total carbon dioxide removal in the scenarios from the IPCC AR5 scenario database, 15th to 85th percentile range (Rogelj et al., 2015).

Perhaps the most extensively studied CDR method and the most dominantly used in IAMs to generate negative emissions is BECCS (IPCC, 2014; Smith et al., 2016), bioenergy with carbon capture and storage. Biomass is grown to absorb CO_2 from the atmosphere via the photosynthetic process and is subsequently combusted in a bioenergy plant fitted with carbon capture technology to capture the CO_2 from the flue gases that are being emitted. The carbon is then liquefied, transported and geologically stored in dedicated storage sites such as deep saline aquifers, coal beds or depleted oil and gas fields. The net result of applying this technology would be the removal of CO_2 from the atmosphere. BECCS appears to be the CDR technology with the one of the largest potentials, the greatest technological maturity and could be introduced relatively easily in the existing energy system due to its 'double benefit' of generating electricity (McGlashan et al., 2012; Selosse & Ricci, 2014).

However, the scientific community has been expressing the need for BECCS for and other CDR methods for roughly a decade now, and no successful efforts have been made yet to upscale these technologies. Hence, there is a considerable number of barriers and constraints associated with BECCS, such as the future demand for land and water, the short-term investment needs, unknown effects of land use change, public support for the technology and the slow development of large scale commercial carbon capture and storage (CCS) projects (Klein et al., 2014; Smith et al., 2016). Elaborate research has been done to identify the biophysical and techno-economic constraints in BECCS systems and how to deal with them (McGlashan et al., 2012; Smith & Torn, 2013; Smith et al., 2016). Research on potential deployment policies has been conducted for these two technologies separately, e.g. on policy incentives for carbon capture and storage in Europe (Von Stechow et al., 2011) and the effectiveness of different deployment policies in the European Union regarding—among others—bioenergy (Klessmann et al., 2011). However, specific policy recommendations to mitigate the barriers that are in place for BECCS specifically have not been developed yet, which is troubling when considering the lacking awareness on the need for CDR methods among the key political stakeholders and the closing window of time to deploy CDR methods such as BECCS (Azar et al., 2010; Gasser et al., 2015; Kriegler et al., 2013; McGlashan et al., 2012; P. Smith et al., 2016; Vergragt, Markusson, & Karlsson, 2011). Failing to deliver CDR methods that have the potential to deliver large scale negative emissions significantly increases total mitigation costs and will considerably reduce the chance of achieving the climate targets that countries worldwide committed to in the Paris Agreement (Kriegler et al., 2013; Van Vuuren et al., 2015).

1.2 Research framework

The aim of this research is to largely eliminate this existing gap in literature by providing policy recommendations that aid the European Commission and Member States to facilitate the uptake of BECCS by the private sector in the EU. This scope was determined due to the role of the EC in providing guidance to Member States in stimulating technological development and its relatively homogenous and ambitious climate policy compared to other regions in the world. Another aim is to propose a timeline in which these recommendations should be implemented if the EU desires to be consistent with a 2 °C pathway. It is urgent that this information be available for decision-makers, as awareness on negative emissions is lacking among the policy community, often stemming from the complexity of the barriers involved. Making this issue more tangible by emphasising the policy areas that require action is expected to enhance the level of awareness among policy makers. These aims together serve the more general purpose of providing governments worldwide with tools on how to tackle a significant part of the existing barriers for actors in the energy industry that currently hinders the deployment of BECCS. Hence, increasing the chance that countries worldwide manage to limit their emissions to the 2 °C carbon budget in order to avoid the most dangerous impacts of climate change.

Following from this need to deploy technologies like BECCS and the urgency of staying below this 2 °C threshold, the following main research question was formulated that will guide the direction of research:

"How does BECCS need to develop under a 2 °C consistent emission pathway in the European Union and which political efforts can be taken to achieve this?"

A complete and thorough answer to the main question is expected to flow from the following set of sub-questions (SQs):

1. *How is BECCS represented in the existing 2 °C consistent integrated assessment models and what does this imply for its deployment course in the EU?*
2. *What are the determining factors for the cost of electricity generation and CO_2 removal with BECCS and how does this compare to other similar technologies?*
3. *Which deployment barriers for BECCS is the private sector in the EU currently facing and on which governance level should these be mitigated?*
4. *Which policy measures have the potential to mitigate these barriers, which specific efforts need to be made to do so, and by when?*

Each question has been addressed in a separate chapter and the first sub-question is addressed in Chapter 2.

The aim of SQ1 was to develop a deployment roadmap for the EU that outlines the policy goals for BECCS deployment, based on 2 °C-consistent scenarios from a set of IAMs. Furthermore, technological pathways were identified to illustrate which BECCS methods could be utilised to achieve these policy goals.

SQ2 has tried to quantify one of the barriers to BECCS deployment by modelling the cost of electricity generation of the identified BECCS methods. The aim of this section was to determine the level of support that is needed to create a viable business case for the private sector.

SQ3 aimed to identify the most dominant deployment barriers the EU private sector is currently facing and ranking them by their prevalence to determine the barriers that require top-down action. Furthermore, this section has determined which of these barriers need to be addressed at the EU level or on a Member State level.

The goal of SQ4 was to assess which policies are already in place that could address the identified barriers and which barriers would require additional policy efforts to ensure a level of BECCS deployment consistent with a 2 °C pathway. This yielded a set of tangible policy actions the European Commission could take into account to stimulate the private sector. Another aim here was to include these actions into the initial policy framework to come to a deployment roadmap. This process and utilisation of methods is visualised in Figure 2. A thorough synthesis of the findings was expected to result in a complete answer to the main question.

Figure 2: Methodological process.

Chapter 2 – Integrated assessments and policy goals

2.1 Introduction

One of the key challenges in climate modelling is integrating the many human and natural factors that interact with each other and eventually influence the global climate. These are factors such as energy demand, economic activity, climate policy and changes in demographics. Integrated assessment models (IAMs) try to incorporate the known interactions and feedbacks between these human and natural systems. IAMs are fundamental to our understanding of how political decisions affect our climate, hence also to the effects of certain mitigation measures on the atmospheric concentration of carbon dioxide. In the following chapter, the most widely used IAMs will be examined to present how BECCS is represented in the 2 °C-consistent scenarios and how this affects the deployment course of BECCS in the EU. The chapter will be concluded with a policy roadmap up to 2050, which includes key milestones and components of the deployment path of BECCS if the EU wants to be on the right track for staying below 2 °C by the end of the century. This will also frame the policy objectives that will be used in the rest of this report. Consequently, this chapter will answer the research question *'How is BECCS represented in the existing 2 °C-consistent integrated assessment models and what does this imply for the deployment course in the EU?'*

2.2 Methodology

The research question was answered using methods of quantitative analysis and literature research. To determine how BECCS is represented within the existing IAMs, data was extracted from the LIMITS Scenario Database that is available online (IIASA, 2014). Data on secondary electricity generation by BECCS was extracted from the GCAM, IMAGE, MESSAGE, ReMIND, TIAM-ECN and WITCH models. The only model that was excluded was AIM-ENDUSE, but due to the medium-term character of the model, which models up to 2050, it was not included in this analysis to ensure a homogenic dataset. For this report, the standard 450 scenario was chosen, which is in line with the 2 °C pathway up to 2100. As the alternative 'RefPol' and 'StrPol[1]' scenarios do not differ significantly from the 450 scenario in terms of BECCS deployment (less than 2%), these were not taken into account.

Subsequently, secondary electricity data was converted to nameplate capacity, which is more meaningful in terms of deployment. A capacity factor range of 75—85% was assumed here. As the data is decadal (e.g. 2030, 2040…), a polynomial interpolation approach was used to determine the average deployment speed of the years that are in-between.

To determine how each of the BECCS methods could contribute to these deployment goals, their potentials were estimated using a range of data. For the 'fossil CCS co-firing'

[1] Abbreviations represent 'reference policy' and 'stringent policy', respectively. These are scenarios that differ in climate policy stringency.

approach, data on electricity generated with fossil CCS was used from the identified IAMs, assuming a co-firing rate of 30% and with a decreasing growth factor from 2030 due to increasingly stringent climate policy and to avoid locking in fossil CCS. The 'bioelectricity CCS retrofit' pathway was determined by analysing CCS-ready bioelectricity plants in Europe from the Platts database, which contains information on all biomass boilers in Europe (Platts, 2016). Under the assumption that a CCS retrofit is viable at a nameplate capacity of >100 MW, 30% of the electricity generation capacity in Europe can be fitted with CCS. In combination with the PRIMES projections for biomass electricity up to 2050, this yields the results projected in the roadmap (EC, 2013). Finally, the remainder of the required BECCS capacity should be complemented with dedicated BECCS.

2.3 Results

The results from this chapter will be presented by first (1) describing how BECCS electricity is represented in the assessed IAMs and how some of the assumptions affect the model output, subsequently (2) explaining what this implies for the policy objectives that need to be set and finally (3) describing the roadmap that was constructed, where each part is discussed in one paragraph.

2.3.1 BECCS in integrated assessments

TWh yr^{-1}	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Global	*15*	*586*	*2,334*	*3,778*	*5,471*	*6,696*	*7,348*	*7,831*	*8,001*
EU27	*2*	*82*	*316*	*441*	*468*	*476*	*405*	*371*	*356*
Share EU27	***12,33%***	***14,04%***	***13,53%***	***11,66%***	***8,55%***	***7,10%***	***5,51%***	***4,74%***	***4,45%***

Table 1: Electricity generated by BECCS in the EU27 and worldwide, from 2020 to 2100, based on the assessed IAMs (Source: LIMITS Scenario Database, 2016).

Firstly, it is good to emphasise that this thesis specifically analyses the deployment of biomass electricity with CCS, and not BECCS technologies that produce energy carriers such as liquid fuels or hydrogen, which are also included in many of the assessed IAMs. This is primarily due to the expected dominant role of BECCS electricity and the upscaling potential of solid biomass BECCS in terms of carbon dioxide removal compared to BECCS technologies that produce other energy carriers (Luckow et al., 2010; Koornneef et al., 2011).

The mean electricity generated by BECCS worldwide and in the EU is shown in Table 1. A share of 4—14% is expected to come from these European countries, with the 2020—2050 period being in the higher range, largely due to the presumption that the EU is an early adopter of ambitious climate policy relative to the rest of the world. Individual variations in electricity generated by BECCS between the different models are present in part due to different underlying assumptions and coupling with other models (Figure 3). For instance, GCAM, IMAGE and ReMIND are coupled with a land-use model to incorporate the dynamic impacts of bioenergy on land use, among others. Differences in the assumed carbon price over time are also present in the models and range from

$126 in GCAM to $635[2] in WITCH, both in the year 2050. Other important differences between the IAMs include the bioenergy constraints imposed, which simultaneously affects the potential of BECCS. GCAM and IMAGE do not impose such constraints on the biomass supply, whereas the other models apply constraints ranging from 140—300 EJ yr^{-1}. The choice to allow for the international trading of biomass feedstock also differs—trade of biomass feedstock is not allowed in IMAGE, MESSAGE and WITCH as opposed to the others. This also holds in the case of secondary energy trade, which GCAM, ReMIND and WITCH do not allow for (Calvin et al., 2013). These different assumptions largely explain the different outputs. The models that produce the lowest data are GCAM, ReMIND and WITCH and correlates with the assumption that interregional secondary energy trade is not possible. A reason for the relatively high values in IMAGE could be the exclusion of heat from biomass and liquid fuel CCS technologies (Calvin et al., 2013), which could lead to a more favoured position for bioelectricity CCS in the model.

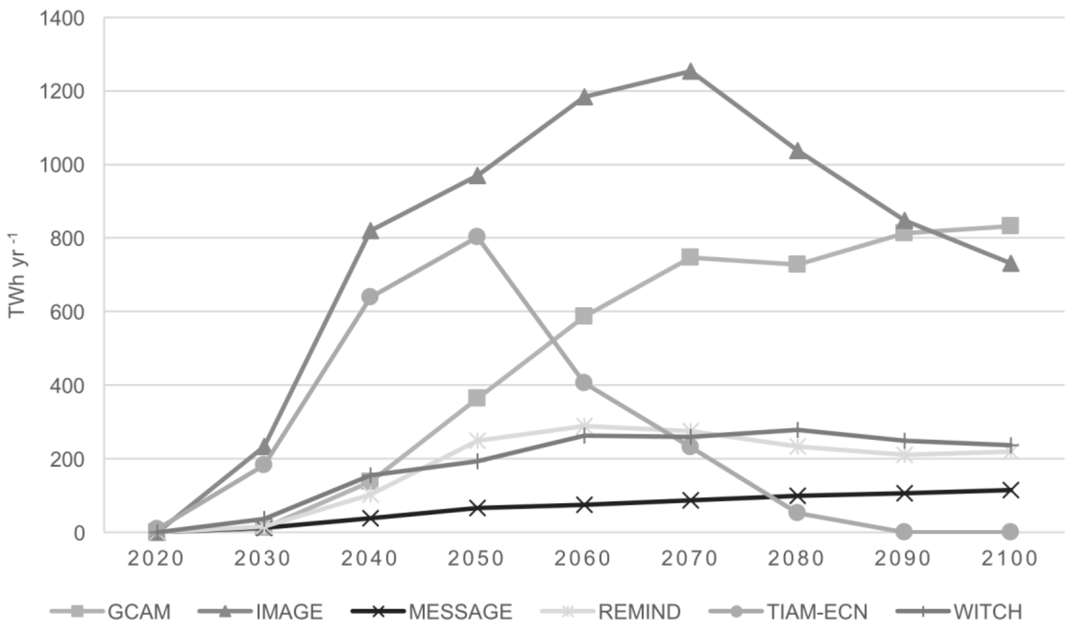

Figure 3: Electricity generated by BECCS up to 2100 in the 6 assessed IAMs in EU27 countries (Source: LIMITS Scenario Database, 2016).

2.3.2 Policy goals and milestones

For use further in this report, data is needed with regard to the required installed capacity of BECCS in the EU over the timeframe that is within reach of policy decisions. This is useful to know in order to determine the level of ambition that is required to meet a 2 °C-consistent pathway in terms of BECCS deployment. Also, such tangible deployment goals could assist in decision making if it comes to by which point in time policy efforts should have been made to ensure sufficient upscaling of the technology as modelled by the IAMs.

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[2] Both carbon prices are in 2005 US$.

Climate targets set by governments often go as far as 2050, in part because this is the maximum reach of policies that are designed in the near-term and because global emissions up to 2050 will largely determine the global average temperature at the end of this century and investment cycles up to 2050 are currently being planned (EC, 2011b). Hence, the timeframe of this analysis will be a period of up to 2050, starting in 2020, as the integrated assessments assume minor scale-up from this year and there is considerable consensus among scientists that CCS will enter the commercial phase around 2025, although progress towards this has recently been slow (EC, 2013; Koelbl et al., 2014).

Figure 4 presents the policy objectives that were derived from the model data. After a polynomial interpolation to derive annual figures, the electricity generated was converted to a tangible peak capacity. With a capacity factor of 75—85% (NREL, 2010), the EU as a whole should aim for 1 GW_e of installed BECCS capacity in the sixth year, 2025. Other milestones include exceeding 10 GW_e in 2029 and 50 GW_e in 2042.

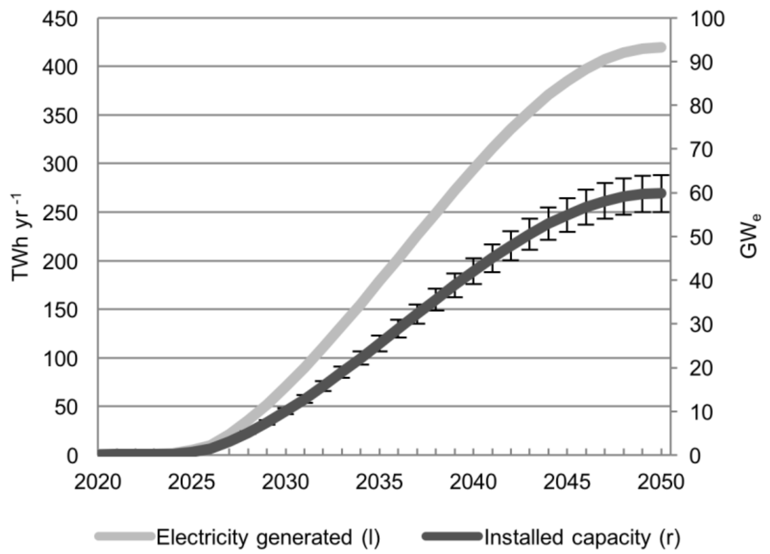

Figure 4: Electricity generated by BECCS in the EU27 up to 2050 and the required installed plant capacity in GW_e as modelled in the IAMs' 2 °C emission scenarios.

The final target in 2050 should be 60 GW_e of installed bioelectricity CCS capacity, assuming an average capacity factor of 80%. To give an impression of the current status of electricity production with biomass in the EU, the amount of secondary energy produced in the EU in 2012 was 142 TWh (Scarlat et al., 2015), which corresponds to 29 GW_e peak capacity in practice because the capacity factor was lower than 80%. This is usually due to feedstock shortages (IRENA, 2012). This implies that in order to achieve the 2050 target, an additional 31 GW_e will need to be installed and all the bioelectricity existing plants need to be fitted with CCS, while at the same time increasing the amount of load hours for all these power plants up to 80%. This is considerably less ambitious than the potentials that were estimated by the *2011 IEAGHG* report (Koornneef et al., 2011), which foresees a technical potential of about 1500 Mton CO_2 yr^{-1} capture and storage in Europe, which corresponds roughly with four times the BECCS capacity assumed in this assessment, though the IEAGHG potentials did not assume cost-optimal deployment. Also the CO_2 capture from all bioelectricity production in Europe in 2020 in the National Renewable Energy Action Plans (2009/28/EC) foresee an abatement potential of 200 Mton CO_2 yr^{-1}, which corresponds to approximately 35 GW_e BECCS capacity (ZEP, 2013). Nevertheless, the 60 GW_e that was derived from the IAM data is ambitious when placing it into a European context. Following the same trend as the generated electricity, CDR by BECCS electricity would be 450 Mton CO_2 yr^{-1} in 2050, with a cumulative amount of 6.3 Gt CO_2 yr^{-1} over the period 2020—2050[3].

The feasibility of achieving this level of deployment will depend on, among others, the overall cost of the technologies, the availability of biomass feedstock and the effectiveness of the BECCS policies. These aspects will be addressed in the following chapters. The achievable scale-up rate could also be a limiting factor; the largest absolute increase of installed BECCS capacity in this assessment can be witnessed between 2036 and 2037, with 6.7 GW_e. To put this in to perspective, bioelectricity capacity in the EU increased by nearly 4 GW_e from 2010 to 2012, which was primarily due to strong developments in the UK, Sweden, Germany and Italy (Scarlat et al., 2015). This indicates that a potential for stronger overall increases in biomass capacity in Europe exists. Future practices should point out whether these capacity increases can simultaneously be fitted with CCS technology.

2.3.3 Roadmap

Roadmaps can be defined as specialised strategic plans that outline activities or an organisation can undertake over specified timeframes to achieve stated goals and outcomes (IEA, 2014). Hence, in this assessment three fundamentally different approaches were identified by which BECCS electricity capacity can be scaled up to the levels that are required for the EU to be in line with a 2 °C pathway as displayed in Figure 5. The first potential method is to increase the share of co-fired biomass feedstock in fossil fuel CCS plants. It is assumed that the fossil CCS is able to co-fire 30% biomass with minor adjustments (Koornneef et al., 2011). Projections for secondary electricity generated with fossil CCS were taken from the IAM data and are assumed to be generated at 80% of the load hours (IRENA, 2013). As biomass co-firing at a level of 30%[4] merely requires increased levels of feedstock pre-processing and small boiler modifications, it can be assumed that the first increases in BECCS capacity will be achieved through this method (Koornneef et al., 2009; ZEP, 2013; Lomax et al., 2015). In 2050, 20% of the BECCS capacity could consist of 30% biomass co-firing fossil fuel CCS installations, with a milestone capacity of 10 GW_e achieved in 2029.

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[3] Assuming a capture efficiency of 85% and carbon content of 112 kg/GJ primary energy (IPCC, 2014).

[4] Currently 20% co-firing is feasible with minor adjustments and is expected to increase to at least 30% in the coming decades.

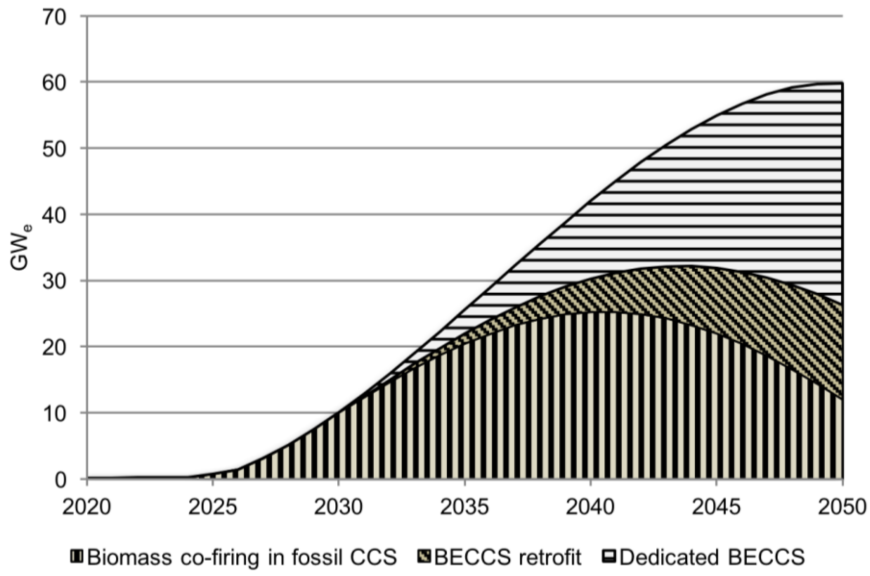

Figure 5: Roadmap showing the required increase in BECCS capacity for the EU27 countries and the contribution of the three different approaches.

The second method concerns the retrofitting of existing bioelectricity plants. The EU PRIMES model estimated that bioelectricity capacity will grow to 49 GW_e[5] in 2050, but it is likely that not all of this can be retrofitted as most bioelectricity plants have a nameplate capacity in the order of 10s of MWs (IRENA, 2012). It would therefore not be cost-efficient to retrofit plants of that size, also because installations of this size often do not meet the criteria to apply for funding programs. Hence, the retrofitting potential of biomass boilers in Europe was assessed and it was found that under the assumption that retrofitting boilers above 100 MW_e capacity is economically viable, 20% of the existing biomass stock can be retrofitted into BECCS installations. Article 33 of the CCS Directive (Directive 2009/31/EC) requires all biomass facilities with an output higher than 300 MW to be built CCS-ready (EC, 2009a). This excludes a considerable share of the existing biomass facilities, which means that it will be costlier to integrate these into a CCS grid at a later stage. In order to increase the effectiveness of this retrofitting approach, one of the more imminent policy objectives should be to lower the threshold in the CCS Directive and to encourage the construction of large-scale biomass plants (> 300 MW) to make CCS retrofitting more widely applicable in the future.

The third approach is constructing dedicated BECCS electricity facilities, which could be from scratch or by modifying a fossil CCS plant as such that it becomes a BECCS installation. It is assumed that all novel bioelectricity plants from 2030 can be fitted with CCS technologies (Koornneef et al., 2011). The business-as-usual projections in the PRIMES model expect 14 GW_e of newly installed bioelectricity capacity in the period 2030—2050, which implies that an additional 20 GW_e dedicated BECCS is required

[5] Calculated with a capacity factor of 80% from 342 TWh.

outside of the business-as-usual trajectory for the EU to be consistent with the 2 °C pathway assumed in the IAMs.

2.4 Discussion

Noteworthy are the limitations of the IAMs on which this analysis was built. They use elements of physical, economic and social models which requires making many assumptions. The models assume that in the short term, several inertia factors are at play, such as the lifetime of fossil fuel plants, consumer preferences or negotiation processes on climate policy (Van Vuuren et al., 2015). This leads to assumptions on a certain discount rate, which favours postponed climate action over immediate deep emission cuts, as this could be more expensive due to the inertia in the system. This is also a reason for the large scale deployment of negative emissions technologies in the second half of the century. Other limitations of the models are that they find it difficult to incorporate climate events that are uncertain but catastrophic ('tipping points'), such as the melting of the Greenland ice sheet or methane release from melting permafrost. If a smaller inertia would be assumed, and accordingly a lower discount rate, or if these tipping points would want to be avoided at all cost, considerably faster emission reductions would be seen in the first half of the century, reducing the need for negative emissions from BECCS.

Furthermore, models have not yet managed to include other CDR methods than BECCS and afforestation and reforestation. This has proven to be more difficult to include or data on them is simply too uncertain. This does give rise to the possibility that models in the coming decade years will include other CDR methods in their scenarios, which could reduce the need for BECCS, rendering this analysis less accurate but will change accordingly to the electricity generation output of the models. In addition, any lacking ambition in all other areas of climate policy will require upscaling the efforts in generating negative emissions to be able to achieve global climate targets and will also alter the outcome of this analysis.

It is also important to consider that, when tracking progress of the deployment of BECCS in the EU, measuring should not be done on the basis of installed capacity but rather the amount of electricity generated by BECCS or the amount of CO_2 that is stored with BECCS. Capacity factors of centralised energy generation plants in Europe are rather uncertain for the future, as the outlook is that this will become much more decentralised with a higher penetration rate of intermittent renewables.

Moreover, besides implicitly carrying the assumptions of the IAMs, the roadmap analysis in this section has had to make additional assumptions on when certain technologies would be available and with which methods the larger shares of the scale-up would be achieved. Although this was as much as possible based on estimates from scientific literature, the 'dedicated BECCS' pathway had to be used partly to fill up the remaining deployment capacity that was required to be consistent with the IAMs. Hence, this method does not carry the definition of a technical potential.

2.5 Conclusion

The primary aim of this chapter was to illustrate how BECCS is represented in 2 °C-consistent scenarios and what this means for the presumed deployment course in the EU. One of the first conclusions that was drawn was that considerable differences exist in how prominent BECCS is across the IAMs. These differences can largely be attributed to varying assumptions, such as whether intercontinental trade of biomass feedstock or secondary energy is allowed, height of carbon prices or coupling with other models such as models for land-use.

The models show that by 2050 a nameplate capacity of about 56—64 GW_e should be deployed in the EU to be consistent with a 2 °C emission trajectory. Other capacity milestones include having 1 GW_e in 2025, 10 GW_e in 2028 and 50 GW_e in 2035.

This level of capacity deployment can fundamentally be achieved using three different approaches, namely (1) increasing the level of biomass feedstock co-firing in fossil CCS electricity plants, (2) retrofitting a part of the existing bioelectricity stock with CCS technology and (3) constructing dedicated BECCS facilities. It is likely that the first approach will serve as a means of achieving the first milestones because of its lower cost and short-term availability. It is expected that the other two approaches can be scaled up from 2030. Furthermore, a considerable share of BECCS capacity can be converted from the business-as-usual power plant stock, meaning that roughly 20 GW_e of additional non-BAU capacity will be required.

Considering that this is an ambitious pathway and that evident policy challenges exist, some policy efforts could already be identified to unlock the full potential of the mentioned approaches. This includes lowering the 300 MW 'CCS-ready' threshold to increase the retrofitting potential in Europe, which would make the EU less dependent on future dedicated BECCS deployment.

Chapter 3 – The economics of electricity generation and CO_2 removal with BECCS

3.1 Introduction

This chapter has been dedicated to researching which cost components make up the costs for the construction and operation of a BECCS installation, and which of these components have the largest potential to increase or decrease this cost. This is done to identify the cost factors that need to be addressed by a financial incentive and how much support the identified technologies would need to receive to make them cost competitive with other methods of electricity generation, such as regular biomass electricity. Furthermore, the influence of carbon pricing on the competitiveness of BECCS is discussed. This chapter will find an answer to the research question: *What are the determining factors for the cost of electricity generation and CO_2 removal with BECCS and how does this compare to related technologies?*

3.2 Methodology

Quantitative methods of analysis were applied to set out the cost components for electricity generation with BECCS. An approach that is often used for such purposes is the levelised cost of electricity (LCOE), which incorporates the cost of constructing and operating an electricity plant over its expected lifetime and translates that to a price per unit of electricity, usually per kWh or MWh. This allows for easy comparison of the components within the LCOE or between different technologies of electricity generation. Required input for the LCOE includes at least the capital costs, the fixed and variable operational and maintenance (O&M) costs, the fixed charge rate (FCR), which relates to the cost of capital and the operational lifetime, and the capacity factor or amount of load hours (EIA, 2015). The LCOE was calculated by using Formula 2.1.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{F_t}{(1+r)^t} + V_t}{\sum_{t=1}^{n} E_t} \quad (2.1)$$

Where n is the operational lifetime of the plant; F_t are the fixed costs in year t; V_t are the variable costs in year t and are not discounted; E_t is the number of units electricity generated in year t; and r is the FCR, which was calculated using Formula 2.2.

$$r = \frac{d}{1-(1+d)^{-N}} \quad (2.2)$$

Where d is the discount rate, the sum of the actual interest rate and the inflation rate; and N is the number of years for payment (Holbert, 2011).

Uncertainty was dealt with by constructing 3 different cost scenarios, Minimum, Median and Maximum. The Maximum scenario refers to a situation where the value estimates were chosen that result in the highest LCOE, whereas for the Minimum scenario values were chosen that result in the lowest LCOE. The Median scenario refers to either the average of the values that were chosen, or a medium value that was provided in scientific literature.

The required level of carbon pricing required to be cost-competitive with a reference technology was determined by setting up a what-if analysis in Excel. The 'goal seek' function was used to equal the LCOE of BECCS, dependent on the carbon price, to the LCOE of the reference technology.

Another measure that is used in practice to determine whether an investment will be profitable is the net present value (NPV), which is basically equal to the numerator of Formula 2.1. However, this approach is often used to decide which technology should be favoured over the other, whereas this analysis has mainly tried to find the financial support requirements per unit electricity or per tonne CO_2 compared to a reference technology or the wholesale electricity price.

3.3 Results

This section will discuss the main findings that have come forward from the LCOE analysis and technology comparisons. Before novel data could be calculated, assumptions needed to be made on the specific technologies used in the analysis. Hence, these will be described in 3.3.1. Subsequently, the results of the LCOE analysis are discussed and compared per technology in 3.3.2, where after these LCOE values are put into a market perspective in 3.3.3 by comparing them to: (1) the LCOE of reference technologies, (2) determining the effect of a carbon price on the LCOE and the cost-competitiveness of BECCS and finally (3) by comparing the level of financial support required to supply the generated electricity to the wholesale market.

3.3.1 Technology specification

In this section, three fundamental approaches were identified to increase the capacity for BECCS electricity in the EU, namely (1) the increased co-firing of biomass feedstock in fossil CCS electricity plants, (2) retrofitting existing bioelectricity plants with CCS technology and (3) constructing dedicated BECCS plants. This latter option can either be executed by converting fossil CCS plants to BECCS plants or by installing a BECCS facility from scratch. In order to calculate the LCOE for these different approaches information was needed regarding the specific technologies that are used within these approaches, such as the type of biomass boilers used and the type of CCS technology.

The first approach, increased co-firing with biomass in fossil CCS electricity plants, will in this analysis be technologically defined as supercritical pulverised coal (SCPC) technology fitted with post-combustion carbon capture and storage. To be able to co-fire up to a level of 30% biomass, increased levels of feedstock pre-processing and small boiler modifications are required and is defined as direct co-firing (SCPC-CCS-DC). A case in which biomass makes up 50% of the primary energy input will also be assessed. However, co-firing at such levels requires a separate biomass boiler that supplies steam to the same steam cycle of the SCPC plant and significantly increases the capital costs

(IEA-ETSAP & IRENA, 2013). Hence, this method will be defined as parallel co-firing (SCPC-CCS-PC).

The efficiency of fluidised bed boilers is generally less sensitive to higher levels of co-firing compared to pulverised fuel boilers, can handle more types of biomass than other boilers and is thus the most commonly used boiler in Europe for biomass fuel combustion (ASME, 2012). Other options exist as well, such as the integrated gasification combined cycle (IGCC). However, these technologies are expected not to be commercially available up to at least 2030 for biomass combustion and are therefore excluded from this research (source). Among the fluidised bed boilers, there is a distinction made between circulating fluidised bed (CFB) and bubbling fluidised bed (BFB). In CFB boilers, the air velocity is typically higher than in BFB boilers, which results in a more efficient combustion process and lower emissions due to a better circulation of hot particles. Also, this technology is especially suitable for large load ranges (ASME, 2012). Therefore, this technology is chosen to be used in the parallel co-firing method in combination with the SCPC boiler.

Post-combustion capture was chosen as it is currently the most developed CO_2 capture technology, and projections estimate that this will remain the more economical and mature alternative until at least 2030 compared to pre-combustion gasification (IGCC), oxy-fuel capture or second-generation capture technologies (ZEP, 2011).

For the second approach, the CFB technology is also be assumed to be used, but retrofitted with post-combustion CCS (CFB-r).

The third approach, dedicated biomass with CCS (CFB-CCS) essentially uses the same technologies but is built with CCS all at once, meaning there is no time between the construction of the boiler and the CCS technology, which makes it different from the second approach in that sense.

3.3.2 LCOE comparison

Table 2: Levelised cost of electricity for the four identified technological approaches to BECCS deployment in the EU.

		SCPC-CCS-DC			SCPC-CCS-PC	
€/kWh	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**	**Maximum**
Fixed costs	*0.0370*	*0.0473*	*0.0591*	*0.0579*	*0.0825*	*0.1137*
Variable costs	*0.0592*	*0.0719*	*0.0940*	*0.0675*	*0.0830*	*0.1097*
LCOE	***0.0961***	***0.1191***	***0.1532***	***0.1254***	***0.1655***	***0.2235***
		CFB-r			CFB-CCS	
€/kWh	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**	**Maximum**
Fixed costs	*0.0398*	*0.0600*	*0.0885*	*0.0398*	*0.0600*	*0.0885*
Variable costs	*0.0921*	*0.1166*	*0.1569*	*0.0866*	*0.1092*	*0.1462*
LCOE	***0.1319***	***0.1767***	***0.2454***	***0.1264***	***0.1693***	***0.2347***

For each of the three approaches the levelised cost of electricity was modelled (Table 2). Even though specific technologies were chosen, cost estimated for capital and operational costs can still differ substantially due to varying estimates. This holds for CCS technology as well, as the variations in the cost of transport, for instance, primarily depend on the distance over which the CO_2 has to be transported. Costs for storage relate strongly to the type of reservoir that is chosen and could be up to a factor 15 higher than the most economical option. These uncertainties with regard to the different cost components can be partly reduced by creating several cost scenarios for each technology. In doing this, an LCOE range is calculated for every approach, thus making the uncertainty more visible by presenting where the largest uncertainties are located.

SCPC-CCS

From Table 2 it can be seen that the total LCOE of direct co-firing at 30% in a SCPC-CCS plant ranges from 9.6—15.3 eurocents/kWh, with the Median value being 11.9 eurocents/kWh. This cost can be split up in variable costs and fixed costs, of which the latter is the most sensitive to cost assumptions and predominantly makes up the difference in the LCOE between the three cost scenarios. There is a large uncertainty with regard to the cost of CO_2 transport and storage, which ranges from 3—10 €/tCO_2 and 1—13 €/tCO_2, respectively. This mainly depends on the transporting distance and in which type of reservoir the CO_2 will be stored. The LCOE of parallel co-firing at 50% lies in the order of 12.5—22.4 eurocents/kWh and a median estimate of 16.6 eurocents/kWh, which is substantially higher than was seen in the direct co-firing method. This is primarily due to uncertainty within the fixed cost component. Parallel co-firing is estimated to cost between 1,424—2,225 €/kW and this range is mainly reliant on economies of scale (IRENA, 2014). An elaborated overview of cost assumptions and data on these technologies (e.g. CO_2 captured) is given in Annex A and Annex B.

CFB-CCS

The cost of generating electricity through the CFB-CCS approach is somewhat higher than the previous approach with a total LCOE of 12.6—23.5 eurocents/kWh and a median estimate of 16.9 eurocents/kWh (Table 2). Both the variable costs and the fixed costs contain a relatively large range of price estimates. The difference between the Minimum and the Maximum value, for instance, is almost a factor 2 for the levelised fixed costs. A large factor of uncertainty here are the capital costs that are associated with the construction of a biomass CFB boiler, which range from €1,632—3,383 per kW (IRENA, 2013). The capacity factor (75—85%) and the operational lifetime (20—30 years) also strongly influence the levelised fixed costs and are not yet certain for this approach; technology deployment should reveal more practical knowledge and give more certainty on these values. Looking at the capital investment costs into more detail, the FCR is a major factor of influence. For the Median scenario it was assumed to be 11%, resulting in an annual payment of €72 million, together with the fixed O&M. When the FCR would be lower, e.g. 9%, as some calculations for wind power facilities assume (EIA, 2011), the annual fixed costs would drop from €181 to €155 million, reducing the LCOE by 1 eurocent/kWh. An elaborated overview of cost assumptions and data on this technology is given in Annex C. Furthermore, the cost of primary energy is of great importance for the levelised cost of electricity, for a large part due to the relatively low efficiency of this BECCS approach. An increase of primary energy fuel of

€1/GJ in the case of dedicated BECCS led to an increase in the LCOE of 1.3—1.4 eurocents/kWh.

CFB-r

The LCOE of this approach might seem similar to the dedicated CFB-CCS approach at first. However, this LCOE reflects the costs per unit electricity generated as a result of the CCS retrofit, which incorporates the likeliness that the electrical efficiency of the retrofitted biomass boilers will be lower than the new CFB boilers in the CFB-CCS approach, as the former are older. This in turn leads to marginally higher fuel costs and thus a higher LCOE than the mere difference between the CFB-CCS approach and the CFB reference approach. Also, because the efficiency is lower more CO_2 is captured per kWh generated, which would lead to higher costs for CO_2 transport and storage if no economic value for carbon is taken into account. Due to this lower efficiency, the influence of the cost of biomass feedstock is even larger with this method compared to the CFB-CCS approach and is thus also more sensitive to changes in this cost. The LCOE for this approach is estimated to be 13.2—24.6 eurocents/kWh, with the Median scenario being 17.7 eurocents/kWh (Table 2). An elaborated overview of cost assumptions and data on this technology is provided in Annex D.

3.3.3 Market perspective

Reference technology comparison

Table 3 Difference in LCOE between the SCPC-CCS-DC approach with 30% biomass co-firing and regular SCPC-CCS. Example: 18.15 €/MWh = 0.0182 €/kWh.

€/MWh	Minimum	Median	Maximum
Fixed costs	***2.7***	***3.5***	***4.3***
Capital payments	*2.6*	*3.3*	*4.2*
Fixed O&M	*0.1*	*0.1*	*0.2*
Variable costs	***9.1***	***12.9***	***20.1***
Variable O&M	*0.1*	*0.1*	*0.1*
CO_2 transport	*0.3*	*0.9*	*2.9*
CO_2 storage	*0.1*	*0.9*	*3.8*
Fuel cost	*8.6*	*10.9*	*13.4*
Total difference	***11.8***	***16.3***	***24.5***

Putting the LCOE of the direct co-firing approach in perspective by comparing it to a reference technology can be useful to see how much financial support is needed to realise a similar LCOE. This approach was compared to regular SCPC-CCS (Table 3), in which case no co-firing takes place. The price difference mainly takes place within the variable cost component, which in turn consists primarily of a difference in fuel costs as a result of co-firing the biomass and the corresponding efficiency drop. Other variable costs also turn out to be higher, such as the CO_2 transport and storage due to a lower plant efficiency, leading to more captured CO_2 per kWh of electricity generated. However, this is under the condition that no carbon price is in place. Although the annual capital payment and fixed O&M costs for the co-firing approach in the Median scenario are approximately €19 million higher than the reference approach, the levelised fixed cost is merely €3.5 per MWh higher because these costs are spread out over the annual units of electricity that are generated. More impactful on the total levelised cost is the fuel cost, as mentioned, amounting to a difference of about €10.9/MWh.

As for the PC approach (Table 4), the difference with the reference technology is four times that of the DC approach, which can primarily be attributed to a substantial increase in the variable costs due to the efficiency loss and an increased variable O&M. Furthermore, the levelised capital investment is substantially higher resulting from a larger specific capital cost of 3,424—4,225 €/kW, which is amplified by the FCR.

Table 4: Difference in LCOE between the SCPC-CCS-PC approach with 50% biomass co-firing and regular SCPC-CCS.

€/MWh	Minimum	Median	Maximum
Fixed costs	***16.4***	***38.2***	***66.1***
Capital investment	*15.8*	*36.7*	*63.6*
Fixed O&M	*0.6*	*1.5*	*2.5*
Variable costs	***17.4***	***24.0***	***35.8***
Variable O&M	*0.1*	*0.1*	*0.1*
CO_2 transport	*0.4*	*1.4*	*4.3*
CO_2 storage	*0.1*	*1.4*	*5.6*
Fuel cost	*16.8*	*21.1*	*25.8*
Total difference	***33.8***	***62.2***	***101.9***

Table 5: Difference in LCOE between the CFB-CCS approach and regular CFB biomass electricity generation.

€/MWh	Minimum	Median	Maximum
Fixed costs	***19.2***	***28.7***	***42.0***
Capital investment	*21.4*	*24.5*	*29.2*
Fixed O&M	*0.8*	*0.6*	*0.5*
Variable costs	***29.6***	***44.6***	***74.0***
Variable O&M	*3.7*	*3.7*	*3.7*
CO_2 transport	*2.7*	*5.5*	*13.5*
CO_2 storage	*0.9*	*5.5*	*17.6*
Fuel cost	*22.3*	*29.9*	*39.1*
Total difference	***48.8***	***73.3***	***116.0***

Comparing the dedicated BECCS approach, CFB-CCS, to the LCOE of a regular biomass CFB boiler would give us insight into the financial support that is needed to make this technology financially competitive with regular biomass electricity. When observing the Minimum scenario, the fixed costs dominate the difference in LCOE (Table 5). However, as the cost estimates for CCS become higher, the variable costs start occupying the largest share. The difference in the levelised cost of capital investment is related to the additional costs of CCS, amounting to €1,397, on top of the costs for installing the CFB boiler. Furthermore, additional O&M costs of €84/kW need to be taken into account, which is even higher than the O&M costs for the boiler (€61/kW). Besides an efficiency drop, the addition of CCS to the combustion process also requires additional variable O&M costs, which are assumed to be equal to the costs for CCS at fossil fuel facilities, amounting to €3.71/MWh (EIA, 2011). The total difference of the LCOE between the two technologies is €46—79/MWh, which is what is necessary to make this approach financially competitive in addition to the financial support the reference technology already receives. In 2013, biomass electricity received between €11—147/MWh in the EU28 countries (CEER, 2015), showing that this level of support is not unusual.

When comparing the LCOE of the CFB retrofit approach to that of regular biomass electricity generation with a CFB boiler of similar size, the LCOE of the former is only slightly higher than the latter (Table 6). Although the difference in capital costs is substantially smaller, especially when following the Median and Maximum scenarios, the fuel costs are again higher as a result of the occurring efficiency loss and the notion that boilers that are being retrofit are typically of higher age than dedicated BECCS facilities and thus have a lower efficiency to begin with. As the difference between the CFB-r approach and the reference approach does not differ greatly from the dedicated BECCS approach, one might favour the dedicated BECCS approach more than was first expected.

Table 6: Difference in LCOE between the CFB-r approach and regular CFB biomass electricity generation.

€/MWh	**Minimum**	**Median**	**Maximum**
Fixed costs	***14.5***	***16.4***	***19.4***
Capital payments	*13.9*	*16.1*	*19.0*
Fixed O&M	*0.5*	*0.4*	*0.3*
Variable costs	***31.1***	***51.1***	***86.7***
Variable O&M	*3.7*	*3.7*	*3.7*
CO_2 transport	*2.8*	*5.9*	*14.6*
CO_2 storage	*0.9*	*5.9*	*19.0*
Fuel cost	*23.6*	*35.6*	*49.5*
Total difference	***45.6***	***67.5***	***106.1***

Influence of carbon pricing

A factor that was not included in previous LCOE calculations was the price of emission allowances, which can lower the LCOE if they are being sold under the European Emissions Trading Scheme (EU-ETS). From a financial perspective, this could help a BECCS facility become profitable. However, when the emission allowances that result from the capture and storage of CO_2 are being sold to other companies for them to emit more CO_2, the operation of a BECCS plant does not make sense anymore from an environmental perspective. The potential of BECCS to mitigate climate change will thus depend on the cap of the ETS and should be proportionally lowered as a result of negative emissions generation to have any significant effect under such a scheme. But even if this is not the case it could still be valuable to know at which price level the technology in question could be competitive with a similar method of electricity generation by offsetting the difference in LCOE. For instance to ensure a BECCS deployment that is sufficiently large to be on track for a 2 °C scenario.

For the PC-CCS direct co-firing route, which has relatively little additional costs compared to the regular PC-CCS route, the allowance price at which this difference would be offset ranges from €16—32/tCO_2, with a median estimate of €20/tCO_2. The parallel co-firing route would need a substantially larger emission allowance of €42—125/tCO_2, with the Median scenario requiring a value of €77/tCO_2. The CFB-CCS approach would require an allowance price of €55—131/tCO_2 to have a similar LCOE to the regular CFB approach. The median value here is €83/tCO_2. Contrastingly, the retrofitting approach, CFB-r, requires a slightly lower allowance level, even though the difference in LCOE that has to be offset is higher compared to the CFB-CCS approach. This is because the efficiency is assumed to be lower in the CFB-r approach, which results in more primary energy use and thus a larger amount of carbon captured at equal electricity production. The carbon price that is necessary in this approach is €48—73/tCO_2, with a median value of €57.

It should be stressed that the way in which carbon is priced or traded affects the way in which the LCOE is influenced. Under an ETS, a BECCS plant would be allowed to emit the carbon that is not captured from the combustion process, depending on the cap, whereas a regular carbon tax would mean that these resulting emissions have to be paid for. A general carbon tax would result in BECCS becoming cheaper compared to more carbon-intensive methods of electricity generation, whereas an ETS would lead to an absolute decrease of the LCOE.

Wholesale market price comparison

€/kWh	Minimum	Median	Maximum
Pulverised coal-CCS direct co-firing (30%) (PC-CCS-DC)	*0.0230*	*0.0460*	*0.0801*
Pulverised coal-CCS parallel co-firing (50%) (PC-CCS-PC)	*0.0523*	*0.0924*	*0.1504*
Circulating fluidised bed BECCS (CFB-CCS)	*0.0533*	*0.0962*	*0.1616*
Circulating fluidised bed BECCS retrofit (CFB-r)	*0.0588*	*0.1036*	*0.1723*

Table 7: Financial support required per technology, i.e. the LCOE minus the average wholesale market price for electricity in the EU (€0.0731/kWh).

At this point, two different types of support have been discussed. Namely, the amount of support that is needed to reach a similar LCOE compared to a certain reference technology and what the emission allowance price should be in order to offset this difference and make this technology competitive. What is not taken into account in these approaches is that the reference technology might already receive financial support under various support schemes in Europe. Hence, it is valuable to calculate the average need for support per kWh for the project developers to be able to sell the generated electricity to the grid at the market price, which was on average 7.31 eurocents/kWh in 2016 excluding VAT and other levies (Eurostat, 2016).

Looking at the total amount of support that is needed to get sufficient returns on investment, the one lowest in support is the PC-CCS direct co-firing approach, with a median estimate of 4.57 eurocents/kWh additionally (Table 6). That would make this technology the cheapest of the four for a government in terms of support for a technology that generates electricity while producing 'negative emissions'. However, what is not taken into account is that not all of the emissions that are captured and stored are biogenic. Hence, not all emissions are 'negative' and this process of electricity generation would still add to the cumulative carbon dioxide emissions.

€/tonne stored biogenic CO2	**Minimum**	**Median**	**Maximum**
Pulverised coal-CCS direct co-firing (30%) (PC-CCS-DC)	*101*	*176*	*262*
Pulverised coal-CCS parallel co-firing (50%) (PC-CCS-PC)	*129*	*191*	*258*
Circulating fluidised bed BECCS (CFB-CCS)	*60*	*88*	*119*
Circulating fluidised bed BECCS retrofit (CFB-r)	*62*	*88*	*118*

Table 8: The cost per tonne of stored biogenic CO_2 for the assessed BECCS technologies.

This can be expressed in another way, namely by expressing the amount of support that needs to be given for a kWh of electricity produced in the amount of 'negative emissions' that are generated. An overview of such an expression is given in Table 1 and shows that the technology that was considered the cheapest in support from an economical perspective is now among the most expensive from an environmental perspective, looking at the support that is needed for a tonne of carbon to be actually removed from the atmosphere and sequestered.

3.4 Discussion

This analysis assumed that BECCS electricity deployment can be classified into three specific technologies. This is a simplification of reality, as other types of boilers, electricity generation methods and CCS technologies exist. Furthermore, the assumption was made that technology costs would be equal up to 2050, which is not likely, but necessary due to data constraints on variables such as discount rates and fuel prices, which are highly uncertain for the future compared to variables such as the overnight capital cost. Furthermore, the support required for the various BECCS methods was based on a constant average electricity price. First of all, these prices are variable between Member States and therefore the required support as well. However, the general trend will be that electricity prices decrease in the future, and if the LCOE does not manage to follow this trend, support requirements will be higher.

Additionally, the LCOE of the BECCS methods is highly sensitive to biomass feedstock prices, the capacity factor and interest rates, which are relatively uncertain at this point and may vary significantly per country. Part of this uncertainty has been covered in the different cost scenarios, but future differences may exceed the range expressed in the scenarios. Moreover, it was assumed that all the stored emissions of biomass were 'negative'. This does not account for the emissions that take place in the supply chain of the biomass feedstock and is thus an optimistic estimate. These estimates should therefore be understood with caution and are merely indicative.

3.5 Conclusion

This chapter was aimed at discovering the main factors of influence to the levelised cost of electricity of the identified technologies that could be deployed to increase BECCS capacity in the EU. Another aim was to find out which technology should be favoured over the other in terms of the support that is needed to make it competitive with other technologies on the market and to have the owners sell their electricity to the grid. Other findings pointed out the effect of carbon pricing on the competitiveness of the technologies and illustrated which technology is the most cost efficient in sequestering biogenic CO_2, i.e. in generating 'negative emissions'.

In order to identify the influential factors of the LCOE of the respective technologies the LCOE itself first had to be calculated. With a median estimate of 17.5 eurocents/kWh, the CFB retrofit approach turned out to be the dearest of the four. The dedicated CFB-CCS and the parallel co-firing approach are just under that with 16.9 and 16.7 eurocents/kWh, respectively. The direct co-firing method has the lowest LCOE with a median value of 11.9 eurocents/kWh.

The factor that in all cases dominated an increase of the LCOE with respect to a reference technology was the fuel cost, and to a lesser extent the capital investment cost, which is linked to the fixed charge rate and the specific investment costs (€/kW). An increase of primary energy fuel of €1/GJ in the case of dedicated BECCS led to an increase in the LCOE of 1.25—1.35 eurocents/kWh. The increased fuel costs are resulting from either the increased use of biomass, a drop in the efficiency or both. Chapters 4 and 5 discuss how the influence of these factors can be reduced

Furthermore, it was found that for the direct co-firing and the parallel co-firing technologies the emission allowance price should be €25/tCO_2 or €91/tCO_2 respectively to offset the difference in LCOE between these technologies and coal-fired CCS without co-firing. For the biomass CFB retrofit and the dedicated CFB-CCS this was €70/tCO_2 and €56/tCO_2, respectively. However, this merely denotes the difference that has to be overcome to be able to compete with the reference technology. The actual support that would be needed for the project developers to ensure that their electricity can be supplied at the wholesale market price is somewhat higher, as the reference technologies often already receive some form of support. For the direct and parallel co-firing approaches this is 4.6 and 9.6 eurocents/kWh, respectively. The retrofit and dedicated CFB approaches would require 9.4 and 10.2 eurocents/kWh, respectively. The cost-effectiveness of this support can be expressed in the amount of support given in € per sequestered tonne of biogenic CO_2, i.e. 'negative emissions'. This puts the retrofit and the dedicated CFB approaches on top with €86/tCO_2 and the direct and parallel co-firing methods at the bottom with €175/tCO_2 and €198/tCO_2, respectively and is thus not realistic from a negative emissions perspective.

This chapter has provided novel data on the LCOEs of the different BECCS approaches and has shortly illustrated the difficulties that arise when judging which technology should be favoured above the other in terms of cost effectiveness. It was shown that dedicated BECCS facilities can generate negative emissions more cost effectively, whereas co-fired coal plants with CCS do render some negative emissions, but at a relatively high support cost per tonne of sequestered biogenic CO_2. Furthermore, the carbon price that is required to increase the cost-competitiveness of the different BECCS approaches to a level higher than existing methods of electricity generation is unlikely to speed up deployment soon, except for BECCS co-firing compared to fossil CCS, which requires a price of €25/tCO_2.

Chapter 4 – Deployment barriers for the private sector

4.1 Introduction

The main aim of this chapter is to formulate the barriers that are in place for project developers to engage in BECCS. It will investigate why investments in this technology are hampering by looking at a broad range of barriers on the EU level, but also on a country level by scoping in on the UK, Norway and the Netherlands and comparing the presence of barriers among these countries. This latter approach will also give insights into whether it is efficient to mitigate these barriers on an EU level or if we should focus on a country specific approach. It is expected that the need for political action will logically flow from the most prevalent risks within the BECCS system and on which scale these risks should be mitigated. Thus, this chapter will answer the question "*Which deployment barriers for BECCS is the private sector in the EU currently facing and on which governance level should these be mitigated?*"

4.2 Methodology

Table 9: Experts interviewed for risk analysis.

Name	Institution/Company	Date
Henrik Karlsson	*Biorecro*	27/09/16
Joris Koornneef	*TNO*	23/08/16
Chris Hendriks	*Freelance*	19/09/16
Nilay Shah	*Imperial College London*	06/09/16
Mark Workman	*Imperial College London*	24/08/16
Gert-Jan Kramer	*Shell/Utrecht University*	18/08/16
Sabine Fuss	*Mercator Research Institute*	19/08/16
Paul Noothout	*Ecofys*	12/07/16
Daniel L. Sanchez	*Stanford University/Center for Carbon Removal*	08/09/16
Guy Lomax	*The Nature Conservancy/Virgin Earth Challenge*	20/09/16

To identify the barriers for the private sector, this analysis relied on interviews with experts in the business sector as well as in the academic sector (Table 9). These were consulted because of their experience with BECCS research projects or business activities. All the interviewees were provided the three most prominent barriers based on the literature research that was conducted in previous chapters and were subsequently asked to reflect on this by either adding or removing barriers. Furthermore, the experts were asked to identify the most prominent barrier the private sector is currently facing. Afterwards, these answers were aggregated into a categorisation that was derived from scientific literature to identify the type of barrier that is most prevalent within the BECCS system. Moreover, a literature analysis was performed in which 67 academic papers on BECCS were scanned for the barriers that were mentioned.

The second assessment in the case study was performed through a policy and literature analysis, combined with consulting policy experts that have specific country knowledge. Based on these sources, a relative risk estimation was performed and again aggregated into the existing risk categories.

4.3 Results

The main findings from this sections will be presented by first describing the key barriers for the private sector to engage in BECCS in 0; highlighting which barriers are the most prominent and require policy action in 4.3.2; and subsequently determining on which governance level these key barriers should be mitigated—EU or national—in 4.3.3.

Table 10: Barriers mentioned in expert interviews (n=10) and in scientific literature (n=67).

Type of barrier	*Identified barrier*	*Mentioned in literature*	*Mentioned in interview*	*Mentioned as most prevalent barrier*
Political/ regulatory	Absence of recognition and remuneration for negative emissions	*13*	*7*	*4*
	Ambiguity around legal and financial aspects of CCS legislation	*7*	*1*	*/*
	Absence of common sustainability standards for biomass feedstock for electricity	*11*	*3*	*/*
	Uncertainty around upfront funding for large-scale demonstration	*8*	*6*	*3*
Economic	Volatile prices for biomass feedstock	*6*	*2*	*1*
	Lacking CCS infrastructure	*4*	*3*	*/*
	Position of BECCS in the merit order	*/*	*1*	*/*
	Cost overruns and construction delays	*2*	*1*	*/*
Social/ environmental	Public opposition	*6*	*3*	*/*
	Lacking awareness at the political level	*5*	*3*	*/*
	Environmental or health impacts	*2*	*/*	*/*
Technical/ operational	Reduced continuity of operation	*2*	*2*	*/*
	Carbon capture from biomass flue gases	*4*	*1*	*/*

4.3.1 Deployment barriers

The type of barriers that BECCS project developers can face can be categorised as follows: political/regulatory, economic, social/environmental and technical/operational and are presented in Table 10. This categorisation was adapted from IEA's *Climate Policy Uncertainty and Investment Risk* report and was complemented with a category on social/environmental barriers, which is especially relevant for (BE)CCS projects (IEA, 2007).

Political and regulatory

Political or regulatory barriers are often defined as characteristics within domestic or regional politics, policies or regulations. For example, a situation where specific policy that would otherwise facilitate deployment is either absent or ambiguous.

Absence of recognition and remuneration for negative emissions

The most frequently mentioned barrier during the expert interviews relates to the accounting and rewarding of a tonne of removed biogenic CO_2. In 2009 the EU Directive on the geological storage of CO_2 (Directive 2009/31/EC) was put into place, because until then there was no common regulatory framework in place that ensured the safe geological storage of carbon dioxide (CEC, 2008). However, Member States also received the option to count stored CO_2 from fossil CCS plants as 'not emitted' in the EU ETS under Article 24. On the contrary, negative emissions from BECCS are not recognised for under the EU ETS as only a transfer of fossil carbon to geological reservoirs is allowed to be subtracted from the required amount of emission allowances. Future uncertainty around this issue within the EU ETS, but also within other carbon pricing mechanisms worldwide, increases business risk for projects that depend on a reward for the negative emissions they generate. Currently, a tonne of negative emissions in a biomass co-firing installation with fossil fuels would merely result in a lower demand for EUAs for the co-firing installation. Credits are not issued under the EU ETS due to the baseline mechanism of the scheme where a reduction of required allowances is granted when an emission reduction is achieved compared to the installation baseline.

Nevertheless, even if negative emissions were to be recognised under the EU ETS – or for BECCS the issuance of allowances for bioenergy plants introduced, a perspective on increasing EUA prices is absent as a result of an estimated surplus of 2 billion allowances that are currently hanging above the market (CEPS, 2016). Together with the reform of the EU ETS and the introduction of the MSR[6] in 2019 this surplus will likely remain until the late 2020's (UK Government, 2014).

It should be noted, however, that negative emissions from BECCS can be recognised and accounted for in the national GHG inventories of Parties to the UNFCCC and the Kyoto

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[6] MSR = market stability reserve. Instrument designed to bring stability to the allowance market from EU ETS phase 3 by transferring allowances to a 'reserve' with an annual maximum of allowances being transferred out of the system of 100 million if the market surplus exceeds 833 million allowances. These then return to the market when the surplus has decreased back to 400 million allowances.

Protocol. This is because biogenic GHG emissions from power plants are included in the 2006 IPCC Guidelines. Also project-based schemes, such as the Clean Development Mechanism and Joint Implementation recognise negative emissions from BECCS because of this reason. Emissions from biofuel BECCS can be accounted for under the EU Renewable Fuel Directive and the EU Fuel Quality Directive (IEAGHG, 2014). The common denominator of these schemes is that they operate on the portfolio level, meaning that positive emissions can be compensated by mitigation activities or it allows for the generation of emission credits when achieving an emissions reduction compared to a baseline scenario.

Ambiguity around legal and financial aspects of CCS projects

The CCS Directive has led to increased awareness around environmental and human safety in the context of CCS projects, but still leaves a number of issues open for improvement in some countries (WRI, 2010; Pershad & Stewart, 2010; Bassi et al., 2015), for example:

- dealing with non-permanence and the financial considerations around it;
- defining project activity boundaries with respect to the interaction of CCS activities with the sub-surface;
- the absence of international law in the case of cross-border CCS projects;
- ambiguity surrounding project liability in terms of financial compensation for affected entities and the transfer of responsibility post-closure.

Should these issues not be addressed and incorporated into a regulatory framework that applies to BECCS projects, this would enhance regulatory uncertainty and require increased hedging (Von Stechow et al., 2011).

Absence of common sustainability standards for biomass feedstock for electricity

Additionally, frameworks that consistently assess the sustainability of biomass supply are absent and cannot yet assess the scale of indirect land-use change (ILUC). Some studies have put forward that for some biomass feedstocks the emissions resulting from indirect land-use change even exceed the direct emissions reductions achieved by switching to the biomass feedstock (ZEP, 2013). Furthermore, not only the emissions from ILUC, but also the chain emissions from the biomass supply chain such as transport and feedstock preparation should be accounted for under a regulatory framework. This becomes more urgent as the supply chain expands in geographical size and when players start to engage in large-scale intercontinental trade of biomass to meet demand. Worries exist among scientists that land-use change and supply chain emissions will significantly reduce the negative emissions potential of BECCS. However, the Commission emphasised that "the sustainability risks relating to domestic biomass production originating from wastes and agricultural and forestry residues, where no land use change occurs, are currently low" (EC, 2010). Hence, this barrier mainly relates to the large biomass imports that are already taking place at present.

Uncertainty around upfront funding for large-scale demonstration

Indeed, funding shortages have been a dominant reason for CCS project termination in Europe over the last decade. In 2012, the amount of funding for CCS in the US was $7 billion, whereas in the EU this was just over $3 billion (Global CCS Institute, 2012). It is likely that this is the main reason that of the 14 CCS projects currently in operation, 10 are located in the US, including one installation that may be classified as a BECCS plant. A recent report by AIChE & WISE emphasises this issue by mentioning that current levels of government support do not provide sufficient incentive to attract private investment with its associated technical and economic risks (Wu, 2016). This political climate in Europe, which has not succeeded in providing financial stability to CCS investors, can partly explain why private investments in BECCS initiatives remain absent. One expert mentioned that the absence of government support for BECCS and of awareness around negative emissions could stem from a general lack of comprehension on the issue and an absent sense of urgency among political stakeholders. Furthermore, due to the many unknown risks and knowledge gaps that exist within the BECCS system, politicians are not likely to take on the responsibility of initiating or approving demonstration projects.

Along similar lines, the main EU financing mechanisms that have funded CCS projects, NER300 and the European Energy Programme for Recovery, have failed to deliver, two experts mentioned. The NER300, which was originally intended as a CCS instrument, has had a number of factors that influenced the Award Decision not to go to CCS-related projects. Firstly, a tight set of specifications and criteria for eligibility of CCS projects. Second, a high level of complexity and higher co-funding requirements for CCS projects compared to other energy-related projects such as wind power projects (Lupion & Herzog, 2013). It deserves attention that CCS had to compete with renewable energy projects—which entered the competition in a late stage—although these are two considerably different mitigation options that might best complement each other instead of having to compete for funding. Separate funding would have been more logical if CCS demonstration was desired. Hence, this funding situation is unfavourable for project developers that are looking to demonstrate an integrated BECCS system.

Economic

The few levelised cost of electricity (LCOE) estimates that have been done prove to be fairly consistent on solid biomass BECCS, e.g. an estimate of €205/MWh[7] (Talal, 2011) and a range of €135—219/MWh (this study). However, the cost per tonne of CO_2 mitigated differs considerably in literature, ranging between €53—222/tCO_2 (Kemper, 2016). As future business cases will require the inclusion of a reward for the carbon emissions that are mitigated, such a broad range of estimates might prove difficult to build a business case on. However, it can be debated whether this 'ballpark' range can be attributed to uncertainty in the operational or overnight capital costs or merely to varying assumptions on the specific technology that is chosen (e.g. type of boiler and carbon capture method). If the latter is the case, from the perspective of a project

[7] Converted from GBP 177.70 at GBP 1 = EUR 1.156.

developer this might not necessarily pose a risk. The LCOE analysis conducted in Chapter 2 was built on the CFB boiler technology and assumed post-combustion capture (amine scrubbing technology) and pointed out that under three varying parameter scenarios the mitigation costs would be between €144—154/tCO_2, not taking into account revenue from a carbon price.

Moreover, Sanchez & Callaway state that "biomass supply, scaling exponents, and technology costs are large drivers of optimal scale [in a BECCS plant]", which indicates that should any of these factors change over time, the BECCS plant will operate under sub-optimal conditions and consequently deviating operational costs (Sanchez & Callaway, 2016).

Other qualitative economic barriers are discussed below, and are defined as certain characteristics or developments of an economic nature that could affect the revenue of a BECCS project.

Volatile prices for biomass feedstock

Additionally, the price of biomass feedstock has shown to vary considerably over the past decade. For example, prices for wood pellets on the Danish biomass market have more than doubled in 10 years' time to €9.40/GJ in 2012[8] and are expected to increase by at least 50% up to 2050 under policy efforts that restrict global warming to 3 ˚C by 2100 (Danish Energy Agency, 2013). Also, the market for pellets and chips is currently still immature and sensitive to short-time changes in demand and supply (DECC, 2012). Under a scenario where BECCS will be actively incentivised, it can be assumed that competition for biomass feedstock will even be higher, corresponding with a larger price risk. Klein et al. also emphasised that if the EU or its national governments would formulate such policy, resulting in an increasing carbon price, pressure on the agricultural sector would increase. This could lead to unintended negative impacts on land-use systems, and bioenergy prices of up to $70/GJ (Klein et al., 2014). One expert recognised this and emphasised the need for strong regulatory and sustainability frameworks around biomass trade to avoid skyrocketing prices under BECCS deployment. Moreover, the LCOE of BECCS is very sensitive to fluctuations in the price of biomass feedstock, which is explained in more detail in Chapter 0.

Lacking CCS infrastructure

One expert mentions that a significant barrier lies with the unclear outlook that exists with respect to the availability of a capital intensive CO_2 transport network and who will carry this financial responsibility, leading to uncertainty in the prospects of reduced CO_2 transport costs. Additionally, to build a CO_2 network there are only a limited amount of locations in Europe where CO_2 can be transported from a point-source of carbon to a storage cost effectively. Fortunately, alternatives exist in the shipping of CO_2 to sequestration hubs (Noothout et al., 2014). Hence, the absence of a pipeline network would likely only result in increased operational costs and could decrease economic project viability.

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[8] Converted from DKK 70 at DKK 1 = EUR 0.13.

Position of BECCS in the merit order

Currently, the energy system in Europe is slowly shifting from a large-scale centralised system towards a more decentralised small-scale provision approach. This trend also appears to be desirable from a socio-economic perspective (Jansen & Seebregts, 2010). However, this trend also leads to a shift in the merit order, which already today affects the sale of baseload electricity to the electricity grid. As renewable energy sources such as solar and wind have considerably lower marginal operational costs compared to baseload sources, renewable energy installations are guaranteed to sell their electricity to the grid based on the merit order, forcing the more expensive baseload sources such as coal and gas, but also BECCS plants to ramp off. One expert expressed his concerns about the position of BECCS installations in a decentralised energy system with a high penetration of intermittent renewables, where the difference in operational costs will be even higher between that of BECCS and the wholesale electricity price. This prospect of an increased need of government support to be able to sell the produced electricity to the grid can potentially affect future investment decisions. Also, this effect could reduce the capacity factor if the installation has to repeatedly ramp up and down.

However, the first BECCS deployment is likely to be seen in the retrofitting of bioelectricity plants. One way to allow these plants to be more flexible in the future energy system is if they switch off the CCS when the wholesale prices are highest. In that way, they would be generating the most revenue, as CCS consumes a part of the electricity that is produced. At low wholesale prices, CCS is switched on to make the most efficient use of its carbon revenue. Depending on this potential carbon price, BECCS systems could even deliver electricity at a negative price to the grid (Karlsson, pers. comm.). It is important to consider that the previous paragraph only holds when a carbon price or incentive scheme is absent. Also, if the EU would move away from the spot market the effect of this barrier will decrease.

Cost overruns and construction delays

As touched upon earlier, upfront investment costs can vary considerably, with the overnight capital costs of a CFB boiler alone ranging between €1,632—3,383/kW (IRENA, 2013). Additionally, CCS projects in the past decade have often faced cost overruns, primarily due to construction delays and regulatory uncertainty (Sanchez & Kammen, 2016).

Some researchers express concern with respect to the capacity of the learning effect in BECCS, which might be weaker than is commonly seen in emerging technologies (Laude & Jonen, 2011). This concern is rooted in the idea that several elements out of which a BECCS plant consists have been under development for multiple decades. For instance, biomass burning in CFB boilers has been around since the 1990's and even longer so for pipeline transport of CO_2. However, reduction potential remains in emerging combustion technologies such as IGCC and also with carbon capture technologies, which are expected to face a global progress ratio of 12% per doubling of the CCS capacity (McKinsey, 2008). Factoring this into the total cost of BECCS, the overall reduction potential decreases considerably. If investors were to take this into account, they might identify risk in whether BECCS is a technology that will experience enough learning and cost reductions to become competitive in the energy system if market mechanisms or other incentives weaken in the future. In the long-term, this effect could influence investment decisions as a result of the capital costs not decreasing as expected, which make up a predominant share of the LCOE of the different BECCS methods.

Social and environmental

Social and environmental barriers relate to societal (e.g. behavioural, cultural) and/or environmental impacts or developments that could affect a BECCS project negatively. The identified barriers of such a nature are discussed below.

Public opposition

Traditionally there has been opposition against CCS in many EU Member States. This was illustrated during Shell's CCS project in Barendrecht, the Netherlands, where widespread opposition from the communities surrounding the CCS location led to severe delays and eventually cancellation (Terwel et al., 2012). In the case of BECCS, biomass energy also enters the equation. And opposition against energy from biomass is not entirely uncommon. Examples include local opposition against biomass energy development in the UK in the previous decade (Upreti & Van der Horst, 2003) and in Germany (Zoellner et al., 2008). One expert illustrated that because of this reason, BECCS will likely face less public opposition in Austria, which has a reasonably developed biomass sector, in comparison to Germany. Furthermore, only 4—22% of the laymen in acceptance studies have generally heard of CCS. Taking into account that BECCS is a concept that is likely even less familiar with laymen, the effect on their subjective or constructivist risk perspective might even be stronger with BECCS (Stigson et al., 2011), leading to stronger public opposition if not properly managed. However, one study concluded that the NIMBY effect of BECCS projects might be weaker than with regular CCS projects (Wallquist et al., 2012). Also, in a public perception study that touched upon BECCS, Upham & Roberts found that a high percentage of the respondents in a number of EU countries gave a "no opinion/do not know" answer, and after being provided with additional information on the technology shifted to a negative opinion (Upham & Roberts, 2011). However, the authors link this response to a likely misunderstanding of how the technology works and the association with CCS. Another study found that CCS was perceived as less negative among the general public in the context of biomass compared to a context that includes fossil fuels (Dütschke et al., 2014).

Lacking awareness at the political level

The need for CDR methods such as BECCS has been expressed by the scientific community for roughly a decade. However, no significant political efforts have been undertaken to facilitate the deployment of such technologies. Multiple experts have pointed out that there is a clear disconnect between BECCS and key stakeholders at the political level, even though "BECCS could serve to strengthen and reinforce the biomass niche in the same manner as CCS could reinforce the fossil fuel regime" (Vergragt et al., 2011). This could have arisen from the complexity of the BECCS system and the historical public opposition involved from bioenergy and CCS seperately.

Environmental or health impacts

The use of biomass for electricity generation and the subsequent transport and geological storage of CO_2 obviously bring along environmental concerns. These concerns could include the occurrence of ILUC, chain emissions from biomass supply chains or CO_2 leakage from pipelines or geological reservoirs. Clear environmental standards or regulations that outline which existing standards account for BECCS projects could aid in mitigating this type of risk.

Along similar lines, a shortage of available sustainable biomass could be identified as an environmental risk. If feedstock suppliers would resort to non-certified biomass feedstock produced outside of the EU, this could have a considerable impact on existing ecosystems and could result in ILUC (EC, 2010). However, this risk is strongly interlinked with the presence of regulatory frameworks for biomass feedstock and is thus an avoidable risk. Additionally, this risk only becomes significant at larger scale deployment, one expert mentions, as existing global sustainable biomass feedstocks could meet early BECCS demand.

Technical and operational

This section aims to describe barriers that concern events or challenges related to the technical or operational characteristics of BECCS. The identified barriers that can be categorised as such are described below.

Reduced continuity of operation

In the present premature stage of BECCS deployment, running a continuous operation would be fundamentally dependent on three factors. Namely, a sufficient supply of biomass feedstock, grid availability and CO_2 storage potential. From this perspective, regular bioenergy plants would only have to deal with the aspects of a continuous biomass supply and being able to load electricity into the grid. Being dependent on one additional physical element, continuous geological storage capacity, gives rise to the risk of operating at a lower capacity factor than anticipated. Options for the storage of biomass feedstock do exist, but these are often expensive and do not make up for the large year-to-year variations in biomass production (Golecha & Gan, 2016). As for the CO_2 output, one expert mentioned that current CCS installations are not built to have a continuous output. By applying pressure management, the flow of CO_2 can be broadly variable, obviously still within pre-defined boundaries. However, these risks might affect the capacity factor of BECCS operations.

Along similar lines, under *economic risk* it was mentioned that “biomass supply, scaling exponents, and technology costs are large drivers of optimal scale [in a BECCS plant]” (Sanchez & Callaway, 2016). This also implies a high risk of operating at a lower capacity factor, should any of these factors change significantly over time.

Carbon capture from biomass flue gases

Although dedicated biomass energy with amine scrubbing technology has one of the highest maturity levels of the existing BECCS options (Bhave et al., 2016), engineers still identify some key technical issues in its application. As amine absorption is currently used under different operating conditions, the characteristics of the flue gases are different from those in biomass combustion. This results in amine degradation and equipment corrosion. However, these technical issues can be mitigated fairly easy, be it under higher O&M costs (IEAGHG, 2009).

4.3.2 Most prevalent barriers for the EU

The conclusions from the expert interviews that were conducted give a clear indication of the prevalence of the barriers in the European context. The experts were first asked to reflect upon the barriers that were found in literature, which yielded the results in the second column (Table 10). This column indicates how many times the corresponding barrier or risk was mentioned in one of the interviews and was acknowledged to be indeed a risk that should be taken into account by policymakers. The third column expresses how many times one of the experts mentioned that the corresponding barrier was the most dominant in hindering investments from the private sector and that alleviating these risks or lifting these barriers should be among the top priorities in the policy community.

On the basis of the expert interviews the most pressing risks are '*Absence of recognition and remuneration for negative emissions*' and '*Uncertainty around upfront funding for large-scale demonstration*'. The experts shared common ground on the notion that an incentivising mechanism is detrimental to the scale-up of BECCS and that not recognising their capacity to deliver negative emissions will discourage investors to engage in this technology. The second most prevalent risk was chosen for multiple reasons. Other barriers that were mentioned frequently include the notion that biomass that is used for electricity lacks clear common sustainability standards, while others said that uncertainty around the prospects of a widespread CCS infrastructure was a key risk. Other experts mentioned that future operational costs are likely to be uncertain due to volatile prices of biomass feedstock, which is not yet a stable commodity on the global market. Future developments could increase this risk when supply is not able to cope with the increasing demand for biomass to achieve stringent climate goals. Moreover, public opposition and lacking awareness at the political level were mentioned. Experts believe that this could stem from the complexity of BECCS together with a general negative sentiment from the association with bioenergy and CCS.

Based on the literature analysis, a more or less similar picture comes forward. However, a few discrepancies exist. For example, '*Absence of common sustainability standards for biomass feedstock for electricity*' was more frequently mentioned in scientific literature, and so was '*Ambiguity around legal and financial aspects of CCS legislation*'. The experts that were interviewed could have been more unfamiliar with these topics. On the contrary, the need for demonstration and the uncertainty around mechanisms currently providing upfront funding for demonstration projects was more pronounced in the expert interviews compared to the assessed literature, but still relatively dominant.

Finally, for nuance it is good to stress that looking at BECCS deployment from a perspective of barriers does not offer the whole picture. Technology deployment is also very much a matter of opportunities, and if these opportunities well outweigh the perceived risks, policy makers might provide the regulatory tools to enable technology scale-up. However, if these opportunities are not communicated clearly enough, are not trusted due to a questioned legitimacy of IAMs, or are not well understood due to the complexity of the BECCS system in this case, scale-up becomes rather challenging, two experts mentioned.

4.3.3 Case study

In this case study, the identified barriers have been studied on a country level to find out whether these barriers are present in the Netherlands, Norway and the UK. Although Norway is not an EU Member State, it belongs to the EEZ and the EU can provide guidance on a number of areas, including CCS. These countries were also chosen due to data availability on legislation concerning these barriers and connections with several country-experts that had already been established in the previous section and could consequently be consulted. Furthermore, these countries are geographically, politically and socially distinct from one another, so hypothetically interesting results were expected to come about.

Table 11: Country-specific risk analysis for BECCS deployment.

Type of barrier	*Identified barrier*	*Netherlands*	*Norway*	*UK*
Political/ regulatory	Absence of recognition and remuneration for negative emissions	++	++	++
	Ambiguity around legal and financial aspects of CCS legislation	-	o	--
	Absence of common sustainability standards for biomass feedstock for electricity	o	o	-
	Uncertainty around upfront funding for large-scale demonstration	o	-	++
Economic	Volatile prices for biomass feedstock	+	+	-
	Lacking CCS infrastructure	+	+	o
	Position of BECCS in the merit order	+	++	o
	Cost overruns and construction delays	o	o	-
Social/ environmental	Public opposition	o	--	+
	Lacking awareness at the political level	+	+	+
	Environmental or health impacts	-	--	--
Technical/ operational	Reduced continuity of operation	+	o	o
	Carbon capture from biomass flue gases	--	--	--

Risk comparison

Table 11 presents the results from the case study.

Absence of recognition and remuneration for negative emissions
Although negative emissions from BECCS are recognised in domestic GHG inventories through the IPCC Guidelines, they are not recognised and rewarded under existing emission schemes such as the EU ETS. Therefore, no differentiation of the presence of this barrier is made between the Member States. However, potential exists for countries to individually stimulate BECCS through domestic policy.

Ambiguity around legal and financial aspects of CCS projects
Regarding the ambiguity around legal and financial aspects of CCS legislation, the EU has provided the CCS Directive and allowed Member States to include this into their domestic policy. With this, Member States received the possibility to count captured and stored CO_2 from power plants as 'not emitted' under the EU ETS, lowering the need for emission allowances. However, Member States had to transpose this into their domestic laws for the Directive to have effect. Some countries have done this more extensively than others. When looking at CCS legislation in the three respective countries, the UK currently has the most extensive legislation in place. Already in 2008, the UK Energy Bill contained provisions for the offshore geological storage of CO_2. The subsequent Energy Act includes a framework for the licensing, enforcement and registration of storage sites (UK Government, 2008). For the Netherlands, geological storage of CO_2 has been embedded in regulation through an amendment of the 2003 Mining Act. Although Norway seems to have the longest experience with CCS projects, they have not yet found a suitable provision in their law for issuing permits to sequester CO_2, as this is currently done through the Pollution Control Act whereby a permit is given to 'pollute' the CO_2. Therefore, responsibility for leakages is not satisfactorily regulated under Norwegian law (Makuch et al., 2013). However, Norway is currently assessing possibilities to improve the permitting process through However, Norway is currently assessing possibilities to improve the permitting process through their *Guidelines on the Financial Security and Financial Mechanism for CO_2 Storage* (Global CCS Institute, 2016). Liability issues are properly integrated into law in all the countries that were assessed this case study (Global CCS Institute, 2015a). The *Legal and regulatory indicator* of the Global CCS Institute underwrites this by attributing a score of 65, 56 and 40 to the UK, the Netherlands and Norway, respectively based on the availability of CCS-specific laws that are applicable across the CCS (Global CCS Institute, 2015b).

Absence of common sustainability standards for biomass feedstock for electricity
Sustainability of biomass feedstock used for electricity is currently guaranteed in some countries. Although this is not covered under the RED, some Member States have chosen to develop certification schemes themselves—Belgium and Italy, among others. IEEP mentions that the UK (and Germany) are ahead compared to the rest of Europe with regard to regulation that sets sustainability criteria for biomass feedstock for electricity (Kretschmer & Bennett, 2011), which is of significant importance in the scale-up phase of BECCS to help increase the biomass supply sustainably. The Netherlands,

however, was said to make good use of waste resources for bioenergy, in comparison to other Member States (Kretschmer & Bennett, 2011).

Uncertainty around upfront funding for large-scale demonstration

With regard to uncertainty around upfront funding for demonstration projects, the government of Norway is currently looking into the potential of BECCS to contribute to staying below 1.5 °C of global warming. This is a study in collaboration with the UK Met Office Hadley Centre (UiO, 2016). The Norwegian government does not exclude the use of BECCS and recognises its potential, but considers the frameworks for both biomass and CCS a serious challenge (SINTEF, 2013). Norway also has the CLIMIT programme since 2005, which has seen substantial investments in CCS RD&D, more than €200 million in some years. This is more than the UK and the Netherlands (UKCCS, 2016; Brouwer, 2014). In addition, the Dutch government recently announced that achieving a CO_2 neutral energy system is nearly impossible without the use of negative emissions from BECCS, for instance. However, they also stressed that because of its scarce domestic biomass resources, it would be best to allocate them to purposes without low-CO_2 alternatives such as fuels for the aviation and shipping industry around 2050. That implies that The Netherlands is not likely to invest in BECCS in the absence of substantial imports. However, it should be noted that the Dutch government did co-invest €100 million into the ROAD CCS demonstration project. In the UK, financial uncertainty surrounding (BE)CCS demonstration is likely to be higher, taking into account the recent government decision to stop the CCS Commercialisation Programme, which would award GBP 1 billion to the White Rose CCS project. This project was going to co-fire biomass and would thus be the first major BECCS project in Europe. This event considerably reduced the likelihood of CCS project developers receiving government funding in the coming decade (Cozier, 2016). The likelihood of government funding is the only factor by which the presence of this barrier can differentiate as all EU Member States will likely be able to apply for funding from the 'NER 400' Innovation Fund that is set to start in phase 4 of the EU ETS in 2021 (EC, 2016).

Volatile prices for biomass feedstock

For the availability and price of biomass supply, risks will be highest for countries that cannot domestically source their biomass such as the Netherlands and the UK, which are even under current demand dependent on biomass imports. Norway on the other hand is one of the largest net exporters of woody biomass feedstock in Europe and can also rely on neighbouring Sweden and Finland that both have a well-developed biomass sector (Hewitt, 2011).

Lacking CCS infrastructure

Cheap transport of CO_2 form a point-source to a sink is dependent on pipelines that are capable of transporting the CO_2, and are different from natural gas pipelines. Most of the experience in transporting CO_2 lies in the US where it is used for EOR. However, Europe also has some pipeline infrastructure, predominantly in the UK (42 Mton CO_2 yr^{-1}) and the Netherlands (6.3 Mton CO_2 yr^{-1}) (Noothout et al., 2014). A relatively small pipeline trajectory is located in northern Norway (0.7 Mton CO_2 yr^{-1}), which is not likely to be near any potential BECCS facilities in the future.

Position of BECCS in the merit order

Based on the merit order, BECCS is not likely to be introduced in Norway. Their electricity prices are among the lowest of Europe as a function of their large hydropower capacity, which has a high intermittency due to a significant share being run-of-the-river hydropower (IRENA, 2012). This implies that using BECCS in the Norwegian energy system as a back-up will be extremely costly due to the high difference in marginal operational costs compared to the spot market price. The Netherlands will be expanding its interconnectivity in the coming decade, so it will profit from cheap imported renewable electricity (Frontier Economics, 2015). This will make integration of BECCS into the energy grid challenging as well. Based on the merit order, the UK is the most likely country to adopt BECCS, as their electricity prices are currently among the highest in Europe (Eurostat, 2016). Furthermore, their interconnected capacity is relatively low, being an island state, leading to higher operational costs for renewables (UK Parliament, 2011). Also, due to their difficult position in the EU at the moment they might not be able to receive as much funding to improve their interconnectivity and link to the North Sea super grid[9]. However, it should be stressed that an assessment based on the merit order for BECCS is not entirely appropriate, as it would be penalised for its high marginal costs, whereas its characteristic to generate negative emissions is neglected which could well be the most valuable commodity of BECCS (Sanchez & Kammen, 2016).

Cost overruns and construction delays

Currently, there are 5 CCS projects either 'on hold' or 'cancelled' in the Netherlands (MIT, 2016). In the UK and Norway, this number is 4. However, the UK and Norway also see 4 succeeded or 'in operation' projects. For the Netherlands this number is 3 (Global CCS Institute, 2016). This would suggest that—based on previous CCS projects—the risk of project failure is slightly higher in the Netherlands than in the other two countries. Nonetheless, this difference is not significant enough to be meaningful. Upfront investment costs can differ considerably between countries, depending on matters such as the supply contracts that were closed for the required materials, the labour costs of the construction workers, or the lead time for delivery. In general, the CAPEX costs of power projects in the UK are lower than in other OECD countries (World Energy Council, 2013). Taking into account that the UK has a more coherent legal CCS framework, together this might result in the UK having a lower risk of construction delays and unexpected high upfront costs.

Public opposition

When discussing public attitudes towards BECCS it is useful to take into account that Norway is often considered a global leader in the field of CCS due to their experience

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[9] A collaboration between EU member-states and Norway to create an integrated offshore energy grid which links wind farms and other renewable energy sources across the northern seas of Europe that is likely to receive a substantial amount of EU funding (EC, 2014b).

with large commercial CCS projects (Van Alphen et al., 2009). Also, their CCS RD&D budget is among the largest globally (IEA, 2011). As a result of this, stakeholders' attitude towards CCS projects is generally positive. Stakeholders from the UK and the Netherlands generally have a more negative attitude towards CCS, with those the Netherlands being the most sceptical (EC, 2011a). Furthermore, there is generally more support for bioenergy in countries with a well-established forestry sector and that have positive experiences with bioenergy in the country, such as Norway, Sweden and Finland (Ericcson et al., 2004). Public opposition against biomass in the UK is relatively high at 14%, compared to only 5% for the Netherlands, which is on the same level as Norway (EC, 2011a; Karlstrøm & Ryghaug, 2014).

Lacking awareness at the political level

Research groups in the UK (AVOID2), the Netherlands (PBL) and Norway (KLIMAFORSK) are looking or have looked into the potential of BECCS for their countries. However, these conclusions have not materialised into action so far in any of these countries. Hence, we can state that the level of awareness at key political stakeholders is such that notable efforts to facilitate deployment have been non-existent in all three countries.

Environmental or health impacts

The risk of environmental and health impacts that were discussed mainly related to the risk of leakage from geological reservoirs and the use of uncertified biomass feedstock, possibly leading to ILUC. These factors are however mostly dependent on the status of the countries' regulatory frameworks with respect to safety, liability and feedstock certification. Population density could also be a risk factor in the case of a leakage event or pipeline defect, as more people will be affected in a high density area. Earthquake hazard potential also plays a role, but one could argue that no CCS projects will be undertaken in high potential areas. Hence, no significant risk distinction can be made for this category.

Reduced continuity of operation

The risk of operating at a low capacity factor was predominantly related to technical issues and the risk of encountering issues in the biomass feedstock supply chain. For the former it is not likely that there is a risk differentiation between the countries. The latter is mainly determined by the scale of the biomass demand and how much of that demand is domestically sourced, which favours Norway. However, the prioritisation of the merit order could also push out BECCS in the future, hence lowering its capacity factor, implying that a BECCS facility in Norway would be more at risk. The Netherlands knows both risks from the merit order and biomass supply and overall receives a more negative value compared to the other two countries.

Carbon capture from biomass flue gases

Difficulties around capturing the carbon from biomass combustion flue gases are not more prevalent in other countries, as this is per definition a technology-related issue. However, difficulties can be larger if a certain country predominantly use a specific biomass feedstock with varying moisture content. The view of this thesis is that these technological barriers are surmountable and that these could at most increase costs for pre-treatment or that post-combustion capture technology will take longer to develop and thus force BECCS to other point-sources of biogenic CO_2, such as the paper and pulp sector.

4.4 Discussion

It should be stressed that this comparison did not aim to decide upon which of the assessed countries are the most suitable for BECCS deployment. It merely studied the presence of every individual risk or barrier in the countries. It is therefore also not useful to take the cumulative of the countries' risks and compare them, as one risk could well be more influential to BECCS deployment than another, and this was not determined. Moreover, the list of risks might not be exhaustive, but it has aimed to at least cover the most prevalent (type of) risks.

Furthermore, it can be questioned whether the number of experts interviewed truly represents a correct view of the prevalence of the barriers the private sector is facing in terms of BECCS development. This potential bias was partly compensated by the literature analysis, although similar problems arise here. Some barriers may simply be less well-known and thus underrepresented, which is all the more reason for demonstration projects.

In addition, valuing the presence of a certain barrier in the case study can be considered a subjective method, as there is no specific value behind the grading and can thus not be classified accordingly. However, it can be said that one barrier is more prevalent than the other in a certain country, which was the sole purpose of this exercise.

4.5 Conclusion

This chapter studied the question of which specific barriers and risks are currently preventing investments into BECCS projects, and which of these are the most prevalent. Furthermore, it conducted a case study and described how the presence of these risks can differentiate between countries, in this case the Netherlands, Norway and the UK. The results were meant to point out which (type of) barriers require policy action if BECCS scale-up is desired and whether the identified risks should be mitigated on an EU level or on a national level.

Throughout the interviews that were conducted, the most commonly mentioned type of risk was that of a political and regulatory nature. Experts perceived (1) the absence of a framework that rewards negative emissions as the most prevalent risk, combined with the (2) uncertainty around upfront funding for large-scale demonstration projects, which have so far not successfully managed to deliver (BE)CCS projects. Other regulatory barriers that frequently came up were (3) the absence of common sustainability standards for biomass that is used for electricity generation and (4) ambiguity within legal and financial CCS legislation. Economic risks were also mentioned, predominantly related to (5) volatile prices for biomass feedstock due to immature biomass markets. Finally, BECCS also has issues of (6) lacking awareness at the political level, arising from the complexity of the BECCS system and ineffective communication. Hence, the barriers of which their mitigation is essential to BECCS scale-up are:

1. Lacking recognition and remuneration for negative emissions
2. Uncertainty around upfront funding for large-scale demonstration
3. Absence of common sustainability standards for biomass feedstock for electricity
4. Ambiguity within legal and financial CCS legislation
5. Volatile prices for biomass feedstock
6. Lack of awareness at the political level

Moreover, from the case study that was conducted we can conclude that as a function of the complexity of BECCS, and the varying presence of risks that was perceived in the assessed countries, generic EU-wide policy will likely not be the most effective way to alleviate these risks for the private sector. More effective yet, would be to mitigate the risks that are equally present in all countries on an EU level, and address the other risks through domestic policy.

From the identified barriers, it can be concluded that *Lacking recognition and remuneration for negative emissions* and *Uncertainty around upfront funding for large-scale demonstration* should be addressed on an EU level. *Absence of common sustainability standards* and *The lack of awareness at the political level* could also be addressed on this governance level, with participation from the individual Member States. The other barriers that were identified are best addressed through domestic policy, although the EU could well provide guidance.

Chapter 5 – Policies for BECCS scale-up

5.1 Introduction

This chapter will aim to determine, based on the risks that were identified in Chapter 4, which policy actions can be taken by the European Commission and the national governments of the Member States if they were to have the ambition to stimulate BECCS deployment. It was concluded that the *absence of recognition for negative emissions* and the *funding gaps for demonstration* should be addressed on an EU level, as well as the elements from the *absence of common standards for biomass feedstock for electricity*. Furthermore, this section will lay out whether existing pieces of legislation are sufficient to mitigate the existing barriers or if additional policy is required. Finally, this chapter will lay out in which timeframe these policies should be implemented in order to fulfil the policy goals that were set out in Chapter 2. Accordingly, this section will answer the following sub-question: "*Which policies have the potential to lift [the identified] barriers, which specific adjustments need to be made to do so, and by when?*"

5.2 Methodology

This section will aim to answer the sub-question by first defining the energy and climate policy strategy of the European Union and how this relates to the relevant pieces of legislation. Determining whether a piece of legislation, e.g. a directive or regulation, is relevant is done through literature review of these documents. If barriers or their characteristics are mentioned in the legislation it will be valued as relevant. Subsequently, the review of policy to determine whether additional efforts are needed is assisted by matching the legislation with the barriers to identify where action is lacking. Review of these policies in combination with literature research yielded specific policy actions that can be taken to lift the barriers that are in place. Finally, based on available information from EU bodies and national governments a timeframe will be established in which these adjustments should be implemented. This will be combined visually with the roadmap that was constructed in Chapter 2 by depicting by when policies should take effect to be enable BECCS scale-up.

5.3 Results

The main findings of this chapter are discussed in accordance with the structure of EU energy and climate policy, which will be introduced briefly beforehand. Subsequently this section will present which barriers can be addressed by existing EU policy, and which barriers require additional political measures. In 5.3.3, the dimension of time is introduced to show when the identified policy adjustments or additions need to be implemented to enable BECCS deployment. Lastly, in 5.3.4, we will discuss how ambitious the identified solutions are in the current policy context.

5.3.1 EU energy and climate policy

The European Union structures its 'Energy Union and Climate' policies under the Energy Union Framework Strategy (EC, 2015b), which consists of five pillars and corresponds to legislation and other policy initiatives that were already defined before the Energy Union was established (Table 12). The Energy Union pillars that are relevant to the most dominant barriers to BECCS deployment identified in Chapter 4 are (4) decarbonising the economy and (5) research, innovation and competitiveness.

Moreover, the EC recognizes the potential of BECCS in their 2050 Roadmap: "CCS is also an important option for decarbonisation of several heavy industries and combined with biomass could deliver 'carbon-negative' values."

Table 12: EU energy and climate policy pillars and corresponding relevant pieces of legislation for BECCS barriers.

Energy Union pillar	*Relevant legislation/initiatives*
1. Energy efficiency	-
2. Security, solidarity and trust	-
3. Integrating internal energy market	-
4. Climate action—decarbonising the economy	ETS Directive CCS Directive Renewable Energy Directive Monitoring Mechanism Regulation (525/2013)
5. Research, innovation and competitiveness	NER300 SET-Plan

Table 13: Available legislation to address barriers to BECCS deployment. Numbering of barriers is done consistently with Chapter 4 and is done as follows: I. Lacking recognition for negative emissions; II. Non-existent remuneration for negative emissions; III. Absence of common sustainability standards for biomass feedstock for electricity; IV. Volatile prices for biomass feedstock; V. Uncertainty around upfront funding for large-scale demonstration; VI: Lack of awareness at the political level.

Barrier **Legislation**	*I*	*II*	*III*	*IV*	*V*	*VI*
ETS Directive	×	×				
CCS Directive	×					
Renewable Energy Directive			×	×		
Monitoring Mechanism Regulation	×					
NER300					×	
SET-Plan						×
Domestic policies		×		×		

5.3.2 Required policy action

The previous chapter concluded with the most prevalent barriers the private sector in the EU is currently facing. These barriers relate to the subdivision of topics that is made in this section, namely: *I. Lacking recognition for negative emissions; II. Non-existent remuneration for negative emissions; III. Absence of common sustainability standards for biomass feedstock for electricity; IV. Volatile prices for biomass feedstock; V. Uncertainty around upfront funding for large-scale demonstration; VI: Lack of awareness at the political level.*

Currently there are various policies already in place that have the potential to address issues related to the production of biomass energy, carbon capture and storage and BECCS specifically. Depending on the capacity of the policy in question to address the identified barriers, amendments or new policy will be suggested. Table 13 provides an overview of available legislation to address the identified barriers to BECCS deployment, which will be substantiated in the following section.

Lacking recognition and remuneration for negative emissions

When discussing how to incentivise BECCS by recognising its negative emissions potential, essentially three options can be identified that are not mutually exclusive and will be discussed in the following two sections:

1. Amending the EU ETS to reward negative emissions from BECCS installations through the issuance of carbon credits.
2. Developing domestic policy measures that specifically stimulate BECCS technologies in the form of a feed-in-tariff or a 'carbon storage premium'.
3. Establishing an EU remuneration framework for negative emissions in general, which also sets out guidelines for accounting.

Currently, the EU ETS mechanism allows bioenergy installations to report their emissions as 'not emitted' due to the presumed carbon-neutrality of energy from biomass. Hence, they are not obliged to buy emission allowances. This implies that the baseline for a BECCS facility is zero. As the ETS mechanism operates by giving a reduction in the allowances required to comply with the target and does not issue credits when emissions go below-zero, crediting negative emissions from BECCS is currently not possible through the ETS. An option to mitigate this barrier could be amending Article 49 within the EU ETS Monitoring Mechanism Regulation (MMR) and enabling the issuance of EUAs when installations manage to reduce emissions to net negative levels. These actions can be taken through either a direct Commission decision or through the comitology process under Article 23 of the EU ETS Directive (IEAGHG, 2014).

Important considerations in making these policy adjustments include the baseline principle of emissions trading systems. As the emission baseline of a—let us say 100 MW—bioenergy installation would be zero, the emission reduction from capturing 90% of the emissions could be 1 Mton yr^{-1}. However, a 100 MW pulverised coal plant making a fuel switch to biomass feedstock could achieve the same emission reduction and would therefore render the same carbon revenue. Given this principle, BECCS would compete with other mitigation options on a 'per tCO_2 basis'. As negative emissions would be favoured over mere emission reductions from a climate perspective, policy makers should determine whether BECCS requires additional financial incentive.

Furthermore, only the transfer of fossil carbon from installations to geological reservoirs is recognised under the ETS Directive, which may be deducted from a fossil fuel installations GHG emissions. Biogenic CO_2 is currently excluded from this possibility, although this makes sense due to the zero-baseline of bioelectricity facilities. If the EU ETS would be amended with a crediting mechanism, the transfer of biogenic emissions to geological reservoirs should be allowed and made deductible under the ETS Directive.

Another way of achieving BECCS incentivising through the EU ETS is with domestic offsetting under Article 24a. This could also apply to carbon dioxide removal technologies other than BECCS as this mechanism creates provisions for "implementing measures for issuing allowances or credits in respect of projects administered by Member States that reduce GHG emissions not covered by the Community scheme" (IEAGHG, 2014). This mechanism is however not yet clearly defined and would require additional clarification on how the remuneration works with respect to the baseline crediting (ClimateFocus, 2010). Also, this scheme would be merely for non-EU ETS installations, whereas biomass installations currently fall under the EU ETS. This implies that amendments need to be made to the ETS Directive as well in order to make it compatible with domestic offsetting.

Joint Implementation could also play a role, as this is a project-based scheme that uses the IPCC Guidelines, which allows for the recognition of negative emissions from BECCS in national inventories. Eligibility is determined, according to the UNFCCC by "providing a reduction in emissions by sources, or an enhancement of removals by sinks, that is additional to what would otherwise have occurred" (UNFCCC, 2014). However, only little activity under JI has been reported in the last years, leading to low demand and Emission Reduction Unit prices and leaving little potential for use in negative emissions in the future (UNFCCC, 2016). Furthermore, recognising BECCS under JI and the EU ETS might lead to conflicting remuneration.

Due to low and volatile EUA prices, a mere recognition of negative emissions from BECCS within the EU ETS will likely not accelerate the uptake of this technology. It can be assumed that the introduction of the MSR in 2019 will not lead to sufficiently high EUA prices for BECCS viability until at least 2030 (Bassi et al., 2015). Hence, a more logical approach would be to encourage Member States to include BECCS into domestic feed-in-tariff schemes or to set up a separate EU carbon dioxide removal fund. Although the feed-in-tariff mechanism is the most compatible with existing remuneration frameworks in the EU, further research is necessary to determine whether remuneration should be based on the negative emissions or electricity generated, or a combination of both. Irrespective of what the incentive will be, the EU ETS cap should be adjusted accordingly to avoid a weakened price signal due to a reduced demand for EUAs.

Consequently, the second alternative to stimulating negative emissions from BECCS is by incentivising electricity from BECCS by including it into domestic feed-in-tariff schemes. Chapter 0 argued that €62—157/MWh of financial support was required on average for the dedicated BECCS options to generate sufficient returns on investment with the current average wholesale market price in the EU. This level of support given by Member States is not unusual throughout the EU, e.g. the UK government provided offshore wind installations with a strike price of around €190/MWh in the period 2014/15, although this has recently been reduced (DECC, 2013b).

Another, more politically ambitious alternative, would be to establish a remuneration mechanism by which carbon dioxide removal is rewarded in general. These negative emission 'premiums' could be financed from an EU fund such as the NER 400 Innovation Fund scheduled to commence at the beginning of Phase IV of the EU ETS. Ideas on the design of this fund are currently being collected, so a minor timeframe is available to argue for the inclusion of negative emissions funding.

Absence of common sustainability standards for biomass for electricity

In the Renewable Energy Directive, a sustainability scheme is included for biofuels for transport and bioliquids for other sectors (EC, 2009b). Article 17(9) of that Directive provides that the Commission should report on requirements for a sustainability scheme for energy uses of biomass other than biofuels and bioliquids, such as biomass for electricity production. This report has set non-binding standards for Member States that are meant to apply to energy installations of at least 1 MW_{th} and do not require implementation into domestic policy. For biomass from the EU, existing frameworks already largely ensure feedstock sustainability, through the Common Agricultural Policy and national forestry laws, guided by among others the EU Forestry Strategy. Main biomass importing countries such as the UK, Italy, Belgium and the Netherlands have also set up feedstock certification schemes, but these are not always compatible with each other. Furthermore, other voluntary initiatives exist such as ENplus and SBP, but these are not mandatory schemes. This issue should be addressed by a common European framework that ensures biomass sustainability for all biomass that is used for electricity generation (EC, 2010).

Such a common European framework could be included in the Renewable Energy Directive, as this is currently already in place for biofuels and other bioliquids. Currently, the EC is preparing proposals for new biomass criteria up to 2030 (Ends Europe, 2016). These should take into account the implications of potential BECCS scale-up on the biomass supply to the EU in the following decade.

Ambiguity within legal and financial CCS legislation

CCS project developers still face a number of legal and regulatory issues after the CCS Directive and its transposition in domestic law. These issues are mainly related to incomplete or unclear policy formulation, which leaves project developers with a reasonable amount of uncertainty and risk (Global CCS Institute, 2013). Leakage liability is an example of one of such risks. The transfer of responsibility after a project has ended—a minimum of 20 years—is considered too long and arbitrarily determined by key CCS actors (IEA, 2013). Also, the implications of a minor leakage, even if properly managed, is considered disproportionally large, leading to a postponement of liability transfer of 10 years. These issues are some of the main reasons why few of the companies with CCS expertise have indicated a willingness to engage in CCS projects, as this would currently carry too much risk (IEA, 2013). Also, the validation process for storage permits often hampers project development. Some CCS projects have failed due to such regulatory issues surrounding the licensing and permitting of carbon storage. Furthermore, CCS actors stress that insufficient insurance products are available to hedge against project risk.

In order to address the issues that exist with respect to absent or incomplete legal and regulatory frameworks for CCS, ambiguity within the CCS Directive needs to be considerably reduced. This could be partly achieved by adjusting the fixed liability term post-closure by basing this on performance based criteria or putting a cap on the maximum liability term (EC, 2015a). Also, clear financial mechanisms should be established to deal with potential damages resulting from the CCS operation, e.g. through a dedicated liability fund or specific CCS insurance products (Batti et al., 2015). Finally, the validation of storage permits could be accelerated, which is currently a time-consuming process. These measures will likely reduce risk for CCS operators.

Volatile prices for biomass feedstock

Various Member States utilise domestic policies to guarantee a stable feedstock price for biomass energy installations, often with the objective to ensure a stable electricity price and continuous demand. Finland, for example, provides a subsidy per MWh electricity generated with biomass based on the carbon price that applies at that moment in time. At high carbon prices no subsidy is given, whereas under a low carbon price higher subsidies are given. These subsidies are effective in increasing the feedstock supply and can thus function as a tool in managing the feedstock price (IEA, 2013; ZEP, 2013). Furthermore, the international trade in biomass is not well-established in a market, which means that biomass is not a recognised commodity and biomass energy operators often need to arrange individual contracts with biomass suppliers to satisfy their demand. This has led to volatile prices and leaves potential for a stronger growth towards the establishment of an international biomass market.

The European Commission and Member States can ensure a stable biomass feedstock supply and electricity prices through a number of actions:

1. Developing guidelines for biomass supply policy for Member States to incorporate.
2. Stimulating the development towards a mature biomass market to establish price stability and biomass availability.

The former action relates to enabling a stronger increase in biomass supply to the EU to be able to keep in pace with the required growth of BECCS electricity. It is expected that the suggested incentivising strategy of the EU for BECCS and the 20% renewable energy mandate will drive up demand for biomass feedstock, but it is unclear if supply can keep up while maintaining a stable biomass prices. Supply side policies are often direct subsidies to stimulate harvest and enhance profitability and multiple Member States do not yet enforce such policies and could be encouraged by the EU (METLA, 2013). Furthermore, for the sake of price stability and availability the biomass sector would profit from a more mature global market. Transaction costs go down as biomass markets mature and feedstock prices are expected to stabilise due to intervention of an intermediary (Röser et al., 2008). It is expected that the implementation of common sustainability standards will encourage market maturity, however additional action is needed, such as improving the supply infrastructure (e.g. processing capacity) and reducing risks for suppliers in long-term contracts (DECC, 2012).

Uncertainty around upfront funding for large-scale demonstration

Eligibility for the NER300 is determined on the basis of a number of criteria, e.g. the plant nameplate capacity should be at least 250 MW or should store at least 500 kt yr^{-1} CO_2. A minimum capture rate of 85% is maintained. Additionally, the European Investment Bank (EIB) and the Member States individually have to determine whether the value and the structure of public funding is appropriate before an award decision was made by the EC. Initially the fund was expected to deliver 8 CCS projects from the 300 million allowances that were reserved. However, the collapse of the EUA price after the economic crisis of 2008—2009 meant that only 3 CCS projects could now be co-funded. Later on, RES projects were also included in the fund and eventually several Member States could not confirm the pending CCS projects, leading to no funding being awarded to CCS projects. The available funds, now €275 million, would be reserved for a second call (Lupion & Herzog, 2013). The second award round managed to yield one CCS project, White Rose in the UK (EC, 2014a). However, the UK government withdrew its GBP 1 billion subsidy from the UK CCS competition near the end of 2015, which left a huge funding gap leading to the termination of the project.

The main parameter for selection was cost-per-unit performance, which is the public funding and the NPV divided by the amount of CO_2 stored. This naturally favours large scale coal projects due to the CO_2 intensity of coal power.

Other reasons for project failure included governments not willing to co-fund to close funding gaps as a result of austerity measures and choosing for projects with higher chances of success (RES).

Other than the NER300, the EEPR has only been slightly more successful in securing CCS projects, although on a demonstration scale. The EEPR is a separate fund and is part of the EU and EIB budget, as opposed to the NER300. Eventually, six CCS projects got awarded funding. However, in the end of 2013, due to domestic permitting and funding issues, three projects were terminated (EC, 2013). The other three projects are currently not in operation, of which two will not proceed under the proposed conditions.

Obviously, the NER300 has not been capable of securing a large-scale commercial (BE)CCS project. The NER400 Innovation Fund that will commence in 2021 with the start of phase IV of the EU ETS will likely face similar challenges—an uncertain budget and an insufficient focus on (BE)CCS (Butti et al., 2015). Several options exist to address these challenges within the Innovation Fund.

1. Adjusting eligibility criteria for participation in favour of (BE)CCS to increase the number of participants and the chances of coming to an Award Decision.
2. Reducing competition with cheaper low-carbon technologies to ensure a more equal level playing field.
3. Ensuring a minimum available budget within the fund to decrease volatility risk for participants.

Besides the Innovation Fund, the Commission should also consider using the European Structural and Investment Funds (ESIFs) to support investment in less developed regions that would most benefit from CCS (for example, those that rely more heavily on domestic supplies of fossil fuels) or to accelerate the transition to a low-carbon economy in general. Because the fund has a much wider scope than just CCS, the suitability of this fund for such a purpose is currently unclear and should be specified.

Lack of awareness at the political level

Multiple studies have shown that the level of awareness on BECCS is low among political stakeholders and that it is lacking a 'community of support', awareness and credibility (Vergragt et al, 2011; Dowd et al., 2015). Currently, the establishment of awareness is not centrally coordinated, yet workshops are hosted by independently by energy departments—e.g. UK DECC, US DOE—and other organisations and scientific institutes such as the IIASA, IEAGHG, ZEP, IEA, Grantham Institute, Tyndall Institute and UKCCS.

A more centrally coordinated knowledge diffusion on BECCS could be realised under the EU SET-Plan in the form of a European Industrial Initiative (EII), which are technology platforms that bring together countries, industry and researchers in certain key areas. They aim to increase the market uptake of key energy technologies through pooling, funding, skills and research facilities (EC, n.d.). Such an EII specifically for CDR technologies could disseminate information towards the private sector and policy community who currently seem to be unfamiliar with the urgency of and the opportunities in the field of CDR.

5.3.3 Implementation timeline

In order to deploy a sufficient amount of CDR methods to comply with a 2 °C-consistent carbon budget in the year 2100 at assumed optimal cost, the actions that are formulated in the previous section should all be implemented at least before the dedicated BECCS technologies will be required from 2030 onwards (Figure 6). Considering the low levels of required deployment in the period 2020—2025, this can be used as a demonstration/voluntary phase.

The required policy actions can be formulated concisely into six actions that should ideally be implemented within the following timeframes:

1) *Developing a strategy to recognise and incentivise negative emissions.* Start by including BECCS electricity into domestic feed-in-tariff schemes. Ideally, the first provisions are ready in some Member States before the start of the post-demonstration phase (2025—2026), when considerable amounts of capacity should be added for the first time. To grant project developers a sufficient amount of time for planning and construction, these plans should be communicated before 2020.
2) *Clarifying regulatory and financial CCS legislation.* This mainly concerns revising the CCS Directive and establishing financial provisions, should operational damages occur. As this is also of considerable importance to developments in fossil CCS, this should be followed up immediately as the first BECCS deployment will likely rely on co-firing in fossil CCS plants.
3) *Establishing common sustainability standards for solid biomass.* This refers to the inclusion of a common mandatory sustainability framework for biomass used for electricity under the RED. New biomass capacity will grow significantly from 2026—2027 in the roadmap, which implies that sustainability standards should be in place at least before this period to avoid that demand will be satisfied with cheaper and unsustainable biomass. This framework could also be used to correctly remunerate negative emissions from BECCS.
4) *Establishing a more pronounced and prominent role for BECCS within existing funding mechanisms for large-scale demonstration.* Primarily with respect to the NER400 Innovation Fund. Although amendments to the funding mechanism are possible in a later stage, ideally these should be in the fund when it is set to kick off in 2021. The fund is now in its revision phase, which implies that immediate action is required. Furthermore, the potential for (BE)CCS within other funds such as the ESIFs should be clarified.
5) *Encouraging the use of supply side policies in Member States*. Primarily focused on improving the feedstock supply chain infrastructure, reducing supplier risk in long-term contracts and providing direct subsidies to enhance supplier profit. These efforts will have to scale up as soon as the demand for new feedstock increases, which sees increments of 1 GW yr^{-1} additional capacity for the first time starting in 2025. Supply side barriers should thus be addressed in the 2020—2025 period.
6) *Establishing an organisation that is focused on knowledge diffusion surrounding negative emissions.* Such an organisation could take the form of a European knowledge and innovation platform. As knowledge diffusion and awareness on BECCS are detrimental to the required political support to make bold decisions, in chronological order this should be one of the first actions to take to mitigate the existing barriers to solid biomass BECCS deployment.

It should be stressed that these actions specifically address barriers that BECCS deployment in the EU is currently facing. Implementation of these actions does not guarantee that the required deployment target will be achieved and thus progress should be monitored constantly to be able to adjust political efforts when necessary.

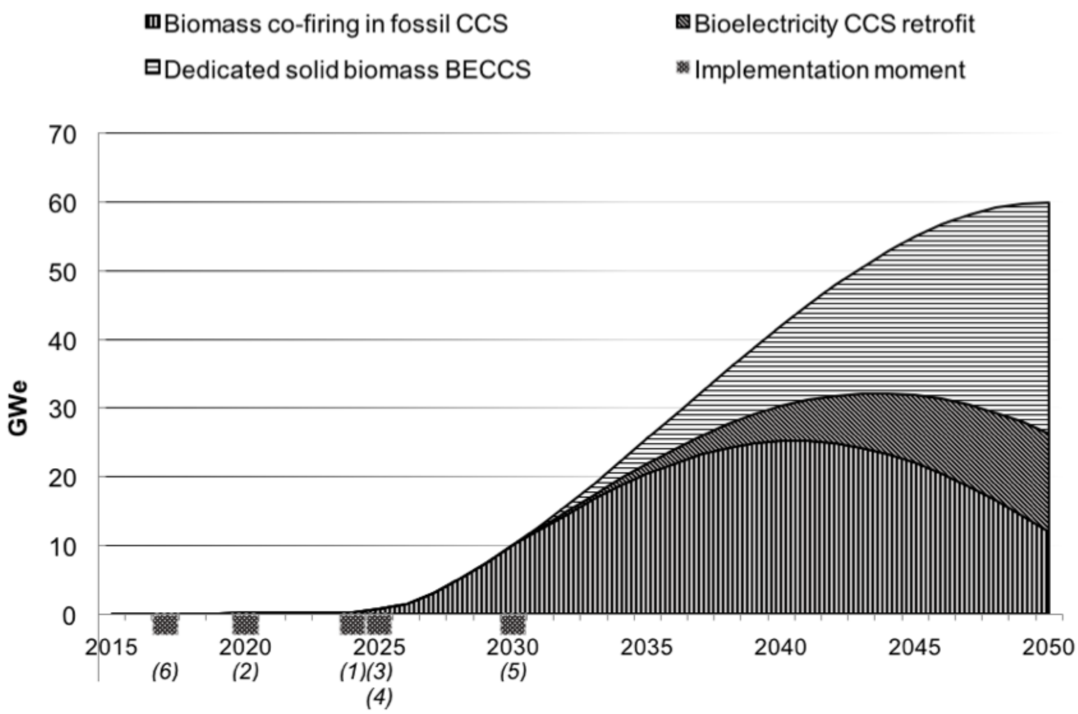

Figure 6: Roadmap depicting the required BECCS deployment path based on 2°C-consistent integrated assessment models output. In addition, the required policy implementation moments to mitigate existing deployment barriers are depicted, referring to (1) Developing a strategy to recognise and incentivise negative emissions; (2) Clarifying regulatory and financial CCS legislation; (3) Establishing common sustainability standards for solid biomass; (4) Establishing a more pronounced and prominent role for BECCS within existing funding mechanisms for large-scale demonstration; (5) Encouraging the use of supply side policies in Member States and (6) Establishing an organisation that is focused on the knowledge diffusion surrounding negative emissions.

5.3.4 Political ambition

The required actions that have been deducted from the policy analysis each differ in political ambition. While some policies are part of the EU's business-as-usual strategy, others will require bold decisions in the field of climate and energy policy in the short term.

Including new renewable energy technologies within existing feed-in-tariff schemes is not unusual. A feed-in-tariff review in the UK recently proposed the inclusion of technologies such as wave and tidal stream power. However, doubts existed as to if the most innovative types of technologies should be included in the existing schemes or in a separate funding mechanism (DECC, 2015). The other option proposed in Section 5.3.2, establishing a carbon dioxide removal fund, is currently unprecedented and would require significant political efforts. However, such a fund would only be needed during a period of insufficient carbon price incentive and will likely not need to have a capacity of covering and administering multiple gigatonnes of removed and stored carbon.

Other non-BAU recommendations include the establishment of a more pronounced and prominent role for BECCS within existing funding mechanisms for large-scale demonstration. The inclusion of criteria for BECCS within the Innovation Fund has not been confirmed yet, although the design phase is far from completed (NER400, 2016).

However, some thoughts have been expressed by stakeholders in EU's consultation on the revision of the EU ETS Directive, namely that it might be worth favouring BECCS in the NER400 (EC, 2015a). Nevertheless, a place for BECCS in the Innovation Fund will require initiative from the European Commission.

Other policy actions that were proposed are more common and fit within the existing patterns of policy actions. For example, (2) clarifying regulatory and financial CCS legislation or (3) establishing common sustainability standards for solid biomass.

5.4 Discussion

The policy recommendations that are made merely state the possibilities that are out there, whereas it is uncertain to which extent the identified barriers will be mitigated by introducing one of the suggested measures. Therefore further in-depth study is required, as well as policy iterations to accumulate best practices in incentivising BECCS deployment.

Furthermore, the case study that was conducted made conclusions on the basis of an assessments of three countries. However, it could be that besides these countries the presence of certain barriers is relatively homogenous in other Member States. Further studies are therefore needed to assess the BECCS potential per EU Member State while taking into account the barriers that are in place in that particular country.

However, if at some point in the future BECCS has still not been demonstrated, substantial investments in BECCS will likely not be as cost-efficient as it would be now. Therefore, it could be debated if BECCS would then be a logical choice to generate the level of negative emissions that are needed to limit warming to 2 °C. Its potential contribution to achieving this will then have seriously reduced due to long technological development and lead times. It is urgent that scientists determine this moment to make a meaningful prioritisation of CDR methods. On the other hand, one could argue that the final goal should not be the year 2050 or 2100, and that BECCS could still have a meaningful contribution to climate policy afterwards.

The measures proposed in this section should also take away some of the main concerns scientists have with BECCS, among which are environmental impacts in terms of water and nutrient use, accounting and the effect of BECCS deployment on global biomass prices.

5.5 Conclusion

This chapter has set out the required policy actions with respect to the existing barriers to BECCS deployment from the private sector. It has provided a deeper understanding as to how current policies do or do not address the identified barriers. Furthermore, it has stressed which aspects of these policies should be adjusted or which types of new policy could be introduced to mitigate these barriers. Furthermore, these policy actions were put into the context of the deployment roadmap that was designed in Chapter 2 to identify when the policies should and could take effect to enable BECCS scale-up.

It was concluded that the EU ETS will likely not play a decisive role in the upscale of BECCS in the EU and that an additional policy instrument will be necessary. The most compatible and short-term option within the currently policy system is including BECCS into existing domestic feed-in-tariff schemes. Another—more politically ambitious, yet likely effective—option would be establishing a carbon dioxide removal fund to reward negative emissions from, among others, BECCS. Legal and regulatory barriers can be mitigated by reducing ambiguity within the CCS Directive and including mandatory sustainability standards for solid biomass under the Renewable Energy Directive. The chance of funding BECCS projects can be increased by designing the new Innovation Fund differently compared to the NER300, such as decreasing price volatility risk for participants and reducing the competition with other low-carbon technologies, which currently disfavours (BE)CCS. Biomass feedstock supply and stable electricity prices should be ensured by maturing the global feedstock market. This could be stimulated by introducing domestic supply policy, which could focus on reducing supplier risk in long-term supply contracts and improving the supply-chain infrastructure. Awareness among political stakeholders in the EU could be increased through the establishment of a European technology and innovation platform that is focused on knowledge diffusion surrounding negative emissions.

Most of the required policy actions should be implemented before 2025 to enable BECCS scale-up, which implies that the European Commission and Member States should act now and set out their policy ambitions with respect to BECCS to allow the private sector to respond before 2025. Especially the remuneration of negative emissions and the establishment of a more central role for BECCS in demonstration funds will prove to be politically ambitious, and will require a sound message from the scientific community and project developers.

Conclusions

To be able to achieve their 2 °C climate goals, the European Union will need to develop a considerable amount of carbon dioxide removal (CDR) technologies, where BECCS could well play a dominant role due to its upscaling potential and relative technology maturity. However, although the concept of BECCS has been discussed in scientific literature for about a decade, very few successful efforts have been made to generate negative emissions with BECCS. Failing to do so in the first half of this century will severely reduce the chance of achieving global climate targets. This implies that considerable challenges lie ahead, with very little time to address them to make any meaningful contribution to achieving the goals that were committed to in the Paris Agreement.

The main question this thesis has aimed to answer is: *"How does BECCS need to develop under a 2 °C consistent emission pathway in the European Union and which political efforts can be taken to achieve this?"* We can conclude that to be able to limit global warming to 2 °C by the end of the century, the EU will need to deploy 56—64 GW_e of solid biomass BECCS capacity. Upscaling can fundamentally be realised by either (i) increasing the level of co-firing in fossil CCS plants, (ii) retrofitting existing bioelectricity plants or (iii) constructing dedicated BECCS plants. These three methods vary in technological readiness and even more so in costs. Besides these challenges, BECCS knows a considerable number of other complex barriers the EU private sector is currently facing and therefore require ambitious political support before BECCS deployment can become a reality.

One of the quantifiable challenges includes attracting sufficient returns on investment due to the high levelised cost of electricity (LCOE) and the limited revenues from the wholesale electricity prices. Hence, some of the BECCS methods require levels of financial support that are in the upper ranges of support currently given to bioenergy technologies, amounting up to €172/MWh in one of the higher estimates. However, carbon prices can significantly reduce the levels of support required, with a carbon price of €83/tCO_2 being sufficient to have a similar LCOE to regular electricity from solid biomass.

Expert interviews and the literature analysis yielded barriers of varying natures, although the most prominent barriers where those of a political or regulatory nature. One of these barriers is the absence of recognition and remuneration for negative emissions, which has so far led to an insufficient incentive for key actors to engage in BECCS. Interestingly, the barrier analysis also conducted a case study, which concluded that the presence of these barriers in different Member States can vary considerably and that generic EU wide policy will therefore not be effective. To mitigate some of the barriers, the development of country-specific policy should be considered.

Specific political efforts that can be made were also discussed in this thesis. Indeed, most of the identified barriers can be addressed through existing EU policy, such as the Renewable Energy Directive and the Emissions Trading Scheme Directive. However, for some barriers, existing policy will not be sufficient to alleviate them. It was found that the EU ETS, even when amended, would still not be capable of sufficiently incentivising negative emissions from BECCS and that therefore additional funding is essential. Here, too, the window of time to introduce amendments and new policy is tightening, because to deploy BECCS efficiently from a mitigation cost perspective, fast upscaling should start in 2025. Hence, there should be a short-term focus on raising awareness on BECCS and negative emissions, while simultaneously starting discussions on how to address the barriers that BECCS is facing and taking into account the policy recommendations that have been brought forward in this thesis. Failing to take on an early leading role in this debate will severely reduce the chance of realising the goals that have been committed to in the Paris Agreement, with undesirable known and unknown consequences.

Discussion

One of the primary aims of this thesis was to largely eliminate the gap in literature on policy frameworks to address issues surrounding BECCS deployment. This served the purpose of supporting decision-makers within the European Commission and Member States to facilitate the uptake of BECCS by the private sector in the EU. This thesis has succeeded in coming to a tangible list of policy actions that can be taken in the short term to ensure this. However, the reader should consider the following notions while interpreting these results.

Implementing the policy recommendations that have been formulated do not ensure that the barriers will be mitigated. These recommendations have been made based on available literature, economic analysis and expert interviews, but the effects are *likely* to lead to a reduction of identified obstacles. Hence, the link between the model interpretations and the policy recommendations does not imply a causality, as the policy recommendations do not lead to 10 or 20 GW more BECCS, for example. These interviewing and literature analysis have predominantly determined the barriers that were identified in this study. It can be assumed that analysing literature and interviewing experts yielded the most *well-known* prevalent barriers. Less well-know—but equally prevalent—barriers could be underrepresented and could have therefore gotten less attention in this thesis. The assumption was made that if certain barriers came up frequently in literature and interviews, it was likely to be a prevalent barrier, while this is not necessarily the case. In addition, it could well be that more research on BECCS will reveal additional barriers, which will require repeating or modifying a study like this.

With this in mind, the following suggestions for further research could catalyse the impact of this study and deepen the understanding of barriers to BECCS deployment. It would be valuable to identify the presence of the barriers in all Member States to single out countries that have a high potential to develop BECCS demonstration projects. Furthermore, interesting results could come about from a study on the cost reduction potential of BECCS when ‘piggybacking’ on a neighbouring CCS facility by using its network. However, as BECCS—mainly due to its land-use and other biophysical—will not be the silver bullet technology, other CDR technologies require increased scientific attention as well. It is likely that a diverse portfolio of CDR methods is needed to achieve the levels of negative emissions seen in the 2 °C emission pathways. Therefore, it is recommended that this study be repeated for other CDR options too.

In conclusion, this research has been a unique and relevant addition to existing BECCS literature by providing a multidisciplinary approach in combining methods of economics, modelling, and policy analysis to come to concrete short-term policy recommendations.

Annex

Annex A: Cost assumptions PC-CCS with 30% direct co-firing

PC-CCS with 30% biomass direct co-firing

Cost categories	Unit	Minimum	Median	Maximum
Fixed costs	(€/kWh)	***€0.0370***	***€0.0473***	***€0.0591***
Capacity factor	(%)	85%	80%	75%
Fixed charge rate	(%)	12.1%	14.6%	17.2%
Operational life	(years)	40	35	30
Capital investment	(million €)	1,506	1,076	646
Fixed O&M	(million €)	65	47	28
Plant capacity	(kWe)	700,000	500,000	300,000
Plant efficiency	(%)	35%	34%	33%
Annual fixed cost payment	(million €)	193	166	117
Variable costs	(€/kWh)	***0.0592***	***0.0719***	***0.0940***
Fuel cost	(€/MWh primary)	18	19	21
Variable O&M	(€/kWh)	0.0056	0.0056	0.0056
Yearly production	(GWh)	5,212	3,504	1,971
CO_2 transport	(€/tCO2)	3	5	10
CO_2 storage	(€/tCO2)	1	5	13
Total captured CO_2 annually	(kton)	3,956	3,059	2,010
CO_2 transport	(€/kWh)	0.0023	0.0044	0.0102
CO_2 storage	(€/kWh)	0.0008	0.0044	0.0133
Fuel cost	(€/kWh)	0.0506	0.0576	0.0650
LCOE	(€/kWh)	***0.0961***	***0.1191***	***0.1532***
Required competitiveness support	(€/kWh)	***0.0118***	***0.0163***	***0.0245***
Can be offset by a carbon price of	(€/tonne)	***16***	***20***	***32***
Diff. with avg. EU electricity price (0.0731)	(€/kWh)	***0.0230***	***0.0460***	***0.0801***

Other variables used

Capital costs	**Unit**	**Minimum**	**Median**	**Maximum**
Pulverised coal plant	(€/kW)	1325	1325	1325
Direct co-firing up to 30%	(€/kW)	152	152	152
Carbon capture	(€/kW)	675	675	675
O&M				
Pulverised coal plant	(€/kW)	40	40	40
Co-firing	(€/kW)	13	13	13
Carbon capture	(€/kW)	40	40	40
Other				
Capture rate	%	90	90	90

Annex B: Cost assumptions PC-CCS with 50% parallel co-firing

PC-CCS with 50% biomass co-firing in a parallel CFB boiler				
Cost categories	**Unit**	**Minimum**	**Median**	**Maximum**
Fixed costs	(€/kWh)	***€0.0579***	***€0.0825***	***€0.1137***
Capacity factor	(%)	85%	80%	75%
Fixed charge rate	(%)	12.1%	14.6%	17.2%
Operational life	(years)	40	35	30
Capital investment	(million €)	2,397	1,912	1,268
Fixed O&M	(million €)	65	47	28
Plant capacity	(kWe)	700,000	500,000	300,000
Plant efficiency	(%)	33%	32%	31%
Annual fixed cost payment	(million €)	302	289	224
Variable costs	(€/kWh)	***0.0675***	***0.0830***	***0.1097***
Fuel cost	(€/MWh primary)	19	22	24
Variable O&M	(€/kWh)	0.0056	0.0056	0.0056
Yearly production	(GWh)	5,212	3,504	1,971
CO_2 transport	(€/tCO_2)	3	5	10
CO_2 storage	(€/tCO_2)	1	5	13
Total captured CO_2 annually	(kton)	4,220	3,391	2,294
CO_2 transport	(€/kWh)	0.0024	0.0048	0.0116
CO_2 storage	(€/kWh)	0.0008	0.0048	0.0151
Fuel cost	(€/kWh)	0.0588	0.0678	0.0774
LCOE	(€/kWh)	***0.1254***	***0.1655***	***0.2235***
Required competitiveness support	(€/kWh)	***0.0338***	***0.0622***	***0.1019***
Can be offset by a carbon price of	(€/tonne)	***42***	***77***	***125***
Diff. with avg. EU electricity price (0.0731)	(€/kWh)	***0.0523***	***0.0924***	***0.1504***

Other variables used				
Capital costs	**Unit**	**Minimum**	**Median**	**Maximum**
Pulverised coal plant	(€/kW)	1325	1325	1325
Parallel co-firing up to 50%	(€/kW)	1424	1825	2225
Carbon capture	(€/kW)	675	675	675
O&M				
Pulverised coal plant	(€/kW)	40	40	40
Co-firing	(€/kW)	13	13	13
Carbon capture	(€/kW)	40	40	40
Other				
Capture rate	%	90	90	90

Annex C: Cost assumptions CFB-CCS retrofit

Biomass CFB boiler with CCS retrofit

Cost categories	**Unit**	**Minimum**	**Median**	**Maximum**
Fixed costs	(€/kWh)	***€0.0398***	***€0.0600***	***€0.0885***
Capacity factor	(%)	85%	80%	75%
Fixed charge rate	(%)	9.7%	11.9%	14.2%
Operational life	(years)	30	25	20
Capital investment	(million €)	814	637	365
Fixed O&M	(million €)	44	29	15
Plant capacity	(kWe)	300,000	200,000	100,000
Plant efficiency	(%)	29%	28%	26%
Annual fixed cost payment	(million €)	89	84	58
Variable costs	(€/kWh)	***0.0921***	***0.1166***	***0.1569***
Fuel cost	(€/MWh primary)	23	27	30
Variable O&M	(€/kWh)	0.0075	0.0075	0.0075
Yearly production	(GWh)	2,234	1,402	657
CO_2 transport	(€/tCO_2)	3	5	10
CO_2 storage	(€/tCO_2)	1	5	13
Total captured CO_2 annually	(kton)	2,121	1,651	958
CO_2 transport	(€/kWh)	0.0028	0.0059	0.0146
CO_2 storage	(€/kWh)	0.0009	0.0059	0.0190
Fuel cost	(€/kWh)	0.0808	0.0974	0.1159
LCOE	(€/kWh)	***0.1319***	***0.1767***	***0.2454***
Required competitiveness support	(€/kWh)	***0.0456***	***0.0675***	***0.1061***
Can be offset by a carbon price of	(€/tonne)	***48***	***57***	***73***
Diff. with avg. EU electricity price (0.0731)	(€/kWh)	***0.0588***	***0.1036***	***0.1723***

Other variables used

Capital costs	**Unit**	**Minimum**	**Median**	**Maximum**
CFB boiler	(€/kW)	1316	1786	2256
Carbon capture	(€/kW)	1397	1397	1397
O&M				
CFB boiler	(€/kW)	61	61	61
Carbon capture	(€/kW)	84	84	84
Other				
Capture rate	%	90	90	90

Annex D: Cost assumptions CFB-CCS dedicated

Biomass CFB boiler with post-combustion CCS

Cost categories	Unit	Minimum	Median	Maximum
Fixed costs	(€/kWh)	***€0.0398***	***€0.0600***	***€0.0885***
Capacity factor	(%)	85%	80%	75%
Fixed charge rate	(%)	9.7%	11.9%	14.2%
Operational life	(years)	30	25	20
Capital investment	(million €)	814	637	365
Fixed O&M	(million €)	43	29	15
Plant capacity	(kWe)	300,000	200,000	100,000
Plant efficiency	(%)	31%	30%	28%
Annual fixed cost payment	(million €)	89	84	58
Variable costs	(€/kWh)	***0.0866***	***0.1092***	***0.1462***
Fuel cost	(€/MWh primary)	23	27	30
Variable O&M	(€/kWh)	0.0075	0.0075	0.0075
Yearly production	(GWh)	2,234	1,402	657
CO_2 transport	(€/tCO_2)	3	5	10
CO_2 storage	(€/tCO_2)	1	5	13
Total captured CO_2 annually	(kton)	1,984	1,539	889
CO_2 transport	(€/kWh)	0.0027	0.0055	0.0135
CO_2 storage	(€/kWh)	0.0009	0.0055	0.0176
Fuel cost	(€/kWh)	0.0756	0.0908	0.1076
LCOE	(€/kWh)	***0.1264***	***0.1693***	***0.2347***
Required competitiveness subsidy	(€/kWh)	***0.0488***	***0.0733***	***0.1160***
Can be offset by a carbon price of	(€/tonne)	***55***	***83***	***131***
Diff. with avg. EU electricity price (0.0731)	(€/kWh)	***0.0533***	***0.0962***	***0.1616***

Other variables used

Capital costs	**Unit**	**Minimum**	**Median**	**Maximum**
CFB boiler	(€/kW)	1316	1786	2256
Carbon capture	(€/kW)	1397	1397	1397
O&M				
CFB boiler	(€/kW)	61	61	61
Carbon capture	(€/kW)	81	81	81
Other				
Capture rate	%	90	90	90

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