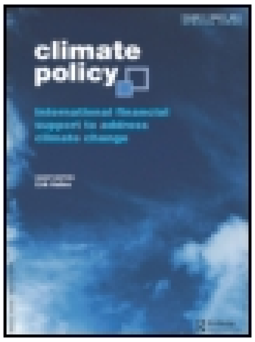

Climate Policy

ISSN: 1469-3062 (Print) 1752-7457 (Online) Journal homepage: http://www.tandfonline.com/loi/tcpo20

Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement

Asbjørn Torvanger

To cite this article: Asbjørn Torvanger (2018): Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement, Climate Policy, DOI: 10.1080/14693062.2018.1509044

To link to this article: https://doi.org/10.1080/14693062.2018.1509044

CLIMATE POLICY
https://doi.org/10.1080/14693062.2018.1509044

Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement

Asbjørn Torvanger

CICERO Center for International Climate Research, Oslo, Norway

ABSTRACT
Studies show that the ‘well below 2°C’ target from the Paris Agreement will be hard to meet without large negative emissions from mid-century onwards, which means removing CO_2 from the atmosphere and storing the carbon dioxide in biomass, soil, suitable geological formations, deep ocean sediments, or chemically bound to certain minerals. Biomass energy combined with Carbon Capture and Storage (BECCS) is the negative emission technology (NET) given most attention in a number of integrated assessment model studies and in the latest IPCC reports. However, less attention has been given to governance aspects of NETs. This study aims to identify pragmatic ways forward for BECCS, through synthesizing the literature relevant to accounting and rewarding BECCS, and its relation to the Paris Agreement. BECCS is divided into its two elements: biomass and CCS. Calculating net negative emissions requires accounting for sustainability and resource use related to biomass energy production, processing and use, and interactions with the global carbon cycle. Accounting for the CCS element of BECCS foremost relates to the carbon dioxide capture rate and safe underground storage. Rewarding BECCS as a NET depends on the efficiency of biomass production, transport and processing for energy use, global carbon cycle feedbacks, and safe storage of carbon dioxide, which together determine net carbon dioxide removal from the atmosphere. Sustainable biomass production is essential, especially with regard to trade-offs with competing land use. Negative emissions have an added value compared to avoided emissions, which should be reflected in the price of negative emission ‘credits’, but must be discounted due to global carbon cycle feedbacks. BECCS development will depend on linkages to carbon trading mechanisms and biomass trading.

Key policy insights

- A standardized framework for sustainable biomass should be adopted.
- Countries should agree on a standardized framework for accounting and rewarding BECCS and other negative emission technologies.
- Early government support is indispensable to enable BECCS development, scale-up and business engagement.
- BECCS projects should be designed to maximize learning across various applications and across other NETs.
- BECCS development should be aligned with modalities of the Paris Agreement and market mechanisms.

ARTICLE HISTORY
Received 25 January 2018
Accepted 30 July 2018

KEYWORDS
Negative emissions; sustainable biomass; carbon capture and storage; emissions accounting; rewarding; Paris agreement

1. Introduction

There is a stunning gap between the large number of studies showing the need for negative emission technologies (NETs) to achieve the Paris Agreement’s goal of limiting warming to ‘well below’ 2°C and preferably 1.5°C, and the status of research, development, and deployment of these technologies. Biomass Energy combined

CONTACT Asbjørn Torvanger asbjorn.torvanger@cicero.oslo.no CICERO Center for International Climate Research, Gaustadalléen 21, Oslo 0349, Norway

with Carbon Capture and Storage (BECCS) is the NET that tends to be given most attention in emission scenarios (IPCC, 2013; Rogelj et al., 2015). In this respect, it is worth noting that the Paris Agreement emphasizes that 'Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases … including forests'. (Article 5.1). It may seem surprising that no Nationally Determined Contributions (NDCs) include a commitment to NETs, and only three NDCs mention Carbon Capture and Storage (CCS) as a priority area, but this can be seen as an indication of political risks associated with NETs, not least related to bioenergy and to CCS (Fuss et al., 2016).

NETs is a family of technologies that are characterized by their potential to remove CO_2 from the atmosphere and store the gas in other sinks with large capacity, such as in forest biomass (afforestation and reforestation), chemical bonding to certain minerals (mineralization), deep ocean sediments (ocean fertilization), increased carbon content of soil (biochar), and suitable geological formations[1] (BECCS and Direct Air Capture (DAC)) (Fuss et al., 2014; Peters & Geden, 2017; UNEP, 2017). These technologies are also referred to as Carbon Dioxide Removal (CDR). Most of the NETs literature examines the need for negative emissions to meet the 1.5 to 2°C target from the Paris Agreement and the overall feasibility of them doing so, or estimates the potential of a technology given bio-physical and economic constraints. Larkin, Kuriakose, Sharmina, and Anderson (2018) argue that more attention should be given to GHG mitigation, and that short-term action is urgent, whereas an optimistic view of contributions from NETs endangers the 2°C target. Studies furthermore discuss whether the prospect of NETs may lead to less efforts to mitigate CO_2 emissions. In this respect, Merk, Pönitzsch, and Rehdanz (2018) find no evidence of CDR or solar radiation experts supporting less GHG mitigation efforts (i.e. 'moral hazard') than climate-change experts. Since all NETs are prone to constraints and uncertainties, it is likely that a mix of these technologies will be needed to have a reasonable chance to meet the climate target from the Paris Agreement.

The concept of BECCS involves using biomass with CO_2 fixated through photosynthesis to produce heat and/or power from combustion, or produce synthetic natural gas or hydrogen from biomass. CO_2 is then captured with the help of CCS technologies, compressed and cooled, and transported with ships or through pipelines, before finally being injected into suitable geological formations for permanent storage (Azar et al., 2010; Kemper, 2015).

At the time of writing, only five BECCS operations existed: three in the USA, one in Canada, and one in the Netherlands (OECD/IEA, 2016). All are fermentation plants producing ethanol from agricultural products, foremost corn. For two of these, dedicated storage of CO_2 in geological formations is ongoing or planned, whereas the other three supply CO_2 for Enhanced Oil Recovery (EOR).[2] This state of BECCS deployment reflects that CO_2 emissions from fermentation are concentrated and less costly to capture, with EOR giving sufficient value to incentivize CCS in some applications. For the last two BECCS operations, additional incentives for geological CO_2 storage are needed. In the absence of much stronger incentives for BECCS through higher carbon prices, or specific rewarding frameworks for negative emissions, BECCS will remain a small niche globally.

A major issue for BECCS is scalability, which relates to the potential scope and importance of this NET to meet the Paris Agreement targets. Scalability on the biomass part of BECCS is in biophysical terms, primarily tied to availability of biomass resources, and avoiding significant negative impacts on other forms of land use. Scalability on the CCS part is mostly in terms of high capture cost, availability of storage sites with low leakage risk, and large investments in infrastructure. Smith et al. (2016) assess biophysical and economic limits to BECCS, DAC, enhanced weathering of minerals, and afforestation and reforestation. They find that using BECCS as the major NET technology to meet the 2°C target would require about 3% of all freshwater currently used by humans, and 25–46% of permanent crop and arable (i.e. temporarily fallow land) area globally, equivalent to 7–25% of agricultural land.[3] Therefore, large-scale BECCS would realistically imply substantial trade-offs with local land use, food crops, freshwater use, environmental values and biodiversity, possibly also in terms of storing carbon in forests (Muratori, Calvin, Wise, Kyle, & Edmonds, 2016; Muri, 2018). Baik et al. (2018) find that the near-term technical deployment potential for BECCS in the US is reduced by around 3/4 due to lack of suitable CO_2 storage capacities, and economic and social barriers on long-distance biomass and CO_2 transport. In addition, there are issues of scalability related to available technologies, high cost and large investments needed, incentives for business to participate, social impacts and public acceptance, legal issues, governance requirements, and overall political feasibility (Geden, Scott, & Palmer, 2018; Honegger & Reiner, 2018; Reynolds, 2018). Scalability constraints may be smaller for biomass produced by marine microalgae (with high productivity) (Greene et al., 2017). The number of challenges for large-scale BECCS, the complexities, and large investments required for research, pilot plants, and full-scale operations, and making BECCS a viable and competitive alternative, speak for long-term and large research and development programmes at the international level.

Further development of BECCS depends on a governance system that can enable the technology in a market context, nationally, and internationally (Fuss et al., 2014). Hufty (2011, p. 405) defines governance as '… processes of interaction and decision-making among the actors involved in a collective problem that lead to the creation, reinforcement, or reproduction of social norms and institutions'. Fuss et al. (2016) mention institutional structures, sustainability risks, legal and liability risks in case of leakage from geologically stored CO_2, accounting rules, policy instruments to incentivize R&D, demonstration and deployment, financial support, public acceptability of these technologies, and local political realities as issues pertaining to governance of NETs.

The lion's part of the literature on BECCS has focused on the technology's technical and physical potential, and often grouped together with other NETs. There is less literature on governance aspects of BECCS, and this literature commonly only mentions challenges, with less emphasis on possible solutions. The seminal 2009 Royal Society report on geoengineering (which includes CDR, as well as solar radiation management) states that: 'The greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than scientific and technical issues'. (Sheperd et al., 2009, p. xi).

This paper focuses on governance aspects of BECCS with the aim to identify pragmatic ways forward for the technology. In this study, the analysis of governance is constrained to three essential aspects, namely: accounting BECCS as a NET – which requires accounting biomass and CO_2 as elements of BECCS; schemes to reward negative emissions and BECCS and thereby incentivize business participation; and an analysis of approaches to link BECCS to the Paris Agreement and market mechanisms. Even if accounting, rewarding and market mechanisms form only a sub-set of governance issues, they are among the most challenging, and are fundamental to moving forward on many other governance aspects. The paper discusses each of these aspects in turn, adding relevant experience from related areas and identifying possible ways forward.

2. Accounting for BECCS as a negative emission technology

Accounting for CO_2 removed through BECCS, and for any resulting CO_2 credits that may be transferred between countries, is essential for confidence in a large-scale BECCS system, not least under the Paris Agreement. Accounting involves Monitoring (of CO_2 streams and transfers), Reporting, and Verification (MRV), to secure transparency and permanency, and avoid double-counting. In this regard, we can build on experience with trading mechanisms under the 1997 Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCC), particularly the Clean Development Mechanism (CDM). Rules for the inclusion of CCS under the CDM were adopted in 2011. Dixon, McCoy, and Havercroft (2015) argue that future mechanisms under the UNFCCC (and now including the Paris Agreement) allowing CCS, should follow the modalities and procedures for CCS in the CDM. In addition, we can build on greenhouse gas emission trading systems, such as the EU's Emissions Trading System. The EU's renewable energy directive framework, containing sustainability criteria for biofuels and bio-liquids, is another useful benchmark (EU, 2009b, 2015).

BECCS, like other NETs, faces an accounting challenge compared to ordinary mitigation of CO_2 emissions. Emissions are not only avoided, but CO_2 removed from the atmosphere. In this regard, we can learn from long-term forest and agriculture management experiences. The 2006 IPCC Guidelines for national greenhouse gas inventories include accounting rules for CO_2 emissions and removals by sinks, e.g. forests and other land use (IPCC, 2006).

There are few co-benefits associated with BECCS compared to standard mitigation of GHG emissions, e.g. through deploying renewable energy or increasing energy efficiency, which reduces air pollution and has health benefits (Honegger & Reiner, 2018). The value of BECCS is tied to net removal of CO_2 from the atmosphere, and thus to accounting methods, like other NETs. Therefore, the framework for accounting of CO_2 removal from BECCS is decisive for estimating the volume of negative emissions generated from a project, and also for rewarding the BECCS project operator(s). The reward should only be given for net removal of

CO_2 from the atmosphere. This necessitates a standardized accounting framework for negative emissions, where the benefits of standardization are balanced by the flexibility needed due to different geographical, sectoral, and technological circumstances. The capacity of BECCS to generate negative CO_2 emissions requires that biomass-based power generates less CO_2 than fossil-based power due to re-growth of forest, but not necessarily that biomass energy is 'CO_2 neutral' (Zakkour, Cook, & French-Brooks, 2014; Zakkour, Kemper, & Dixon 2014).

2.1. Biomass

Verification of negative emissions from BECCS requires that biomass production is sufficiently sustainable, with one implication being that harvested biomass is replaced by regrowth of trees or other plants over the relevant time period.

OECD/IEA (2017) divide biomass sources into the categories biomass from industrial sources and waste, agriculture and forestry residues, and municipal waste. In terms of agriculture and forestry-based biomass, the country and scale of production will be important for competition with local land use, agricultural production, using wood for building purposes, carbon storage in biomass, and biodiversity and ecological values. Politicians, landowners and local communities should therefore develop strategies that optimize the economic and ecological value of land in the local context, not the least when the biomass exporting communities are situated in developing countries. Large-scale BECCS would likely generate fast growth in global trading of biomass for energy (Heinimö & Junginger, 2009). Production and trading will depend on the market for biomass products, national and local constraints on production and exports, biomass prices compared to other energy prices, and biomass transportation and processing costs. An additional difficulty is due to life-cycle perspectives and related uncertainties, specifically how far supply chains and energy use for investments and operations should be included in the accounting framework, including indirect market and price effects. Fajardy and Mac Dowell (2018) examine net electricity balance of an illustrative BECCS facility in the UK, finding a clear trade-off between carbon removal potential and power generation. The energy efficiency of BECCS power generation can be drastically improved, but at a cost of installing more BECCS capacity to meet the carbon removal target.

Commonly, emissions are reported according to the sector where the activity takes place, for example energy use in transport, but independent of the biomass transported and the later use of the biomass for energy production (IPCC, 2006).[4] A sector-based approach, however, makes accounting of net negative emissions very difficult, so instead a project-based accounting framework should be considered. Under project-based accounting, something resembling a life cycle approach is followed, from growing the biomass, through transportation, up to processing and combustion, and CO_2 capture and storage. Such an approach is closer to accounting of CO_2 emission credits under the CDM, but could be more standardized, thus not necessarily treating each negative emission project in an independent manner, but grouping projects according to common features.

Growing biomass, such as trees, captures CO_2 through photosynthesis, but is the use of this biomass to generate energy CO_2 neutral, or at least contributing to lower emissions than combustion of fossil fuels? Is the biomass production and use sustainable? There is a large academic literature on the subject, showing that the effect of biomass energy on CO_2 emissions depends on the biomass type, geography, land used, processing and transport, life cycle perspectives, inclusion of indirect effects (e.g. land-use changes), speed of re-growth of vegetation, and time horizon (IPCC, 2014; Sterman, Siegel, & Rooney-Varga, 2018).[5] Using the ethanol produced as biofuel in transport means that CO_2 capture becomes infeasible in technical and cost terms, so the CO_2 ends up in the atmosphere.[6] The three Drax power units in the UK that have been converted from coal to burning wood pellets provide an interesting case. Conversion of a fourth unit to biomass is planned. Drax is now the largest wood pellets consumer in the UK at 7.5 Mt per year. CO_2 emissions from the biomass units have been estimated, based on lifecycle analysis (including emissions related to transport, processing, fertilizer use, and 'direct' land use). These calculations comply with UK government rules, but ignore emissions from burning the biomass, assuming that replacement trees are grown (Speed, 2017). The Drax Group plans to develop biomass fuel use with CCS at its North Yorkshire power station (Vaughan, 2018). The compressed CO_2 will be sold and used for industrial processes. This is likely the first BECCS project of its kind in the world. The estimated CO_2 emissions are particularly sensitive to the effect that wood pellet production may have on the growth of North American forests over time.

Dependent on the assumptions used, biomass energy can, in the best case, be CO_2 neutral, whereas in the worst case, CO_2 emissions can be similar to coal-based power production. The other major issue is trade-offs with other forms of land use, such as agricultural production, use by local population, freshwater supply, and biodiversity and ecological values (Smith et al., 2016). Since biomass commonly has low energy capacity per weight and volume (i.e. due to high water content), long-distance transport is energy and emissions intensive, which must be accounted for. The efficiency of processing biomass energy to usable energy varies with crop and process.

Due to dynamic interactions with the bio-geo-carbon cycle, there is a ‘rebound’ effect on removing CO_2 from the atmosphere. Jones et al. (2016) show that interactions with the global carbon cycle imply that using NETs to remove one ton CO_2 from the atmosphere leads to a net effect of less than one ton CO_2. The effect of CO_2 removal will be reduced due to relatively less uptake of CO_2 (‘outgassing’) from carbon sinks such as the ocean, and net CO_2 removal may decrease with total negative emissions because of stronger outgassing (Tokarska & Zickfeld, 2015).[7] According to Jones et al. (2016) only around 60–90% of negative CO_2 emissions will stay out of the atmosphere. As long as humankind continues with large CO_2 emissions that cause perturbations of the global carbon cycle, the net effect of CO_2 removal from the atmosphere will change over time. Given the complexities and insufficient understanding of calculating the net negative effect of CO_2 removal due to interactions with the global carbon cycle, the best way forward is likely to agree on a discounting factor for negative emissions, and then also for BECCS. This implies that less than 100% of one ton of CO_2 removal is approved.

Combustion of biomass for heat and power production oxidizes carbon to CO_2, but combustion is not necessarily complete, meaning that there will be some residual (non-oxidized) carbon, dependent on biomass type and the combustion process. Likewise, synthetic natural gas or hydrogen are produced through various industrial processes, and some carbon may become residual. Any residual carbon should be accounted for, since it will escape CO_2 capture and storage.

Sustainability has ethical connotations, and relates to issues such as competition with crop production, interests of local communities, negative impacts on environment and biodiversity, and implications of large-scale biomass production for future generations (Buck, 2016; Fridahl, 2017). Using questionnaire data from UN Climate change conferences, Fridahl and Lehtveer (2018) find that lack of social acceptance of CCS and unsustainable biofuel production are the major barriers to BECCS deployment, together with lack of enabling policy incentives. OECD/IEA (2017) lists the sustainability indicators introduced by Global Bioenergy Partnership (GBEP) as life-cycle GHG emissions, soil quality, harvest levels of wood resources, emissions of non-GHG air pollutants, water use and efficiency, water quality, biological diversity, and land use and land use change. One fairness issue is sharing benefits of biomass production and BECCS between exporting developing countries and importing industrialized countries (Peters & Geden, 2017).

Encompassing high complexity, substantial variation across crops and geography, disputable boundaries on what indirect factors to include, and many uncertainties, the best way forward would be to establish a standardized framework for calculation of the effect of biomass crops and processing on net CO_2 emissions, with some flexibility for crop, geography, and biomass processing (Haberl et al., 2012; Searchinger, 2010; Searchinger et al., 2009). An international standardized framework would simplify assessment of sustainability. This could build on IPCC guidelines for national inventories of GHGs (IPCC, 2006), the EU’s renewable energy directive (EU, 2009b; EU, 2015), ISO (2006), and ISO (2013) standards.

2.2. CCS

CCS operators must show that capture of CO_2 from combustion or industrial processes with biomass inputs works as intended, and that afterwards the CO_2 is safely transported and injected into approved geological storage sites.

There are around 30 operational or planned full-scale CCS operations in the power sector, linked to industrial CO_2 sources, or linked to reduced CO_2 concentration to make natural gas commercial (Global CCS Institute, 2017; OECD/IEA, 2016). Watson et al. (2012) explores how the potential of CCS could be realized in the power sector of the UK, focusing on key uncertainties of CCS, which are listed as choosing CO_2 capture technologies, safe storage of CO_2, scaling up and speed of development and deployment, integration of CCS systems, economic and financial viability, policy, politics and regulation, and public acceptance.

When combusting biomass for power/heat, the CO_2 released can only be captured when emitted from large plants. Only a small percentage of the exhaust from biomass combustion consists of CO_2 (similar to combustion of natural gas and coal). Capturing this CO_2 is energy demanding and expensive. In practical terms, up to 90% of the CO_2 seems realistic to capture, while avoiding excessive costs (IEA GHG, 2012). In the case of fermentation of corn or sugar cane for ethanol production, or biodiesel produced from rapeseed, or some types of bio-waste, process-related CO_2 emissions can be captured, but the CO_2 produced when using these biofuels in a vehicle will escape.

Against the background of a fast narrowing window for fossil-based CCS, support should be based on CCS applied to industrial sources of CO_2, and focus on reducing CO_2 capture cost, cost-effective infrastructure, and reducing risk elements – in particular the risk for CO_2 leakage from geological sinks (Soltanian & Dai, 2017; Torvanger et al., 2012).

Some are sceptical towards CCS because they think the technology can prolong the fossil era instead of going fully for renewable energy and energy efficiency (Krüger, 2017; Ussiri & Lal, 2017). CCS is by some considered immature, with a high cost compared to the climate change mitigation effect, and facing increasing competition from advances in other technologies to reduce GHG emissions (De Coninck & Benson, 2014).

One of the few ways to incentivize CCS presently is to use CO_2 for EOR. The net effect from EOR on CO_2 emissions is uncertain when accounting for increased oil production, and depends on the additional value of storing extra CO_2 (the carbon price) beyond what is profitable to inject for oil production (Armstrong & Styring, 2015; OECD/IEA, 2015; Stewart & Haszeldine, 2015).[8] Mac Dowell, Fennell, Shah, and Maitland (2017) find that EOR can facilitate the deployment of CO_2 transport infrastructure, but maximizing CO_2 storage implies injecting much more CO_2 than what is profitable from an oil recovery perspective.[9]

We have experience only from a few cases of large-scale geological storage of CO_2. One example is Sleipner on the Continental Shelf of Norway, where around one million tons of CO_2 have been injected annually since 1996, and where storage has worked well. However, even with substantial efforts to identify prospective CO_2 storage sites, there will be a non-zero probability of leakage. Furthermore, transportation of CO_2 through pipelines or with ships involves a small risk of leakage or accidents. This means that rules for efficient and safe transport and storage of CO_2 are needed, including allocation of liability or insurance arrangements, should problems arise. Pawar et al. (2015) note that there has been significant progress in geological CO_2 storage risk assessment and management over the last decade, based on 45 field projects and development of regulation frameworks. Risk is broadly divided into site performance, long-term containment, public perception, and market risk. The EU CCS directive is one example of CO_2 storage regulation, where liability is transferred to the state with jurisdiction over the storage site provided certain conditions are fulfilled (EU, 2009a). This type of liability transfer to the state seems to be the most realistic solution. New rules for BECCS must cover both national and international CCS chains, since CO_2 may be exported, and provide guidelines for MRV of safe CO_2 storage.

2.3. BECCS

The challenges of accounting for negative CO_2 emissions are illustrated when trying to include negative emissions in project-based mechanisms (e.g. the CDM) and various types of emission trading systems. Some schemes and mechanisms are accounting for negative emissions, or could be revised in this direction, whereas others are not. The accounting capability depends on handling of sinks such as forests and land use, and on handling of CCS, in explicit or implicit terms. BECCS is difficult to handle by regional 'cap and trade' emission schemes, because biomass energy is generally included in the scheme's 'baseline' or because biomass entities are excluded.[10] Project based schemes, such as the CDM, are more open to recognizing negative emissions. Generally, negative emissions can either be accounted as 'credits', or as 'net-back', the latter meaning that removed CO_2 can be subtracted from positive emissions from other sources in a broad portfolio of emission sources (IEA, 2011; Zakkour, Cook, et al., 2014; Zakkour, Kemper, et al., 2014).

Table 1. BECCS components and accounting of net negative emissions.

BECCS component	Description	Requirements
Biomass growth	CO_2 capture in biomass through photosynthesis. Account for delayed regrowth.	Standardized framework for sustainable biomass production and harvesting management and accounting. Trade-offs with other area uses.
Biomass transport and processing	Account CO_2 emissions from harvesting, transport, and processing of biomass for energy. Life cycle perspective. Delivery chain effects. Indirect effects (from price changes and other effects).	Standardized accounting of the steps required from producing biomass until preparing for combustion or processing, implying CO_2 emissions. Decide on boundaries for life cycle, delivery chain, and indirect effects accounting.
Interaction with carbon cycle	Global carbon cycle dynamics reduce net CO_2 removal.	Standardized accounting framework.
Biomass combustion; Industrial processes	Production of heat and/or power from biomass, synthetic natural gas or hydrogen.	Standardized accounting of biomass carbon to energy, and CO_2 transformation efficiency.
CCS – CO_2 capture	Efficiency of CO_2 capture from exhaust is less than 100%.	Decide on standardized CO_2 capture efficiency from combustion, possibly dependent on capture technology.
CCS – CO_2 transport and storage	Transportation by pipelines or ships. Safe storage in geological formations.	Identify candidates for geological storage sites. Verify suitability according to regulations. Performance monitoring. Contingency plans in case of CO_2 leakage.
Net CO_2 removal	Sum of negative and positive CO_2 emission components.	The BECCS framework determines net CO_2 removal, which is basis for rewarding.

Accounting for net CO_2 emissions from BECCS deployment can be decomposed into six components (see Table 1). In a sector-based approach, 'Biomass growth' and 'Interaction with the carbon cycle' would be accounted for under land use, whereas the other components would be accounted for under energy.

Net removal of CO_2 when applying BECCS depends on all the six components described in Table 1. The components and complexities addressed clearly illustrate the necessity of adopting a unified accounting framework for BECCS as a negative emission technology at the international level, in order to prepare for further development of this technology. Given that several factors reduce net CO_2 removal when using BECCS, as outlined above, rewarding BECCS will likely involve a sizeable discounting factor.

3. Rewarding BECCS

Currently, there are hardly any incentives for business to engage with BECCS, unless government takes on most of the costs and the economic risk. This is mainly due to weak climate policies that imply a low carbon price, and consequently a low value of CO_2 emission mitigation (Sanchez & Kammen, 2016). In addition, business engagement would be facilitated by an additional price (i.e. value) on negative emissions. Given these circumstances, there is no way around government taking on the main responsibility for establishing business models for BECCS that provide sufficient incentives for companies to engage, otherwise BECCS will certainly end up with 'too little – too late'. More support is needed for research, pilot plants, and first full-scale plants to stimulate learning and reducing costs, and generally to scale-up BECCS over a number of years. The learning potentials across different biomass and CCS applications as well as from BECCS to other NETS are less understood, though. Sanchez, Johnson, McCoy, Turner, and Mach (2018) argue that deployment of CCS at existing ethanol bio-refineries in the US is an important learning step to better understand the potential for large-scale BECCS, which could be supported from financial incentives under the low-carbon fuel standard in California and federal tax credits.

International co-ordination and collaboration are important for BECCS development due to large investments with uncertain payback (Reiner, 2016). Well-organized collaboration among countries, with different capacities and competencies, will enable more comprehensive and efficient research and development programmes for BECCS and other NETs.

Regulating CO_2 emissions with a tax or emissions trading system means that emissions become costly, thus providing emitters with an incentive to reduce emissions. In such a regulatory system, applying CCS to, for example, industrial CO_2 emissions puts the same price on CO_2 emissions avoided with the help of CCS.

Consequently, CO_2 emissions that are captured, transported and injected into geological formations according to regulations (i.e. avoided emissions) are exempted from the tax, or do not require permits to cover emissions in an emissions trading system. In the case of negative emissions such as BECCS, however, CO_2 emissions are not only avoided, but there is a net removal of CO_2 from the atmosphere. In order to provide consistent incentives for CO_2 emitters and BECCS operators, net removal of CO_2 from the atmosphere should not only be exempted from paying tax or surrendering permits, but receive a credit based on the same CO_2 price.

Furthermore, CCS – particularly the CO_2 capture component – has high costs, and there are challenges accounting for and rewarding negative emissions, particularly when including these in emissions trading systems and other market mechanisms. Rubin, Davison, and Herzog (2015) give a broad range of CCS costs from USD 50–100 per ton CO_2, based on a review of recent cost studies for CCS applied to the power sector.[11] There is little cost information on industrial CCS available. Some support schemes for CCS exist, but they are largely inadequate to enable the technology (OECD/IEA, 2016).

The net negative CO_2 effect of a BECCS project could be calculated based on a BECCS accounting framework, which would provide the basis for rewarding negative emissions. The value of one ton of CO_2 of negative emissions should be the same as the carbon tax or the permit (quota or allowance) price in an emissions trading system, in order to secure an overall cost-effective emission mitigation system. Due to the discounting factor on negative emissions, however, this means that only BECCS projects with lower costs per ton of CO_2 removed from the atmosphere than the cost of avoiding the emission of one ton of CO_2 (e.g. in industrial CCS projects) can compete in terms of return, and thus be interesting for operators.[12] BECCS projects have an additional value to industrial CCS projects due to the energy produced.[13] If the atmospheric concentration of CO_2 approaches or 'overshoots' a limit, for example as defined by a climate policy target or a steep increase in the negative impacts of climate change, the value of negative emissions increases, since only avoiding emissions will not suffice to reduce atmospheric CO_2 concentration below this limit. In such a situation, additional rewarding of negative emissions would be called for to induce operators to exert sufficient efforts. BECCS is likely more attractive when designed as low capital cost plants, even if the implication is lower efficiency, and operated in a 'base-load' fashion, where spare capacity could be used for hydrogen production (Mac Dowell & Fajardy, 2017). This finding implies that the most attractive BECCS projects not only depend on rewarding net negative emissions, but also depend on capital cost and operation time. Currently, the value of one ton of CO_2 is too low to incentivize participation of companies in either CCS or BECCS (Bollen & Aalbers, 2017; Narita & Klepper, 2016). In the EU ETS, at the time of writing, the allowance price for one ton of CO_2 was about 16 Euro (medio July 2018), whereas BECCS costs have been estimated at 70–250 USD per ton CO_2 (IPCC, 2014; The Center for Carbon Removal, 2017).[14] The cost-value gap and uncertain factors mean that there is no way around substantial government support for BECCS development and scale-up. Investing in pilot plants, infrastructure, and the first full-scale operations will produce learning on how various BECCS cost components can be reduced, on efficient and sustainable design of biomass feedstocks, and on safe geological storage of CO_2.

The '45Q' tax credit in the United States, which was expanded in February 2018, provides some incentives for NETs. Dedicated geological CO_2 storage will receive a tax credit at 28 USD/tCO_2, to increase to 50 USD/tCO_2 by 2026, with CO_2 from power plants, industrial facilities, and DAC eligible as sources (Energy Futures Initiative, 2018).[15]

One option for government to support BECCS is to guarantee a price per ton of CO_2. This price needs to be sufficiently high to bridge the BECCS cost-value gap and reduce the risk for companies' long-term investments in BECCS. Over time, the price support can gradually be phased out, in the expectation that the CO_2 price will increase as stricter climate policies are implemented to fulfil the ambition of the Paris Agreement.

A strategic issue for designing government support is whether this should be narrow – across a few, specific CCS technologies – or broader (Watson et al., 2012). Torvanger and Meadowcroft (2011) argue that support for a few strategically important technologies would deliver the best balance between learning and risk reduction.[16] On the biomass energy component, government support for research and development needs to focus on sustainable use, large-scale production that does not compromise other forms of land use, and increasing the volume of negative emissions obtained relative to total cost.

If Parties to the Paris Agreement fulfil their contributions, and stepwise strengthen their efforts, the value of BECCS will likely gradually increase over time, and together with learning, reduce costs and risk elements, to possibly make BECCS finally commercially viable.

4. BECCS under the Paris agreement

There is uncertainty attached to the implementation and strengthening of the Paris Agreement. Linking BECCS to emissions trading and other market mechanisms is important for the development of BECCS. To make negative emissions attractive, removal of CO_2 must earn extra value compared to avoided emissions, according to an agreed accounting framework. Due to the interaction with the global carbon cycle (see section 2.1), however, one ton of CO_2 removed from the atmosphere will be rewarded as less than one ton. According to the market mechanism at hand, the negative emission reward can be a 'credit' or be subtracted from CO_2 emissions across a group of emission sources (IEA, 2011; Zakkour, Cook, et al., 2014; Zakkour, Kemper, et al., 2014). Allowing negative emissions in an emissions trading system could put a downward pressure on the equilibrium permit price, which could be an unwanted side effect, but this can be managed through reducing the total emissions ceiling (i.e. number of permits) over time.

In Article 6, paragraphs 2 and 4, the Paris Agreement outlines mechanisms for collaboration on emission mitigation across Parties, which can be referred to as market mechanisms.

Given the potential importance of negative emissions for achieving temperature limitation goals, and the Paris Agreement's reference to the importance of CO_2 sinks (Article 5.1), it seems pertinent to make sure that the Paris Agreement's modalities become favourable for the further development of NETs, not least BECCS. Honegger and Reiner (2018) examine design elements of international policy instruments that could mobilize NETs, emphasizing robust quantification of the CO_2 removal effect, and preventing environmental conflicts with land and water use. They suggest that the mechanism under Article 6.4 of the Paris Agreement could be a foundation for implementing NETs at the global level, mobilizing financial flows and making sure that sustainable development impacts are handled well.

The modalities of the Paris Agreement mechanisms, including an accounting and rewarding framework for negative emissions, must be negotiated and adopted by the Parties to the Paris Agreement. One implication should be that accounting rules and the mechanisms under Article 6 allow transferable credits for negative emissions, or that negative emissions can be deducted from positive emissions when a Party manages its portfolio of CO_2 emission sources. Similarly, a Party implementing the Paris Agreement should allow negative emission credits or deductible negative emissions for companies and other entities at the national level.

Experience from the CDM shows that calculation of credits is associated with many uncertainties. CDM credits are calculated relative to a reference path that cannot be established with certainty, even if a comprehensive and costly MRV system is in place (Torvanger, Shrivastava, Pandey, & Tørnblad, 2013). The sustainability objective of the CDM is also very challenging, since clear definitions and verifiable operationalization are missing, and additionally coloured by different national interests, as well as limited data availability. These lessons are not only relevant for the Paris Agreement mechanisms, but also when designing the accounting and rewarding framework for BECCS and other NETs. Clearly, a balance has to be struck between a costly and ambitious system that will never be perfect on one hand, and feasibility, efficiency and operational requirements on the other.

5. Conclusions

Given the potential importance of BECCS as a climate mitigation and negative emission technology to meet the Paris Agreement target, this study identifies a number of governance issues required to further develop BECCS, to be in a position for possibly deployment over the next decades.

The analysis shows that more research is required on sustainable and efficient biomass production and use, the interaction of negative emissions with the global carbon cycle, efficient capture of CO_2 from industrial sources, and safe CO_2 storage in geological formations. Furthermore, research, pilot projects and full-scale plants should receive government support to promote good performance and cost-effectiveness of BECCS as a negative emission technology, including issues of permanency, resource and water availability, and to avoid unwanted side-effects that would negatively affect the value of land areas. Scaling-up BECCS will require government support for a number of years. Biomass production and other land-use must be balanced, to optimize the economic and ecological value of land, minimize trade-offs, and enable multi-use synergies. Both research and development on sustainable biomass and CCS must be designed to maximize learning relevant for BECCS and across other NETs, and should be coordinated in collaboration between willing countries.

BECCS necessitates an accounting framework, which should be standardized and adopted at the international level. To enable business engagement in BECCS development and deployment, and eventually make BECCS commercial, stricter climate policies and an increased carbon price are called for, but also national frameworks that generate a sufficiently high value on negative emissions.

To align BECCS with the development of the Paris Agreement and its market mechanisms, specifically the rulebook for accounting biomass, CO_2 and climate finance domestically and internationally, nations must negotiate and adopt a standardized accounting and rewarding framework for BECCS.

Notes

1. CO_2 is foremost stored in aquifers, but also in abandoned oil and gas reservoirs.
2. EOR refers to an oil extraction technology. CO_2 can be injected to flush out more residual oil from the tail-production phase of an oil reservoir.
3. Gleick and Palaniappan (2010) find that ' … humans already appropriate over 50% of all renewable and "accessible" freshwater flows, … '. Based on 1990 data, total human use of accessible freshwater runoff globally was at 54%, of which agriculture represented less than half (i.e. 23%) (Postel, Daily, & Ehrlich, 1996).
4. International Sustainability & Carbon Certification (ISCC) issues sustainability and GHG savings certificates where emissions related to global supply chains are included (ISCC, 2018).
5. Expanding the scope to account for climate impacts would make even more elements relevant, such as the climate effects of changes to the albedo of land areas used for biomass production.
6. There are examples of small-scale CO_2 capture in submarines, rebreather diving and spacecraft travel, but space, weight and cost considerations have so far made this unfeasible for vehicles.
7. While negative emissions can reduce temperature to the desired 2°C even if it temporarily rises above this warming level ('overshoot'), sea level rise due to ocean heat expansion will not be reversible for centuries.
8. The net effect of EOR on CO_2 emissions depends on three components: (i) Does any CO_2 escape from the reservoir during the EOR phase?; (ii) Will the oil reservoir after production ends be used for CO_2 storage, and allow more CO_2 storage due to EOR?; and (iii) Will the oil produced be additional to, or replace other, oil or fossil fuel production? If so which fossil fuels?
9. Oil recovery per ton of CO_2 falls with total injected CO_2. Mac Dowell et al. (2017) find that optimal oil recovery implies injecting CO_2 until 3.3 barrels of oil is recovered per ton of CO_2, whereas maximizing CO_2 storage implies injecting CO_2 until 1.1 barrels of oil are recovered per ton of CO_2 injected.
10. As an example, negative emissions from bioenergy are not recognized in the EU ETS.
11. CCS cost calculations include capital costs, fuel costs, and operation and maintenance costs for various CCS, coal or natural gas technologies, and power plant designs. Changes in capital costs, levelized cost of electricity, and CO_2 mitigation costs are reported for each power plant system with and without CCS.
12. Assuming that an operator can choose between avoiding emissions and producing negative emissions.
13. For some industrial CCS applications, captured CO_2 can have an additional user value, e.g. in some plastic materials and chemicals, however, with limited CO_2 storage potential and permanency. See also the discussion of EOR in section 2.2.
14. Which is equivalent to 59–212 Euro per ton CO_2, given an exchange rate at 1 Euro = 1.18 USD.
15. EOR and other CO_2 utilization processes will receive a credit at 17 USD/CO_2 in 2018, to increase to 35 USD/tCO_2 by 2026.
16. Selection of technologies should be based on existing strengths and capacities (such as natural resources, science and technological capacity, existing infrastructure, innovation and industrial clusters), monitoring of emerging opportunities, exploring transition pathways, consideration of major strategic technologies, continuous monitoring of developments, consideration of termination of support after a period, and co-ordination and collaboration with other countries.

Acknowledgement

I thank Glen Peters, Erlend Andre T. Hermansen, Henrik Wiig, and three anonymous referees for valuable comments and suggestions.

Disclosure Statement

No potential conflict of interest was reported by the author.

Funding

This work was supported by Norges Forskningsråd [grant number Klimaforsk, 261785/E10].

References

Armstrong, K., & Styring, P. (2015). Assessing the potential of utilization and storage strategies for post-combustion CO2 emissions reduction. *Frontiers in Energy Research*, 3(March), 335. Article 8. doi:10.3389/fenrg.2015.00008

Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vuuren, D. P., den Elzen, K. M. G. J., … Larson, E. D. (2010). The feasibility of low CO2 concentration targets and the role of bioenergy with carbon capture and storage (BECCS). *Climatic Change*, *100*(1), 195–202.

Baik, E., Sanchez, D. L., Turner, P. A., Mach, K. J., Field, C. B., & Benson, S. M. (2018). Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. *PNAS*, *115*(13), 3290–3295. https://www.pnas.org/cgi/doi/10.1073/pnas.1720338115

Bollen, J., & Aalbers, R. (2017). Biomass-Energy with Carbon capture and storage should be used immediately, CPB Netherlands bureau for economic policy analysis, Policy Brief no. 2.

Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: Social barriers and social implications. *Climatic Change*, *139*(2), 155–167.

Center for Carbon Removal. (2017). Bioenergy with carbon capture and storage. Retrieved from https://static1.squarespace.com/static/54a2e4c1e4b043bf83114773/t/56e5f312ab48de1dc3c58a0d/1457910556936/BECCS+Fact+Sheet.pdf

De Coninck, H., & Benson, S. M. (2014). Carbon dioxide capture and storage: Issues and prospects. *Annual Review of Environmental Resources*, 39(October), 243–270. doi:10.1146/annurev-environ-032112-095222

Dixon, T., McCoy, S. T., & Havercroft, I. (2015). Legal and regulatory developments on CCS. *International Journal of Greenhouse Gas Control*, *40*(Special issue), 431–448. doi:10.1016/j.ijggc.2015.05.024

Energy Futures Initiative. (2018). Advancing large scale carbon management: Expansion of the 45Q tax credit, policy paper, May, Washington, D.C. https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5b0604f30e2e7287abb8f3c1/1527121150675/45Q_EFI_5.23.18.pdf

EU. (2009a). Directive 2009/31/EC of the European parliament and of the council on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006, 23 April. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0031&from=EN

EU. (2009b). Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

EU. (2015). Directive (EU) 2015/1513 of the European parliament and of the council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.

Fajardy, M., & Mac Dowell, N. (2018). The energy return on investment of BECCS: Is BECCS a threat to energy security? *Energy and Environmental Science*, *April*. doi:10.1039/c7ee03610h

Fridahl, M. (2017). Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy*, *104*(May), 89–99.

Fridahl, M., & Lehtveer, M. (2018). Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers. *Energy Research & Social Science*, 42(March), 155–165. doi:10.1016/j.erss.2018.03.019

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., … Yamagata, Y. (2014). Betting on negative emissions, commentary. *Nature Climate Change*, *4*, 850–853. doi:10.1038/nclimate2392

Fuss, S., Jones, C. D., Kraxner, F., Peters, G. P., Smith, P., Tavoni, M., … Yamagata, Y. (2016). Research priorities for negative emissions. *Environmental Research Letters*, *11*(November), 115007. doi:10.1088/1748-9326/11/11/115007

Geden, O., Scott, V., & Palmer, J. (2018). Integrating carbon dioxide removal into EU climate policy: Prospects for a paradigm shift. *Wiley Interdisciplinary Reviews: Climate Change*, 9(May), e521. doi:10.1002/wcc.521

Gleick, P. H., & Palaniappan, M. (2010). Peak water limits to freshwater withdrawal and use. *PNAS*, *107*(25), 11155–11162. doi:10.1073/pnas.1004812107

Global CCS Institute. (2017). The global status of CCS 2017.

Greene, C. H., Huntley, M. E., Archibald, I., Gerber, L. N., Sills, D. L., Granados, J., … Walsh, M. J. (2017). Geoengineering, marine microalgae, and climate stabilization in the 21st century. *Earth's Future*, *5*, 278–284. doi:10.1002/2016EF000486

Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubier, Y., Henze, M., … Searchinger, T. (2012). Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*, *45*(June), 18–23. doi:10.1016/j.enpol.2012.02.051

Heinimö, J., & Junginger, M. (2009). Production and trading of biomass for energy – An overview of the global status. *Biomass and Bioenergy*, *33*(9), 1310–1320. doi:10.1016/j.biombioe.2009.05.017

Honegger, M., & Reiner, D. (2018). The political economy of negative emissions technologies: Consequences for international policy design. *Climate Policy*, *18*(3), 306–321. doi:10.1080/14693062.2017.1413322

Hufty, M. (2011). Investigating policy processes: The governance analytical framework (GAF). In U. Wiesmann & H. Hurni et al. (Eds.), Research for sustainable development: Foundations, experiences, and perspectives (pp. 403–424). Bern: Geographica Bernensia.

IEA. (2011). Combining bioenergy with CCS – Reporting and accounting for negative emissions under UNFCCC and the Kyoto Protocol, Working Paper, OECD/IEA, Paris. Retrieved from https://www.iea.org/publications/freepublications/publication/bioenergy_ccs.pdf

IEA GHG. (2012). CO_2 capture at gas-fired power plants, Report No. 8. Retrieved from http://hub.globalccsinstitute.com/sites/default/files/publications/103211/co2-capture-gas-fired-power-plants.pdf

International Organization for Standardization (ISO). (2006). ISO14064-2:2006, Greenhouse gases -- Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements. Retrieved from https://www.iso.org/standard/38382.html

International Organization for Standardization (ISO). (2013). ISO 14065:2013, Greenhouse gases -- Requirements for greenhouse gas validation and verification bodies for use in accreditation or other forms of recognition. Retrieved from https://www.iso.org/standard/60168.html

International Sustainability & Carbon Certification (ISCC). (2018). Certification scopes, Website, downloaded 12 July. https://www.iscc-system.org/process/certification-scopes/

IPCC. (2006). 2006 IPCC Guidelines for national greenhouse gas inventories, IGES, Japan. Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/

IPCC. (2013). Climate change 2013 - The physical science basis, Working Group I Report. http://www.ipcc.ch/report/ar5/wg1/

IPCC. (2014). Climate change 2014: Mitigation of climate change, Ch.11 Agriculture, Forestry and Other Land Use (AFOLU), Working Group III contribution to the Fifth Assessment Report of IPCC.

Jones, C. D., Ciais, P., Davis, S. J., Friedlingstein, P., Gasser, T., Peters, G. P., … Wiltshire, A. (2016), Simulating the earth system response to negative emissions, *Environmental Research Letters*, 11(September), 095012. doi:10.1088/1748-9326/11/9/095012

Kemper, J. (2015). Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control*, *40* (September), 401–430.

Krüger, T. (2017). Conflicts over carbon capture and storage in international climate governance. *Energy Policy*, *100*(January), 58–67. doi:10.1016/j.enpol.2016.09.059

Larkin, A., Kuriakose, J., Sharmina, M., & Anderson, K. (2018). What if negative emission technologies fail at scale? Implications of the Paris agreement for big emitting nations. *Climate Policy*, *18*(6), 690–714. doi:10.1080/14693062.2017.1346498

Mac Dowell, N., & Fajardy, M. (2017). Inefficient power generation as an optimal route to negative emissions via BECCS. *Environmental Research Letters*, *12*(April), doi:10.1088/1748-9326/aa67a5

Mac Dowell, N., Fennell, P. S., Shah, N., & Maitland, G. C. (2017). The role of CO_2 capture and utilization in mitigating climate change. *Nature Climate Change*, *7*(April), 243–249. doi:10.1038/NCLIMATE3231

Merk, C., Pönitzsch, G., & Rehdanz, K. (2018). Do climate engineering experts display moral-hazard behaviour? *Climate Policy*, 37, 1–13. doi:10.1080/14693062.2018.1494534

Muratori, M., Calvin, K., Wise, M., Kyle, P., & Edmonds, J. (2016). Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, *11*(August), 095004. doi:10.1088/1748-9326/11/9/095004

Muri, H. (2018). The role of large—scale BECCS in the pursuit of the 1.5° C target: An earth system model perspective. *Environmental Research Letters*, *13*(4). doi:10.1088/1748-9326/aab324

Narita, D., & Klepper, G. (2016). Economic incentives for carbon dioxide storage under uncertainty: A real options analysis. *International Journal of Greenhouse Gas Control*, *53*(October), 18–27. doi:10.1016/j.ijggc.2016.07.021

OECD/IEA. (2015). Storing CO_2 through enhanced oil recovery – Combining EOR with CO_2 storage (EOR+) for profit. Insights Series. https://www.iea.org/publications/insights/insightpublications/Storing_CO2_through_Enhanced_Oil_Recovery.pdf

OECD/IEA. (2016). *20 years of carbon capture and storage – accelerating future deployment*. Paris: Author. Retrieved from https://www.iea.org/publications/freepublications/publication/20YearsofCarbonCaptureandStorage_WEB.pdf

OECD/IEA. (2017). *Technology roadmap – delivering sustainable bioenergy*. Paris: IEA.

Pawar, R. J., Bromhal, G. S., Carey, J. W., Foxall, W., Korre, A., Ringrose, P. S., … White, J. A. (2015). Recent advances in risk assessment and risk management of geologic CO2 storage. *International Journal of Greenhouse Gas Control*, *40*(Special issue), 292–311.

Peters, G. P., & Geden, O. (2017). Catalyzing a political shift from low to negative carbon. *Nature Climate Change*, *7*(August), 619–621. doi:10.1038/nclimate3369

Postel, S. L., Daily, G. C., & Ehrlich, P. R. (1996). Human appropriation of renewable fresh water. *Science*, *271*(5250), 785–788.

Reiner, D. M. (2016). Learning through a portfolio of carbon capture and storage demonstration projects. *Nature Energy*, *1*(January), 15011. doi:10.1038/NENERGY.2015.11

Reynolds, J. (2018). Governing experimental responses – negative emissions technologies and solar climate engineering. In A. Jordan, D. Huitema, H. van Asselt, & J. Forster (Eds.), *Governing climate change: Polycentricity in action?* (pp. 285–302). Cambridge: Cambridge University Press.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, *5*(6), 519–527.

Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, *40*(Special issue), 378–400.

Sanchez, D. L., Johnson, N., McCoy, S. T., Turner, P. A., & Mach, K. J. (2018). Near-term deployment of carbon capture and sequestration from biorefineries in the United States. *Proceedings of the National Academy of Sciences*, *115*, 4875–4880. doi:10.1073/pnas.1719695115

Sanchez, D. L., & Kammen, D. M. (2016). A commercialization strategy for carbon-negative energy. *Nature Energy*, *1*(January), 15002. doi:10.1038/nenergy.2015.2

Searchinger, T. D. (2010). Biofuels and the need for additional carbon. *Environmental Research Letters*, *5*(June), 024007. doi:10.1088/1748-9326/5/2/024007

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., … Tilman, G. D. (2009). Fixing a critical climate accounting error. *Science*, *326*(5952), 527–528. doi:10.1126/science.1178797

Sheperd, J., Caldeira, K., Haigh, J., Keith, D., Launder, B., Mace, G., … Watson, A. (2009). *Geoengineering the climate: Science, governance and uncertainty*. London: The Royal Society.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., … Yongsung, C. (2016). Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, *6*(December), 42–50. doi:10.1038/nclimate2870

Soltanian, M. R., & Dai, Z. (2017). Geologic CO_2 sequestration: Progress and challenges. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, *3*(3), 221–223. doi:10.1007/s40948-017-0066-2

Speed, R. (2017). *DRAX biomass, Winchester action on climate change*. Winchester University. http://www.winacc.org.uk/sites/default/files/attachments/2017_Drax%20Biomass_0.pdf

Sterman, J. D., Siegel, L., & Rooney-Varga, J. N. (2018). Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters*, *13*(1), doi:10.1088/1748-9326/aaa512

Stewart, R. J., & Haszeldine, R. S. (2015). Can producing oil store carbon? Greenhouse gas footprint of CO2EOR, offshore north Sea. *Environmental Science and Technology*, *49*(9), 5788–5795. doi:10.1021/es504600q

Tokarska, K. B., & Zickfeld, K. (2015). The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environmental Research Letters*, *10*(September), 094013. doi:10.1088/1748-9326/10/9/094013

Torvanger, A., Grimstad, A. A., Lindeberg, E., Rive, N., Rypdal, K., Bieltvedt Skeie, R., … Tollefsen, P. (2012). Quality of geological CO_2 storage to avoid jeopardizing climate targets. *Climatic Change*, *114*(2), 245–260.

Torvanger, A., & Meadowcroft, J. (2011). The political economy of technology support: Making decisions about CCS and low carbon energy technologies. *Global Environmental Change*, *21*(2), 303–312.

Torvanger, A., Shrivastava, M. K., Pandey, N., & Tørnblad, S. H. (2013). A two-track clean development mechanism to improve incentives for sustainable development and offset production. *Climate Policy*, *13*(4), 471–489. doi:10.1080/14693062.2013.781446

UNEP. (2017). The emissions gap report 2017, A UN Environment synthesis report. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf?sequence=1&isAllowed=y

Ussiri, D. A., & Lal, R. (2017). Carbon capture and storage in geologic formations. In *Carbon sequestration for climate change mitigation and adaptation* (pp. 497–545). Springer.

Vaughan, A. (2018, May 21). Drax power station to lead fresh carbon capture trial. *Guardian*. Retrieved from https://www.theguardian.com/environment/2018/may/21/drax-power-station-to-lead-fresh-carbon-capture-trial

Watson, J., Kern, F., Gross, M., Gross, R., Heptonstall, P., Jones, F., … Arapostathis, S. (2012). Carbon capture and storage – Realizing the potential?, UKERC - UK Energy Research Centre..

Zakkour, P., Cook, C., & French-Brooks, J. (2014). Biomass and CCS-guidance for accounting for negative emissions, Report No. 5, IEAGHG, Cheltenham. Retrieved from http://www.ieaghg.org/docs/General_Docs/Reports/2014-05.pdf

Zakkour, P., Kemper, J., & Dixon, T. (2014). Incentivizing and accounting for negative emission technologies. *Energy Procedia*, *63* (December), 6824–6833. doi:10.1016/j.egypro.2014.11.716