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Challenges to the use of BECCS as a keystone technology in pursuit of 1.5^{0}C

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Non-technical summary

Biomass energy with carbon capture and storage (BECCS) is represented in many integrated assessment models as a keystone technology in delivering the Paris Agreement on climate change. This paper explores six key challenges in relation to large scale BECCS deployment and considers ways to address these challenges. Research needs to consider how BECCS fits in the context of other mitigation approaches, how it can be accommodated within existing policy drivers and goals, identify where it fits within the wider socioeconomic landscape, and ensure that genuine net negative emissions can be delivered on a global scale.

Technical summary

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement sets a goal of limiting the global temperature increase to “well below 2°C” and to pursue “efforts to limit the temperature increase to 1.5°C”. Most emission pathways that are compatible with these goals are heavily reliant on negative emissions technologies (NETs), especially biomass energy with carbon capture and storage (BECCS), at a global scale to remove CO_2 from the atmosphere. The use of negative emissions in climate mitigation introduces a complex variety of technologies whose desirability, effectiveness and viability remain highly uncertain. This paper explores six key policy and governance challenges associated with BECCS, suggesting ways in which research could address some of these challenges: 1) How does BECCS fit with carbon budgets? 2) How negative is BECCS? 3) Can BECCS be delivered at sufficient scale? 4) Can sufficient biomass be provided sustainably? 5) How does BECCS fit into the policy context? 6) How does BECCS fit with climate agreements? Consideration of these challenges highlights the importance of a whole systems approach to assessing the use of BECCS and its potential as a keystone technology to deliver negative emissions.

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement sets a goal of limiting the global temperature increase to “well below 2°C” and to pursue “efforts to limit the temperature increase to 1.5°C” [1]. Most emission pathways that are compatible with these goals are heavily reliant on negative emissions technologies (NETs), especially biomass energy with carbon capture and storage (BECCS) at a global scale [2,3] to remove CO_2 from the atmosphere. However, the use of NETs in climate change mitigation introduces a variety of technologies whose desirability, effectiveness and viability remain highly uncertain.

BECCS is an emerging technology that combines large-scale biomass energy applications (including electricity generation) with the capture and storage of CO_2. In the case of BECCS, the negative emissions concept is based on the principle that, since CO_2 is absorbed from the atmosphere during the growth cycle of biomass feedstocks, if the CO_2 produced during combustion of biomass energy is captured and stored indefinitely, removal of CO_2 from the atmosphere can be achieved [4]. There are other suggested approaches for negative emissions such as afforestation, direct capture of CO_2 from the air with geological storage and enhanced weathering, but BECCS is by far the most prominent of these options in climate change mitigation scenarios. This paper explores the policy and governance challenges specific to achieving negative emissions through BECCS [2,5].

Achieving the goals of the UNFCCC Paris Agreement is dependent on tight limits to cumulative emissions of CO_2 (and other greenhouse gases) in order to stabilize their atmospheric concentration. At current emission rates, the cumulative global emissions, and consequently atmospheric CO_2 concentration, continue to rise and the remaining emission ‘budget’

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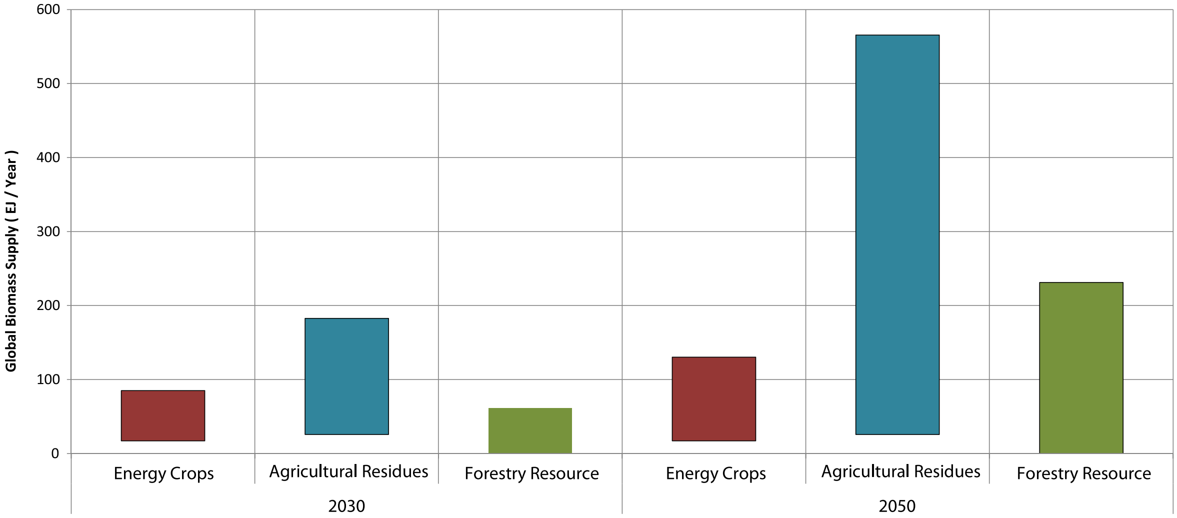

Fig. 1. Global biomass supply ranges of key categories of biomass resource. This figure documents the range in resource availability forecasts from [36,43–58].

contracts, making the task of reaching the targets ever more challenging. In this context, it has been suggested that NETs may be able to contribute in two ways: 1) by offering the potential to reduce mitigation costs or to achieve more ambitious targets at the same cost; or 2) in principle, allowing a temporary overshoot of long term concentration targets and thus limiting the consequences of delays in the year in which emissions peak [6,7]. A large majority of mitigation scenarios that deliver atmospheric CO_2 concentrations consistent with the 2°C target (and indeed many of those associated with temperature increases up to 3°C) require global net negative emissions by about 2070 [2,5,8,9]. Thus, the large-scale deployment of BECCS in emission scenarios appears to be central to the feasibility of not exceeding 2°C and, consequently, 1.5°C, of global mean temperature warming above pre-industrial levels[i]. However, explicit and implicit assumptions about BECCS in the integrated assessment models (IAMs) that generate these scenarios are highly optimistic [10]; moving from modelled worlds to reality raises many challenges.

In this paper, we use three different metrics to describe negative emissions derived from BECCS:

1) CO_2 stored – amount of CO_2 placed in geological storage from BECCS systems. This gives an indication of the amount of storage capacity needed.
2) Negative emissions from BECCS – amount of CO_2 removed from the atmosphere using BECCS systems. This reflects the net emissions from a BECCS supply chain (i.e. accounting for system losses, emissions associated with land-use change and fossil fuel emissions). For a given supply chain, this will be less than the total CO_2 stored, due to ‘positive’ emissions along the supply chain.
3) Global net negative emissions – net amount of CO_{2e} removed[ii] from the atmosphere by human intervention. This is achieved when the CO_2 removed from the atmosphere using negative emissions approaches (such as BECCS) is greater than the CO_2 and other greenhouse gas emissions from all other anthropogenic sources (e.g. energy and agricultural systems) [2]. If anthropogenic emissions are above zero, global net negative emissions will be less than global negative emissions (metric 2).

Whether or not BECCS has the potential to deliver negative emissions at a global scale depends on physical and technical constraints to the technologies as well as equally challenging social and governance constraints. This paper presents six key policy and governance questions associated with BECCS and suggests ways in which research could address some of these challenges: 1) How does BECCS fit with carbon budgets? 2) How negative is BECCS? 3) Can BECCS be delivered at sufficient scale? 4) Can sufficient biomass be provided sustainably? 5) How does BECCS fit into the policy context? 6) How does BECCS fit with climate agreements?

2. How does BECCS fit with carbon budgets?

The global carbon budget is a concept that emerges from findings from Earth system models that show global temperature change is proportional to cumulative carbon emissions [11,12]. Many IAMs use simplified climate-carbon cycle models, which are calibrated against more complex Earth system models, to estimate the required contribution of NETs for different emission scenarios [13]. In principle, the possibility of overspending a carbon budget at the same time as generating electricity (or liquid fuels) makes BECCS particularly attractive.

BECCS is not an alternative to conventional mitigation. Even if it is possible to overcome the many challenges and uncertainties associated with delivering BECCS on a scale sufficient to deliver global net negative emissions, staying within the carbon budgets would require a sharp acceleration in decarbonization. However, BECCS could play a role as a cost-effective way of offsetting the emissions from sectors that are particularly challenging to abate, such as international transport [14]. Taking aviation as an example, few technical options exist for decarbonization in the short to medium term. At a global scale, there is continued growth in the distance travelled by passengers, particularly within developing economies, and demand management is likely to be unpopular with travellers, governments and the industry. Balanced against these challenges, BECCS offers the possibility of compensating for the continued use of hydrocarbons within aviation.

There are huge uncertainties around the extent to which future negative emissions can compensate for an implied near-term overshoot of carbon budgets, should global emissions increase

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or remain at current levels into the 2020s, depending upon the magnitude and duration of the overshoot. There are also uncertainties due to Earth system responses and processes that are not yet represented within Earth system models, such as release of carbon from thawing permafrost [13].

One of the criticisms levelled at BECCS, and other NETs, in relation to carbon budgets is that of moral hazard. A moral hazard can be simply defined as a decision that is made by one entity to accept a particular level of risk but where the balance of risk is borne by another [15]. In the context of carbon budgets, if negative emissions are used to allow overshoot, as an alternative to mitigation within other sectors (such as aviation), and do not deliver as hoped, or should the Earth system not respond as anticipated, it is future generations and those most vulnerable to climate change that will suffer the consequences. Furthermore, given that, to date, mitigation policies have failed to deliver at the scale required to maintain cumulative emissions within the limits compatible with policy goals, investment in BECCS could displace efforts to mitigate in the near term, placing an unjust burden on future generations.

3. Evaluating negative emissions from BECCS – how negative is BECCS?

A BECCS supply chain has multiple stages, from growing, harvesting, treating and transporting biomass, to conversion processes (e.g. energy and industrial process to produce biofuels or chemicals) through to CO_2 capture, compression, transport and storage. Each discrete stage or sub-stage is expected to result in the release or avoidance of greenhouse gas emissions through the material and energy inputs that enable the process, and waste or utilized products replacing alternatives. Life Cycle Assessment (LCA) is a method of accounting for these material and emissions flows generated by a product or a process in relation to the defined functional unit of the analysis. Even though there is robust evidence that bioenergy pathways can reduce emissions significantly compared to fossil fuel based energy options [16,17], there are significant uncertainties with regards to emissions associated with various supply chain processes [18–20].

LCA results depend on how the research question is framed, whether it focuses on emission saving, absolute emission reductions, maintenance of carbon stocks or other environmental impacts [21,22], and therefore how the system under investigation is defined and how boundaries are drawn to include or exclude particular processes. It is thus vital that the scope and design of an LCA analysis are presented in a coherent and transparent way. LCA can address the question of 'how negative is BECCS?' by quantifying the net CO_{2e} emissions to air attributed to BECCS. However, the results of such an assessment are contingent upon a range of explicit and implicit assumptions and involve a multiplicity of variables and/or limited data availability. In the case of bioenergy, these issues are amplified by the variety of feedstocks and variability of its quality, biomass conversion processes, co-products and the substitutional effects for land and materials.

Currently there are few LCA studies of carbon capture and storage (CCS) [23,24] and BECCS (typically applied to biomass co-fired with fossil fuel for power generation applications) [25,26], indicating that negative CO_2 emissions could be attained via BECCS delivering net negative emissions of 67–85 g/kWh [25] with 30% biomass co-firing and 410 [26] and 504 [27] g/KWh with 100% biomass. However, performance is highly dependent on the specific supply chain analysed and there remain many uncertainties around the negative emissions potential from BECCS [25]. In addition to those relating to bioenergy systems, uncertainties in CCS systems [23] make BECCS LCA particularly challenging. Furthermore, there is limited operational data. For this reason the LCA studies mentioned above, for example, do not fully consider performance factors beyond the CO_2 capture stage (i.e. compression, transportation and CO_2 storage) [23,27] or the gas conditioning, plant dismantling and construction phases [25] and should be seen as indicative.

Additional uncertainties relate to counterfactuals and substitution; increasingly, 'consequential' LCA approaches have been applied to bioenergy to address the importance of accounting for wider changes (e.g. land use) [28,29]. Bioenergy supply potentially affects agriculture, construction and energy supply systems, substituting or requiring the substitution of products in these sectors. Determining the net consequential impact of bioenergy entails modelling the effects of bioenergy scenarios compared to a non-bioenergy counterfactual scenario [28,30]. This requires assumptions about the counterfactual case for the biomass products and energy supply, and models to describe relationships within and between systems, introducing variability and subjectivity [30,31]. Significant amounts of biomass energy are included in 2 or 1.5 °C mitigation scenarios, whether or not they include BECCS [32]. The emissions associated with any bioenergy use will depend on the type of feedstock (e.g. whether dedicated energy crops or residues) and how the emissions are accounted [33,34].

Furthermore, it is important to understand the trade-offs in environmental performance inherent in BECCS systems. In theory, while BECCS results in a reduction of net CO_2 emissions to the atmosphere, the process may increase other environmental impact factors from different stages of the supply chain (e.g. terrestrial acidification, eutrophication, terrestrial ecotoxicity, ionizing radiation and ozone depletion) [25,27].

The amalgamation of data uncertainties, variable methodology choices and necessary assumptions and abstractions associated with BECCS presents new challenges for LCA. Nevertheless, BECCS LCA can provide a range of possible emission profiles of the supply chain and can indicate trends and sensitivities, which then help to optimize the system and supply chain processes. Ultimately, work is needed to produce a broadly acceptable approach for accurately accounting for the life cycle environmental impacts of BECCS.

4. Can BECCS be delivered at sufficient scale?

Typically, optimistic assessments of the potential for BECCS are analysed in isolation from the need for supporting CCS infrastructure. To put the scale of the challenge into context, current global CO_2 emissions are around 35 $GtCO_2$/yr; the Gorgon gas processing project in Australia, currently under construction, will be the largest CO_2 storage project with an expected storage rate of 3.4 to 4 $MtCO_2$/yr. This CCS facility is up to four times the size of the single existing BECCS plant (a demonstration project in Decatur, Illinois) or any of the handful of existing CCS projects, which typically store up to 1 Mt CO_2/yr. The range of CO_2 removal through BECCS assumed in IAMs is typically between 2 and 10 $GtCO_2$/yr by 2050 [2,7]. This level of CO_2 storage alone would require the construction of between 500 and 2000 Gorgon project-sized facilities by 2050, each requiring access to a pipeline and storage site. This number of new facilities, implemented through a wide variety of supply chain configurations, each associated with specific implications and challenges, begins to reveal the scale of the task underlying the figures presented in the IAMs.

There are many different options for alternative BECCS supply chains, and each will have their specific characteristics in terms of performance, logistics and economics. Large-scale deployment of BECCS will create the need for trade and transportation of biomass feedstocks (which have a much lower energy density than fossil fuels), connecting available land to produce the biomass resource with energy infrastructure and available storage sites, potentially at intercontinental scales (assuming sufficient storage capacity can be identified and utilized) [10,35]. To supply the required biomass, the CO_2 concentration pathway associated with the 2°C target assumes 300–600 Mha of additional land is available for energy crop production [7,36]. This represents a significant change in land use of an area similar to the size of the European Union (424 Mha according to World Bank Data) and the equivalent of 40% of current global arable land area (although noting that the IAMs assume that bioenergy production is restricted to abandoned agricultural land and natural grassland systems rather than conversion of arable land for energy crops [37]).

Assuming the physical requirements of BECCS can be met, and the policy instruments to enable the expansion of the technology are in place, there are also social and environmental factors to consider (see also Sections 6 and 7). The social licence to operate (SLO) concept offers a useful framing for future deployment of BECCS. The concept can be broadly defined as informal permission given by the local community and broader society to pursue technical work [38]. A SLO can be manifested at multiple levels but is particularly relevant at a local level [39]; in the case of BECCS, this may also involve multiple locations (e.g. where the fuel is grown or where the CO_2 is captured or stored). In addition to technical and logistical challenges, delivering BECCS will depend on achieving and maintaining a SLO. Trust is key to maintaining a SLO, and this will be contingent on regulation along the BECCS supply chain and raises a number of key questions: How do you ensure the sustainability of the biomass source and the extent of any land-use change related emissions? To which nation are the negative emissions allocated? Which nation gets the benefit of reductions that occur across national boundaries? These questions are explored further in Section 7.

5. Can sufficient biomass be provided sustainably?

Many countries are increasingly relying on bioenergy to achieve renewable energy and greenhouse gas emission reduction mandates. The International Renewable Energy Agency [40] predicts that bioenergy could become the most important renewable energy by 2030 if renewable energy strategies of key countries were to be implemented in full, added to which, deployment of BECCS at scale will have significant implications for future biomass energy demands. Research by Smith *et al.* [41] showed that IAM scenarios [42] include global demand for sustainable biomass for BECCS ranging from 100 EJ/yr up to more than 300 EJ/yr of equivalent primary energy by 2050, representing at least a doubling of the IRENA 2030 forecast.

The availability of certain key categories of biomass resource will be integral to balancing the future demands of the bioenergy sector (with or without BECCS). Figure 1 shows ranges of sustainable biomass resource availability by 2030 and 2050. In order to achieve the higher levels of biomass resource potentially available, research is required to understand the specific types and extent that may be available within different geographies and the potential different alternative uses of those resources. National policies and strategies that aim to increase availability of indigenous resources will be needed [59,60] alongside opportunities for sourcing sustainable biomass from key regions around the world and developing global biomass trade markets [61]. The availability of biomass is unevenly distributed; some of the world regions with the greatest resource requirements have comparatively low resource availability. The global trade of biomass, therefore, has an important role to play, with developed countries increasingly importing biomass from less developed countries whose development remains largely reliant on fossil fuels [62].

With global trade and increasing production of biomass come more complex supply chains and barriers that may, directly or indirectly, restrict the production, processing or movement of resources [62]. Barriers may be technical (e.g. ensuring that the traded biomass or processed fuels meet the specifications of the destination bioenergy system or end market); logistical (e.g. developing favourable transport economics, negotiating global agreements to overcome country specific trade barriers); regulatory (e.g. determining both the types and extent that different resources may or may not be imported from a given country). However, potentially most important are geopolitical barriers; supplies from less developed regions may be vulnerable to political instability and limited investment in enabling-infrastructure but also raise issues around equity. Many of these barriers are applicable to all globally traded commodities and can, in principle, be overcome through developing enabling policies and international trade agreements.

Furthermore, bioenergy systems and supply chains have the potential for both wide-ranging positive and negative social, economic and environmental impacts. Sustainability issues are perhaps more acute for bioenergy compared to most other forms of renewable energy pathways, as, in many cases, feedstocks are directly linked to communities, farms, forests and ecosystems from which the resources are produced or extracted, all with significant civil society implications. Prominent bioenergy sustainability issues include: direct and indirect land-use change impacts; competition between land used for bioenergy and food, or for other land-based mitigation actions (reforestation and afforestation); interaction of bioenergy systems with food systems; implications to food prices, food security, land ownership and jobs; direct ecosystem and biodiversity impacts; impacts of biomass production on water systems; and air quality. The impact of biomass energy production on food prices is contentious and more complex than is often presented [63,64]; with a high proportion of bioenergy feedstocks coming from residues in IAM scenarios [32] the focus may shift from food versus fuel to food and fuel [65,66]. In sum, bioenergy production for BECCS has the potential for significant social and justice implications which could severely impede the deployment of BECCS at scale.

6. How does BECCS fit into the policy context?

Despite being a significant feature of mitigation scenarios for more than a decade, fossil CCS has failed to become an established technology; the extent to which BECCS requires successful prior deployment of fossil CCS infrastructure remains unclear. BECCS could be seen as a route out of a potential fossil fuel lock-in associated with CCS [67] and political emphasis on fossil

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CCS may shift towards BECCS. For BECCS to succeed where fossil CCS has so far failed depends on early demonstration of its potential to deliver negative emissions, a strong policy and regulatory environment to establish its deployment and international cooperation to deliver the Paris targets.

Existing policy will play a crucial role in BECCS deployment; European Union climate policy can usefully illustrate important issues that may arise. BECCS does not have a prominent place in EU policy. However, the EU has created a CCS policy framework (especially the 2009 CCS Directive) that is closely tied to the EU Emissions Trading System (EU ETS), which covers 45% of EU greenhouse gas emissions, including those from electricity generation. The ETS is meant to drive CCS deployment by creating a carbon price that makes CCS viable and by funding relevant R&D using revenues from auctioning ETS allowances. However, this strategy has faced significant challenges. From 2005 to 2015, the average ETS carbon price was approximately €11[ii], much lower than those that the existing literature suggests would make BECCS economically viable (e.g. a range of US $59–275 or €55–258) [68]. In fact, the EU's own energy projections have assumed progressively lower shares of CCS in 2030 due to low carbon prices, even while BECCS became increasingly crucial in Intergovernmental Panel on Climate Change (IPCC) scenarios [69–71]. Lower-than-expected carbon prices in emissions trading systems are not confined to the EU [72], suggesting these challenges could be widespread.

If BECCS is deployed at scale, its interactions with existing climate and energy policy will also be important. The EU's CCS Directive provides an incentive for CCS (CO_2 placed in geological storage does not require ETS allowances) but no incentive for BECCS. One recent report suggested that negative emissions from BECCS should be awarded allowances under the EU ETS [73]. However, to ensure that total emissions are reduced in line with the Paris Agreement, 'BECCS allowances' must be defined in such a way that they are distributed only for net negative emissions, rather than for all CO_2 stored. Furthermore, limits to total allowances on the market would be required to ensure that the carbon price remains high enough to incentivize mitigation.

Biomass sustainability regulations and certification frameworks are currently the chosen strategy for ensuring the sustainability, accounting and benchmarking the impact of different resources. These range from top down governmental bioenergy sustainability requirements [74,75] to highly focused schemes developed to benchmark and enhance the sustainability of specific biomass feedstocks (e.g. Forest Stewardship Council [76]; Roundtable on Sustainable Palm Oil [77]; bioenergy and biomass sustainability schemes and regulations are reviewed elsewhere [78,79]). A sustainable future with increased global trade of biomass will be reliant on the alignment of regulations and overall improvement in sustainability performance.

Moreover, international climate and environment agreements complement each other in the pathway towards a sustainable future. The Sustainable Development Goals (SDG) *per se* are highly interdependent. Despite that, assessments directed at limiting global warming to 2 °C do not consider the goals of international environmental agreements such as the Aichi Targets, the Bonn Challenge, the New York Declaration on Forests and the targets of SDG 15. For example, while the implementation of BECCS at scale is linked to an additional need for land, the Aichi Biodiversity Targets, adopted in 2010 by 196 parties of the Convention on Biological Diversity, sets targets for reducing loss of natural habitat, increasing the area covered by the protected areas network and promoting restoration of degraded ecosystems [80]. Such targets were not taken into account by the land-use scenarios used by IAMs [81]. Therefore, national governments face a challenge in implementing climate and environmental agreements simultaneously, as there isn't a global solution to sustainably balancing the use of resources (e.g. the land allocated for BECCS or other land-based mitigation and that used for other environmental purposes). In this context of combining climate change mitigation and biodiversity conservation, national or international mechanisms that incentivize the protection of forests by making habitat conservation financially attractive at the same time as mitigating climate change, such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation [82]), will have a critical role [83] alongside strategic land-use planning.

7. Distributional aspects and emissions accounting: how does BECCS fit with climate agreements?

With a variety of feedstocks of various origins that can be utilized for many different purposes, potentially originating from a non-energy sector (e.g. forestry, agriculture or waste management), the complexity of bioenergy also brings challenges to accounting frameworks. Currently, accounting and emission reporting systems and methodologies are often challenged in capturing the breadth of the bioenergy sector with its related uncertainties across temporal, spatial and sectoral interfaces. Introducing CCS will further complicate accreditation of negative emissions to sectors or nations, particularly across international supply chains, and designing effective monitoring, reporting and verification, and liability arrangements across the very long timescales (i.e. centuries) over which stored CO_2 must remain secure will be crucial.

In forest-based and perennial systems the timing of carbon sequestration and release plays an important role in cumulative carbon budgets [19,84–86]. CCS enables this timeframe to be manipulated, buying time by locking away the biogenic carbon. Nevertheless, to maintain a sufficient magnitude of carbon sequestration in future, forests and perennial crops need to be assessed not only on a plot but at landscape level, whereby harvesting is rotated around multiple plots at different stages in their growth cycles. This spatial landscape scale is also relevant for accounting the carbon balance of a forest since usually one stand is harvested while others continue to grow and sequester carbon [87,88].

Furthermore, biomass is typically produced as part of a wider agriculture and forestry system not established for energy purposes alone. Many forests are managed for traditional wood products (timber, pulp, panel products), while waste products (wood of marginal quality, sawmill and forest residues) are increasingly used for bioenergy generation. Even though dedicated energy crops are common, agricultural residues can also be used, integrating bioenergy activities into existing systems (e.g. by adding an energy crop into the existing rotation) [89] or using final products, such as digestate from anaerobic digestion and biochar, within the agricultural or forest system. In these cases, considering greenhouse gas emissions and carbon balances solely in relation to an energy system does not capture the breadth of the trade-offs and possible impacts.

From an accounting perspective, there is a question of who receives credit for the long-term carbon storage from CCS, since biomass producers are already accounted for the natural carbon sequestration and bioenergy users are currently not accounted for the release of this carbon. Many bioenergy supply chains are international with production in one region and energy conversion and CO_2 storage in other regions. While the IPCC provides methodologies and guidelines for accounting for these emissions nationally [42,90], this does not necessarily capture the breadth and complexity of BECCS systems to deliver global net negative emissions. Considering the life cycle of a full supply chain, rather than national inventories, can provide a clear picture of when, where and what type of greenhouse gases are released, as described in section 3.

The wider benefits and impacts of bioenergy must be taken into account but such complexity raises the question of how emissions and carbon balances should be allocated between the different products and services, as economic and social benefits can be significantly different under different metrics (e.g. economic revenues, job creation, ecosystem services and biodiversity, recreation, etc). The life cycle approach will allow the supply chain to be understood and captured but this must be considered on a case-specific basis, identifying drivers and motivations in order to understand and minimize emissions across other economic sectors and impacts across wider society.

8. Conclusions

The six key challenges presented here clearly identify the importance of a whole systems approach to the use of BECCS to deliver negative emissions. This holistic view is necessary to understand its desirability and effectiveness in the context of other mitigation approaches, accommodate existing policy drivers and goals, identify where it fits within the wider socioeconomic landscape, and ensure that genuine net negative emissions can be delivered on a global scale. While there are many complexities introduced by extensive cross-sectoral and cross-border supply chains, methods do exist to characterize the emissions and other implications of BECCS systems. The levels of BECCS described in scenarios consistent with Paris Agreement aspirations clearly present an immense challenge on many fronts, implying massive investment in infrastructure, and establishing robust regulatory and accounting frameworks. As research communities continue to unpack the potential and implications of BECCS and, given the emerging significance of the technology to our ability to mitigate against the worst consequences of climate change, it seems reasonable to investigate a variety of BECCS supply chains in order to understand whether these challenges can be met.

From a policy perspective, BECCS presents a dilemma in terms of how it should be prioritized relative to other mitigation options. In addition to the technical challenges it presents, its realization at scale would require major investment and innovative policy and regulatory processes. Given the challenge of implementing a low carbon energy system, does its attractiveness as a technical approach, and its fit within our current sociotechnical system, make global net negative emissions using BECCS more attractive than ambitious mitigation in sectors that present apparently harder social and political challenges? Given the constraints of the global carbon budget and our current emissions trajectory, negative emissions delivered by BECCS is potentially a keystone technology in future emission scenarios. Yet there clearly remains a suite of interconnected and critical challenges to translating the idealized, ordered, coherent world of integrated assessment models into reality.

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Notes

i To date analyses have focused primarily on the 2°C target. An Intergovernmental Panel on Climate Change (IPCC) special report on the 1.5°C target will be published in 2018. Hence, the quantitative context of the challenge is presented here in relation to 2°C, noting that the 1.5°C aspiration increases the scale and urgency of the challenge.

ii CO_2 equivalent is a metric that allows comparison of emissions from different greenhouse gases (CO_2, methane and nitrous oxide) based upon their global warming potential. For example, the global warming potential for methane over 100 years is 21; 1 Mt methane emissions is thus equivalent to 21 Mt CO_2 [91].

iii Own calculation based on data from Sandbag, C.E. Delft and the European Environment Agency.

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