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ScienceDirect

Energy Procedia 114 (2017) 6036 – 6043

Energy Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

The role of bio-energy with carbon capture and storage in meeting the climate mitigation challenge: A whole system perspective

Sarah Mander[a]*, Kevin Anderson[a,c], Alice Larkin[a], Clair Gough[a] Naomi Vaughan[b]

[a] *Tyndall Centre for Climate Change Research, University of Manchester, Manchester M13 4PL*
[b] *Tyndall Centre for Climate Change Research, The University of East Anglia, Norwich, NR4 7TJ*
[c] *Uppsala University,Uppsala, Sweden*

Abstract

This paper explores the role and implications of bio-energy with carbon capture and storage (BECCS) for addressing the climate change mitigation challenge. Framed within the context of the latest emissions budgets, and their associated uncertainty, we present a summary of the contribution of BECCS within the Integrated Assessment Model (IAM) scenarios used by the climate change community. Within this discussion we seek to shed light on two important areas. Firstly, that BECCS is a central, but often hidden element of many of the modelling work that underpins climate policy from the global to the national scale. The second area we address are the assumptions for BECCS embedded within IAM models, and the wider system consequences of these implied levels of deployment. In light of these challenges, we question whether BECCS can deliver what is anticipated of it within existing climate change policy.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: Bio energy with carbon capture and storage; carbon budgets; IAMs

* Corresponding author. Tel.: +44 161 3063259
E-mail address: s.mander@manchester.ac.uk

Peer-review under responsibility of the organizing committee of GHGT-13.
doi:10.1016/j.egypro.2017.03.1739

1. Introduction

The 21st Conference of the Parties in Paris in 2015 was an historic event. For the first time, nations globally agreed to address climate change by limiting global mean surface temperature increases to "well below 2°C" as well as to "pursue efforts to limit the temperature increase to 1.5°C". Those engaged in the climate change debate will be aware of the significance of avoiding a 2°C global temperature rise, and be familiar with its use as both a focused global commitment, as well as a political anchor point for the debate [1,2]. However, what is perhaps less commonly understood, is the significance of the associated framing of the Paris Agreement around "well below 2°C", or indeed how much more challenging, or arguably impossible, it will be to "limit the temperature increase to 1.5°C". This paper considers this challenge, with a focus on the role of bio-energy with carbon capture and storage (BECCS) in meeting it.

2. The challenge of a cumulative emissions framing

Whist the concept of a limited stock of CO_2 (the carbon budget) being linearly related to future temperature changes (within certain bounds) is relatively simple, it is harder to gain a clear understanding of the carbon budget constraints given the different frameworks that may be applied. For instance, the budget for keeping the global mean temperature rise to below 2°C in the long-term is different from one associated with passing through that temperature goal en route to a higher temperature [3]. Assumptions regarding the emissions of non-CO_2 greenhouse gases also complicate matters, and there remain long-standing uncertainties surrounding how the global climate will respond to future emissions and resulting changes in the atmospheric CO_2 concentration [4]. Finally, the societal hoice surrounding the probability of exceeding a particular temperature threshold alters any chosen budget. For instance, having a high probability (>66%) of staying below a 2°C temperature rise relates to a much smaller carbon budget over the century, than choosing a lower chance (<33%) of staying below the 2°C threshold. These concerns, the Paris commitments on 2°C and 1.5°C and the carbon budgets enshrined in the most recent IPCC report [5] offer a clear route for generating quantitative energy-system pathways commensurate with the Paris Agreement.

2.1. Converting Paris 2°C and 1.5°C commitments into carbon budgets

In relation to the international community's temperature commitments, the language of the Paris Agreement is very clear; to stay "well below 2°C" – and importantly to "pursue efforts to limit the temperature increase to 1.5°C". Using the IPCC's guidance notes to the authors of their latest report [6], this qualitative framework commitment can be translated into quantitative probabilities – and therefore into carbon budgets. This sequential development of the Paris Agreement leads to a carbon budget, based on the IPCC's Synthesis report, of somewhere between 850 and 1000 $GtCO_2$ for the period 2011-2100. The lower end of this range equates to an "unlikely" chance of staying below 1.5°C (i.e. a probability of 0 to 33% of <1.5°C) with the upper end relating to a "likely" chance of staying below 2°C (i.e. a probability of 66-100% of <2°C).

2.2. Estimating the global energy-only CO2 budget for 2016-2100

The 850 to 1000 $GtCO_2$ range is for all carbon dioxide emissions from all sectors for the period 2011 to 2100. Therefore, in order to understand what emissions are available from 2016, it is necessary to remove from the budget those emissions known to have been released between 2011 and 2016. Based on CDIAC data, extrapolated out to include 2015, at least 150$GtCO_2$ have been emitted since 2011; leaving a range of 700 to 850$GtCO_2$ for the period 2016 to 2100.

Given this analysis relates specifically to the energy sector, it is necessary to remove projected deforestation and industrial process emissions (primarily cement) for the period 2016 to 2100. Based on research published in Nature Geoscience [7], an optimistic interpretation of deforestation and cement process emissions for 2016 to 2100 are, respectively, in the region of 60$GtCO_2$ and 150$GtCO_2$. Both of these figures are dependent on efforts to reduce emissions broadly in line with that required across the energy sector.

Combining recent emissions with those from deforestation and cement (process only) leaves an energy-only global CO_2 budget for 2016 to 2100 of 490 to 640GtCO_2 (i.e. in the region of 500 to 650GtCO_2).

2.3. What would this mean for mitigation in lower income (non-Annex 1) and higher income (Annex 1) nations

This is undoubtedly an area where different interpretations of fairness and equity can give potentially very different results in terms of national carbon budgets. However, the Paris Agreement specifically acknowledges that the peak in emissions from the industrialising and lower income nations will be later than that within higher income nations.

Assuming an aggregate peak in the industrialising nations' emissions by 2025, followed by a programme of rapidly ramping up mitigation rates to deliver around 10% p.a. by 2035, then the total emissions for 2016 -2100 would be in the region of 550 to 600GtCO_2. Put simply, a mitigation agenda across the industrialising nations at a level of ambition far beyond anything discussed in Paris would nevertheless leave, at best, only 50 to 100GtCO_2 for the wealthier industrialised nations for 2016 to 2100. This equates to an aggregate mitigation rate for these wealthier nations of between 13% and over 20% pa starting today.

3. BECCS within Climate Change Assessments

Working Group 3 (WG3) of the IPCC (AR5) describe four Representative Concentration Pathways (RCPs). These have been developed to represent the wide range of emission scenarios from different sources published across the literature; the RCPs are presented as cumulative greenhouse gas (GHG) concentrations over time (1850-2100) and are associated with different levels of radiative forcing. The RCPs provide a consistent set of pathways for subsequent analysis in different areas of climate change research – for example by climate modellers to analyse potential climate impacts associated with the pathways (including projected global average temperature rise) and in Integrated Assessment Models (IAMs) to explore alternative mitigation scenarios consistent with achieving the concentration pathways [8,9].

3.1. The dependence on BECCS for 2^{o}C

There is a growing and significant dependence on biomass energy with carbon capture and storage (BECCS) in future emission scenarios that do not exceed 2°C warming. In the IPCC AR5, over a hundred of the 116 scenarios associated with concentrations between 430–480 ppm CO_2 rely on BECCS to deliver global net negative emissions [10]. This represents a median value of around 616GtCO_2 cumulatively removed by 2100 using BECCS [11]. In order to achieve 430-480ppm CO_2 without BECCS, required a peak in emissions in 2010 [11], which clearly has not occurred.

In the context of contracting carbon budgets, discussed in section 2, and the rate and scale of mitigation required to remain within these budgets, the ability to remove carbon dioxide from the atmosphere and store it for extensive periods of time (beyond 1000 years) potentially enables the overspend of a carbon budget. There are a number of methods of carbon dioxide removal (CDR) but the scalability of BECCS, along with its energy conversion co-benefits means that it is the method of CDR that dominates IAMs scenarios. Afforestation is also included in some but, as a CDR method, it has limited scalability and is more vulnerable to unintended carbon loss through disease, pests and fire as well as potential impacts of future climate change [12].

3.2. The role of BECCS within IAMs

The RCP pathways are grouped according to the estimated radiative forcing due to GHG emissions in 2100. There are two stabilisation pathways, RCP 6 (~850 ppm CO2eq) and RCP4.5 (~650 ppm CO_2eq), a high pathway, RCP 8.5 (~1370 ppm CO_2eq) and a low pathway RCP 2.6 (~450 ppm CO_2eq by 2100). This latter pathway, RCP2.6, includes an 'overshoot' whereby concentrations reach a peak of 490 ppm CO_2eq before declining by 2100; this profile, which peaks and declines, is achieved by including a negative emission component based on deploying BECCS (Figure 1) and, to a lesser extent, afforestation [13, 14] .

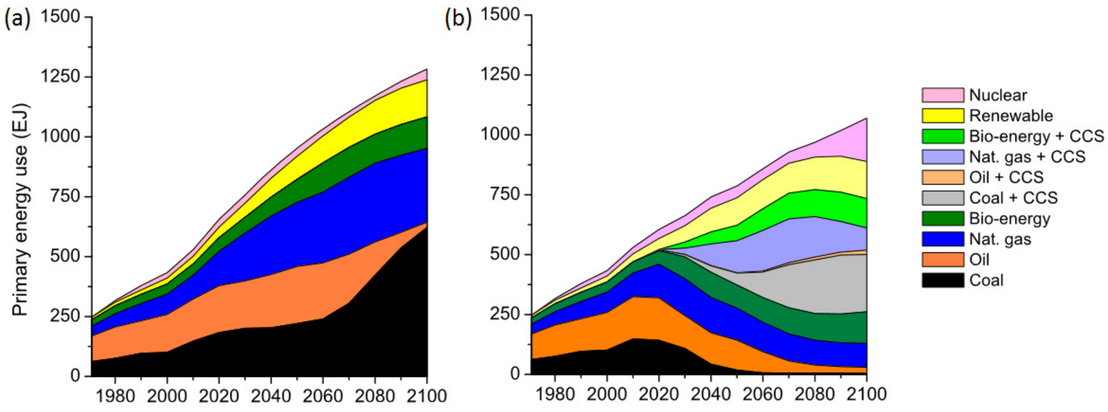

Fig. 1. Trends in global energy use for (a) baseline and (b) RCP2.6 scenario

The option to overspend a carbon budget whilst generating energy makes BECCS attractive as a means of delaying and thereby discounting mitigation costs. It enables more ambitious targets to become feasible than would otherwise be possible, or, by 'buying time' it allows a delay in the year in which emissions peak and facilitates a medium-term and temporary overshoot of concentration targets [15,16,17,18, 19]. Furthermore, in the abstract world of a model, which makes assumptions about the real-world challenges of implementation and where the model is constrained to achieve a particular target, the negative emissions offered by BECCS can support whole system decarbonisation, allowing for higher emissions in sectors that are harder to decarbonise. Taking aviation as an example, there exist few technical options for decarbonisation in the short to medium term. Longer term options, such as hydrogen, are far from commercialization and require both technical innovation and large-scale deployment of capitally-intensive infrastructure. At a global scale, there is continued growth in passenger kilometres, particularly within developing economies, and demand management remains unpopular with travellers and is challenged by the industry. Balanced against these challenges, BECCS offers a theoretically appealing approach for compensating for the continued use of oil within transport sectors such as aviation. Despite this, BECCS should not be seen as a substitute for direct mitigation measures – analysis by Kriegler et al. [20] suggests that its key potential lies in discounting costs associated with balancing emissions from sectors that are technically difficult to abate.

Over 1000 emission scenarios fed into the process through which the RCPs were developed (Fifth Assessment Report of the IPCC (WG3)), including emission pathways likely to exceed 1000 ppm CO_2eq and, consequently, climate warming up to 5°C and beyond. In an analysis of these pathways, Fuss et al. [10] found that in the region of half of all the scenarios include a significant contribution from BECCS. Furthermore, a large majority of the pathways which deliver atmospheric CO2 concentrations consistent with the 2°C target (and indeed many of those associated with temperature increases up to 3°C) assume global net negative emissions by about 2070 [10]. Global net negative emissions are achieved when the negative emissions associated with BECCS are greater than total emissions from all other sources (i.e. anthropogenic and non-anthropogenic) [10]. Ultimately, the large scale deployment of BECCS within the models is central to their interpretation of feasible pathways for not exceeding the Paris "well below 2°C" commitment.

4. The assumptions underpinning BECCS within IAMs

In this section we identify the key assumptions that could be critical in modelling the contribution of BECCS to achieving climate change mitigation targets (Table 1). Some assumptions are explicit and clearly well described in published papers, whilst others are implicit – either not published or tacitly made in constructing the models. The IAMs used to create scenarios variously include both different representations of the global energy system and different levels of detail; as such they make different assumptions about the scale, efficacy and timing of BECCS. Certain assumptions are easy to identify whilst others can be hard to decipher, especially as the models evolve over time. In Table 1 [21] we describe explicit and implicit key assumptions, noting that many of these assumptions are strongly interdependent.

Table 1. BECCS assumptions within IAMs

Assumptions	Details
Future climate change	The earth system response to future climate change, and the impact on the carbon cycle, is implicitly assumed in the cumulative emission budgets used in the IAM.
Bioenergy potential	
Agricultural efficiency gains	Assumed trends in agricultural efficiency gains impact the amount of available land as well as future bioenergy crop yields.
Land area requirement for BECCS	For models that explicitly represent land use, the land area available for energy crops is critical. IAMs without this make an implicit assumption given by total bioenergy potential. Most scenarios assume abandoned agricultural land for dedicated bioenergy crops, to avoid conflict with food production, biodiversity and land use change carbon emissions.
Crop yields	Most scenarios focus on dedicated lignocellulosic crops and assume productivity levels in keeping with abandoned agricultural land (i.e. associated with lower yields than agricultural land). Scenarios have differing fertiliser and irrigation assumptions: most assume rain-fed land. Improvements are achieved through use of irrigation and/or fertiliser use, with an associated trade-off with N_2O emissions and embedded carbon, and technological developments.
Residue availability	Many scenarios include residues as well as dedicated lignocellulosic crops. Residue availability is dependent upon the types and levels of socio-economic activity.
Infrastructure	Some negative emissions can be achieved through co-firing, but most IAMs assume purpose built biomass energy generation plants; assumptions are thus made concerning the existence of transport infrastructure for biomass (although these are not extensively characterised) as well as purpose built biomass energy generation plants.
CCS capability	
Maximum annual rate of CO_2 stored	This refers to the quantity of CO_2 stored annually in geological formations. To equate to CO_2 removal, or project level negative emissions, this assumes that CO_2 is captured only from dedicated biomass plant.
CCS infrastructure	A strong implicit assumption is that CCS infrastructure is established and available to capture, transport and store CO_2. CCS technology is currently entering the demonstration phase, with very limited experience of dedicated BECCS systems.
CO_2 storage capacity	Total storage capacity in suitable reservoirs. Estimates of technical potential capacity in appropriate geological formations cover a very large range; IAMs typically incorporate an assumption of how much of this will be suitable for secure storage. While storage potential in hydrocarbon fields are relatively well-quantified, the size of the potential for large scale, long term storage in saline aquifers remains uncertain, with large variability in estimates of available regional capacity.
BECCS	
BECCS as a % of primary energy	IAMs in WG3 cluster around 20-30% of total primary energy from BECCS, although there are extreme outliers well beyond this.
Cost of BECCS per t CO_2 stored	As IAMs typically optimise on discounted cost, the relative costs of different mitigation options is an important driver. Assumptions lie in the range of 60 to 250 US$/t CO_2 (IPCC, 2014). The role and level of discounting is central to the conclusions of the IAMs
Policy support	Sufficient and effective policy and governance frameworks and incentives are a prerequisite to developing and establishing BECCS technology.
Net negative emissions	Assumed net negative emissions across the full life cycle of the BECCS system; includes large

	uncertainties in bioenergy production, e.g. direct and indirect land use change, fertiliser use and water availability.
Political and socio-economic	
Population, lifestyle, diets	This is a key set of assumptions that feed into the agricultural assumptions that underpin estimates of bioenergy potential as well as of global energy demand.
Sustainable land use	IAMs that strive for sustainable bioenergy, include assumptions about land areas that are not available for bioenergy such as primary forest and food production.
Social acceptability	Most IAMs do not consider social acceptability, indigenous land rights, etc., although some allowance is potentially captured through scaling down of technical potential. This is relevant across the entire BECCS supply chain.
Global participation	Most scenarios assume global participation in emission reductions.
Carbon price (or equivalent)	IAMs assume that an effective (global) carbon pricing mechanism exists.
Global governance system	A BECCS supply chain will incorporate a diverse mix of nations, regions, technologies and actors which will require a coordinated regulatory framework in order to deliver verify and account for negative emissions. IAMs typically are premised on perfect foresight

5. System implications

When we move beyond the abstracted world of models, and begin to consider the practical deployment of BEECS, the sheer complexity of the task required to achieve the emission pathways outlined in figure 1 soon becomes apparent. What is immediately striking is that the deployment of negative emissions at scale and on which the remaining IAM carbon budget is reliant, is typically very early, with some IAMs assuming BECCS as early as 2020 to 2025. Broadly speaking, this will require integration of the three distinct element of the BECCS chain: (1) a biomass supply chain (production, processing and transport); (2) energy generation; and (3) a CCS facility and infrastructure (capture, transport, and CO_2 storage). Table 1 illustrates the challenges, from an infrastructure, policy and global governance perspective that need to be overcome if sustainable biomass supply chains are to be established and an extensive CO_2 transport and storage infrastructure developed. It is useful to reflect as well on the inherent uncertainty within these assumptions [22]. While the emission pathways derived from IAMs rely, in part, on regionally disaggregated data, they nevertheless reflect a more global and top-down framing of mitigation. That said the assumptions made within more bottom-up studies [23] are equally open to examination. In the IEA report on the 'Potential for Biomass with Carbon Capture and Storage' [23], the technically feasible potential for BECCS is estimated at 10GtCO2 p.a. (and 47 EJ of primary energy from biomass) by 2050 for a dedicated biomass and CCS route with biomass integrated gasification combined cycle (BIGCC) and circulating fluidized bed technology (CFB). The economic potential however, is assumed to be much less at 3.5 $GtCO_2$ in 2050 (20 EJ of primary energy from biomass) for gasification routes. These figures are based on IEA estimates of deployment rates of CO_2 transport infrastructure and known storage reservoirs as well as projections of the sustainable supply of biomass. Contrasting the IEA projections of BECCS with those not untypical in the IAMs demonstrates how sensitive emission pathways are to assumptions of uptake of this currently highly speculative technology. The primary energy from BECCS under the RCP 2.6 pathway in Figure 1, suggests in the region of 70 EJ are required by 2050, higher than even the technical potential from the IEA study.

There are a variety of options for combining biomass energy with CCS, of which, as already highlighted, dedicated biomass electricity generation offers the greatest potential for delivering negative emissions [23]. Routes to dedicated 100% biomass electricity generation are offered via combustion in fluidized beds, gasification and biomass chemical looping. Of these and at relatively small scale (up to 100MW), biomass combustion (CFB) is already commercial. Gasification of either coal with biomass, or dedicated biomass is at a smaller scale and less commercially proven. Biomass based chemical looping remains a longer term technology. In the context of BECCS applied to power generation, systems may be either co-fired (with conventional fossil fuels) or dedicated biomass; however, to achieve net negative emissions, co-firing applications above 20%-30% are required [23], which require technical challenges to be overcome.

Taking the requirement of 70EJ p.a. of dedicated BECCS by 2050 and comparing this with the capacity of world's largest non-nuclear thermal power station (5.6GW) illustrates starkly the scale of deployment assumed. By 2050 there would need to be at least 500 fully-BECCS power stations of a size equivalent to the largest thermal plant currently in operation on the planet. Given the fledgling biomass and CCS industry, there is no prospect of a significant roll out of such large biomass plants before 2025 at the very earliest. Even under such unprecedented optimism, there would still need to be one BECCS power station (the size of the largest conventional thermal plant today) constructed and commissioned every eighteen days and for twenty five years in order to deliver the 70EJ of BECCS by 2050. Given that most large modern thermal power stations typically have a capacity of 1 to 2 GW, and again assuming a high annual load factor, a more realistic, but still highly ambitious, capacity for biomass plants would suggest construction and commissioning up to two large BECCS plants each week for a quarter of a century.

Whichever way it is played out, the assumption of BECCS roll out certainly needs much greater scrutiny – particularly when set against the backdrop of the Marshall-style construction programme that RCP2.6 assumes across the complete energy system. For example, the non-biomass CCS uptake outlined in Figure 1 is over twice that assumed for BECCS – so perhaps a coal or gas CCS plant coming online every day or two for twenty five years – alongside two per week BECCS plants. Clearly this pace of deployment has to be considered in light of the recent push back in financial support from some governments such as the UK and in the US.

Whilst the availability of safe and secure CO_2 storage capacity is independent of the source of the CO_2, to date much discussion of relate to total potential storage within a fossil CCS discourse within which CCS is a bridging approach towards a long term goal of decarbonisation and the move away from fossil fuels. Gough and Vaughan [22] describe how BECCS is not typically framed in such time-limited terms and the total usable storage capacity becomes important in terms of how long a significant reliance on BECCS can be sustained, with the potential for BECCS limited by the rate at which storage can be exploited.

Whilst acknowledging that BECCS is not a blue skies mitigation option, it has to be recognised that it is in the early or conceptual stages of development. It is also clear that in order to address the climate mitigation challenge a wholesale and rapid transition to a new, low carbon energy system is required. This begs the question of whether BECCS can deliver what is anticipated of it within existing climate change policy, and indeed the desirability of the potential environmental and social costs associated with BECCS.

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