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Biomass and carbon dioxide capture and storage: A review

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ABSTRACT

This paper provides an overview of biomass with carbon capture and storage (Bio-CCS or BECCS) at the systems level. It summarises the relevant information from the recent 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), describes the progress made since earlier reports and considers additional results recently published in literature. The focus is hereby not on the technical challenges but rather on the surrounding sustainability issues.

Bio-CCS shows significant potential to achieve net CO_2 removal from the atmosphere at a cost that is comparable to conventional CCS technologies. However, uncertainties remain due to the little experience with large-scale Bio-CCS demonstration plants, gaps in climate policies and accounting frameworks, missing financial instruments, unclear public acceptance and complex sustainability issues. A major conclusion is that the deployment of Bio-CCS cannot take place in isolation, thus will require an approach addressing the inextricable links within the food-water-energy-climate nexus.

1. Introduction

The 5th Assessment Report (AR5) of Working Group III (WGIII) of the Intergovernmental Panel on Climate Change (IPCC) emphasises that large-scale changes in global and national energy systems during the coming decades will be essential to reduce atmospheric CO_2 levels (IPCC, 2014a). In this context, deep-reduction scenarios, i.e. those achieving below 450 ppm by 2100, will require far-reaching improvements in energy efficiency as well as an extensive rollout of zero- or low-carbon energy supply by 2050 (Clarke et al., 2014). Options for achieving timely decarbonisation of the energy sector are the deployment of renewable energy (RE), nuclear power, carbon capture and storage from fossil energy (Fossil-CCS) and negative emissions technologies (NETs), also referred to as carbon dioxide removal (CDR). AR5 contains a large set of new scenarios compared to the 4th Assessment Report (AR4) in 2007 (IPCC, 2007).

Carbon capture and storage (CCS) describes a process that separates a relatively pure stream of CO_2 from industrial or power plants and, after conditioning and compression, stores it in suitable geological formations (IPCC, 2014b). The term mostly refers to application of the process to fossil energy, i.e. coal- or gas-fired power plants.

NETs and CDR are means to remove CO_2 from the atmosphere by either increasing natural carbon sinks or using chemical engineering. NETs/CDR lead to a net removal of CO_2 from the atmosphere, whereas Fossil-CCS generally only decreases the rate at which CO_2 is added, at best to nearly zero. It is possible to use the terms NET and CDR interchangeably (McGlashan et al., 2012a; McLaren, 2012; Tavoni et al., 2012). For reasons of consistency, this paper will only use the term NET. AR5 notes that some NETs fall under the category of geoengineering depending on their magnitude, scale and impact. In addition, the differentiation between NETs and mitigation is not clear at all times due to partially overlapping definitions. Examples for NETs are iron fertilization, large-scale afforestation, direct air capture (and sequestration) (DAC(S)), and biomass in combination with CCS (Bio-CCS or BECCS).

Throughout the literature, the terminology and definition of Bio-CCS is not fully consistent. The IPCC's Special Report on Carbon Dioxide Capture and Storage (SRCCS) in 2005 merely described "biomass-based CCS" as "CCS in which the feedstock is biomass" (IPCC, 2005).

The Bio-CCS Joint Taskforce (JTF), brought into life by the European Biofuels Technology Platform (EBTP) and the Zero Emissions Platform (ZEP), defines Bio-CCS as (ZEP and EBTP, 2012):

> "[...] processes in which CO_2 originating from biomass is captured and stored. These can be energy production processes or any other industrial processes with CO_2-rich process streams originating from biomass feedstocks. The CO_2 is separated from these processes with technologies generally associated with CCS for fossil fuels. Biomass binds carbon from the atmosphere as it grows; but with the conversion of the biomass, this carbon is again released as CO_2. If, instead, it is captured, transported to a storage site and permanently stored deep

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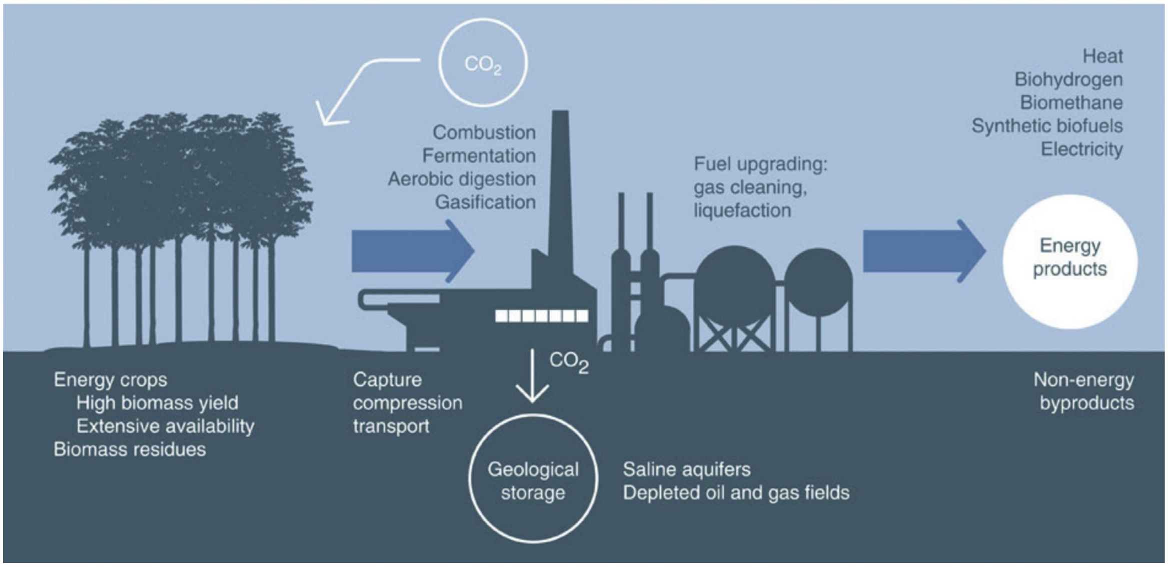

Fig. 1. Concept of Bio-CCS (Sanchez et al., 2015, courtesy of Nature).

underground, this would result in a net removal of CO_2 from the atmosphere."

Fig. 1 illustrates this concept.

A working paper by the Tyndall Centre refers to BECCS and Bio-CCS as alternative terms for the coupling of bioenergy with CCS (Gough and Upham, 2010). The authors use the term BECCS to refer exclusively to the process of biomass combustion for energy and subsequent capture and geological storage of the related CO_2 emissions. They further note that Bio-CCS has generally a wider context of biological sequestration, including the use of CO_2 as a feedstock to produce algal biomass for subsequent conversion to plastics, transport fuels, animal feed or other chemical feedstocks.

AR5 uses BECCS and defines it in a broader sense as the application of CCS technology to bioenergy conversion processes (IPCC, 2014b). In the literature, both Bio-CCS and BECCS appear more or less interchangeably. This paper will use the broader definition of Bio-CCS, which is inclusive of BECCS technologies if defined as related to combustion only. Nevertheless, a review of more exotic options such as algal Bio-CCS will not be part of this paper.

The direct CO_2 emissions from biogenic feedstock combustion broadly correspond to the amount of atmospheric CO_2 sequestered through the growth cycle of bioenergy production. As a consequence, Bio-CCS will generally result in net negative emissions, whereas Fossil-CCS usually results in near-zero emissions at best (IEA, 2011; IEAGHG, 2011). However, the extent of negative emissions will ultimately depend on the total lifecycle emissions, which include emissions from the biomass supply chain, energy penalties, etc. Fig. 2 shows the net carbon balance for different energy conversion systems in comparison.

AR5 highlights Bio-CCS as one of the few technologies that is able to remove historic CO_2 emissions from the atmosphere. Most scenarios leading to 450 ppm or below by 2100 cannot achieve this reduction when they exclude or limit the deployment of Bio-CCS (Azar et al., 2006; van Vliet et al., 2009a; Krey et al., 2014; Kriegler et al., 2014). In this regard, Bio-CCS also provides a valuable temporary flexibility within the mitigation scenarios, allowing for less mitigation in the near term but therefore requiring more profound emission reductions later in the century; a concept known as "overshoot" (Bruckner et al., 2014). However, any overshoot scenario would pose a higher risk of crossing climate tipping points and exceeding envisaged concentration targets. Measures allowing for overshoot, such as Bio-CCS and afforestation, can also help to tackle emissions in sectors where reductions are harder to achieve due to economic, political or technical constraints (e.g. aviation, shipping, iron and steel making, etc.).

Bio-CCS offers the advantage for application to a wide range of technologies with varying amounts of CO_2 emissions, e.g. dedicated or co-firing of biomass in power plants, combined heat and power plants (CHPs), pulp and paper mills, lime kilns, ethanol plants, biogas refineries and biomass gasification plants (Karlsson et al., 2014). Besides, AR5 points out the importance of a timely decarbonisation of both the electricity and transport sector, with efforts in the latter progressing usually at a much lower pace. Electrification of transport is a very promising means of achieving emission reductions in this sector, even more so if the electricity is already largely decarbonised. In many of AR5's deep-cut scenarios, indirect emissions from electricity are largely eliminated by 2050, and the electricity sector even becomes a sink for CO_2 through the use of Bio-CCS (Clarke et al., 2014). Besides, there might be additional options for the supply of energy carriers and intermediate energy storage from bioenergy applications in combination with renewables when considering CO_2 utilisation rather than long-term geological storage, e.g. in power-to-gas (PtG) or power-to-liquids (PtL) applications. These technologies do not produce negative emissions, i.e. CO_2 reductions on the large scale, but can be an interesting option to help decarbonise the transport sector and stabilise electricity scenarios with high RE shares. A recent assessment of PtG/PtL's role in the German energy transition (Energiewende) by Varone and Ferrari (2015) finds that their total CO_2 demand could be between 36 and 147 $MtCO_2$/yr. However, as the authors themselves note, the scenario and assumptions underlying the higher number might be too optimistic to be entirely feasible. The scenarios also assume complete phase-out of fossil fuels until 2050, which would leave biogenic and atmospheric CO_2 as the main sources for synthetic fuels.

As Bio-CCS might play a critical role in mitigation, it will be essential to address the broader issues related to both CCS and bioenergy. CCS technologies and their specific challenges have been discussed quite extensively in the literature (see e.g. Gibbins and Chalmers (2008); Pires et al. (2011); Nykvist (2013); Boot-Handford et al. (2014); Leung et al. (2014) for recent reviews), thus will not be a focal point in this paper. Concerning bioenergy, sustainability of feedstocks and overall efficiency of bioenergy conversion systems