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Environmental assessment of biomass gasification combined heat and power plants with absorptive and adsorptive carbon capture units in Norway

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ABSTRACT

Negative emissions through carbon capture processes integrated with bioenergy plants are frequently seen as an important option to stabilise climate at low temperature levels for reaching the two degree target in a cost effective way. Climate neutrality of biogenic CO_2 emissions is commonly assumed while assessing credits for these systems however this simplification may cause an overestimation of climate benefits for long rotation period woody biomass fuelled plants (time gap between emitted and sequestrated CO_2). Carbon capture processes and associated increase of material and energy demand can lead to environmental trade-offs due to higher values for other mid-point impacts while reducing climate change potential.

In this work, a comparative life cycle assessment study is undertaken. Three configurations have been analysed: i) a combined heat and power (CHP 10 MW_{th} input gasification plant (BGP); ii) BGP with pre-combustion adsorptive carbon capture unit (ADS); and iii) BGP with post combustion absorptive carbon capture unit (ABS).

For both configurations in which CCS processes are incorporated, negative values for climate change potential are reported. A decrease of 144.7% is observed for ADS and a decrease of 195% is estimated for ABS, when employing specially modelled characterisation factors that take into account the temporal asymmetry between CO_2 emission and removal fluxes. For most of the other environmental performance indicators analysed in this work, higher life cycle values have been quantified for the plants with installed CCS processes despite lower on site emissions for some stressors due to co-capture by the separation agents (H_2S, SO_x and PM for ADS). For the plant with post combustion solvent based unit, larger absolute (per kWh_e basis) and specific (per kg of captured CO_2) increases have been estimated thus exhibiting a worse environmental performance than the CHP plant with pre-combustion adsorption CO_2 capture technology.

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1. Introduction

Climate change is regarded as a major global challenge (IPCC, 2007) that has motivated the international community to implement mitigation strategies aiming at limiting the average increase of global temperature (Luderer et al., 2013). A reduction in global emissions of CO_2 can slow down the rate of warming, but a stabilisation of global temperature can only occur if CO_2 emissions approach zero (IPCC, 2013). Energy industries have contributed to approximately 32% of global CO_2 emissions over the last 20 years (Janssens-Maenhout et al., 2012). The decarbonisation of the economy requires a massive transformation of this sector; this involves an increase of renewable shares in the energy mix, improvements in power plant efficiency and the incorporation of carbon capture and storage (CCS) processes. The incorporation of carbon capture units in large scale power plants has been extensively analysed. Studies undertaken by IPCC (2005) and IEA (2007a) highlight the need of developing CCS also for medium scale combustion plants (1–100 MW_{th} input) in order to meet the emission reduction targets required to avoid harmful climate change. However, it must be underlined that CO_2 transport for such small capacities seem not to be very realistic at this stage of the technology development.

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Most of the biomass energy fuelled plants in Europe are small heat and CHP plants (BASIS, 2015). One to ten MW thermal input capacity CHP plants contribute to approx. 11% of electricity generation and 15% of heat production in the EU (CODE 2, 2015). It is forecasted that 20% of power production within the EU will take place in CHPs by 2030 (CODE 2, 2015). Approx. 16% of CHP plants in the EU use renewable fuels, mainly biogenic fuel stocks including woody biomass, biofuels and waste (CODE 2, 2015). Biomass CHPs play a key role in the Finnish and Swedish energy matrix supplying 16% and 50% of the power and heat demand. Norway, which generates the vast majority of its electricity from hydropower, has also created ambitious goals to develop CHP plants using biomass due to its abundant forest resources (NME, 2007).

Biomass can be processed in combustion or gasification plants, the latest ones exhibit higher electrical efficiency (IEA, 2007b). In gasification plants, woody biomass is converted into syngas which is then used as fuel in a gas engine or in gas turbine. Different gasification technologies are available in the market, differing on operating pressure, syngas cleaning system, heat provision to the gasification process and N_2 content of the produced syngas. FCIFB (Fast Internally Circulating Fluidized Bed) gasifier enable a N_2 free syngas using steam as gasification agent at atmospheric pressure and indirect heating (Hobfauer et al., 1997). For plants in the range of 1–5 MW_e, gas engines seem to be the most widespread technology based on surveys presenting information for currently operating plants (CODE 2, 2015; IEA, 2007a; Obernberger and Thek, 2008; OPET, 2004). The implementation of CCS technologies in biogenic fuelled CHP could potentially generate net negative CO_2 emissions (Azar et al., 2010; Fisher et al., 2007; GEA, 2012; Haro et al., 2013) and several emission scenarios consider that BioCCS is required to meet the two degree climate stabilisation targets (IPCC, 2013).

Absorption gas separation using chemical solvents e.g. MEA (mono-ethanol amine) as separation agent is the most widely employed carbon capture technology however its high energy consumption has motivated the investigation of other gas separation processes that can meet the same carbon capture targets but with lower energy penalty (IPCC, 2005; Kuramochi et al., 2012; Markewitz et al., 2012). Physically driven gas separation like Pressure vacuum swing adsorption (PVSA) cycles or membranes could become a more economical alternative for solvent based processes (Merkel et al., 2010; Webley, 2014). Lab scale studies undertaken for PVSA cycles show promising results for the energy consumption associated with CO_2 capture units (Liu et al., 2011; Shen et al., 2012; Xiao et al., 2009; Wang et al., 2012) promoting further research to scale up the technology.

Existing techno-economic studies for biomass gasification plants with installed CO_2 separation units have mainly focused on syngas upgrading for biofuel production (Haro et al., 2013; Heyne and Harvey, 2014; Ng et al., 2013). Fewer works can be found assessing the incorporation of carbon capture units in biomass gasification plants for heat or power production mainly for pre-combustion solvent based technologies (Carpentieri et al., 2005; Corti and Lombardi, 2004; Larson et al., 2005; Meerman et al., 2013; Rhodes and Keith, 2005). Recently Oreggioni et al. (2015) compared the performance of PVSA cycles in the role of pre-combustion technology against a conventional MEA (post combustion) in an atmospheric indirect heating biomass gasification plant.

Several authors Carpentieri et al. (2005), Corti and Lombardi (2004), NETL (2012a,b), and Schakel et al. (2014) have previously undertaken life cycle assessment (LCA) studies aiming to quantify the environmental impacts for BioCSS plants. Schakel et al. (2014) compared the environmental impacts of different levels of biomass co-firing in combustion and integrated gasification combined cycle (IGCC) plants with post and pre-combustion carbon capture units. Carpentieri et al. (2005) and Corti and Lombardi (2004) assessed biomass IGCC plants with MDEA (Methyl diethanolamine) pre-combustion carbon capture while NETL (2012a,b) quantified the impacts for a biomass co-fired power stations with MEA based post combustion CCS processes. In all these works, climate neutrality of biogenic CO_2 emissions has been assumed.

In this work, a process based LCA study has been carried out for three bio-energy plants: a two-zone 10 MW_{input} (approx. 2.8 MW_e output) FICFB (Fast Internally Circulating Fluidised Bed) gasification CHP with and without CCS using either pre-combustion adsorptive (ADS) or post combustion absorptive (ABS) units. The plants are assumed to be located in Norway (Rogaland county) where regionally sourced spruce wood chips are utilised as fuel. The paper consists of 5 sections including this *introduction*. The *method* section provides key technical specifications and inventory assumptions for each bioenergy system. The *results* section presents the life cycle values for the stressors and impacts under study in this work. The *discussion* section provides a critical analysis of method and data used in the study and the *conclusion* section highlights the main findings of this study, their relevance and possible application when analysing and promoting bio-energy systems.

2. Method

Fig. 1a displays the value chains analysed in this work. The different processes that are part of the value chains have been combined in six interconnected system areas taking into account subsequence, location and similarities. Under the denomination of biomass production, processes related to seedling production, planting and transport, pre-commercial thinning, tree harvesting, sawing, round wood loading and forwarding to the closest road are analysed. Biomass transport includes the round wood transport to the chipper plant as well as chip transport to the energy conversion plant. The chipping and the energy conversion plant are modelled as two independent system areas alike the unit operations associated with the disposal of bottom and fly ash formed during the gasification process that are grouped in the system area called ash disposal. Each carbon capture unit is considered itself a system area meanwhile downstream processes related to CO_2 compression, transport and injection are combined in a separate system area. Further details regarding the techno-sphere for each system area and related emission factors can be found in SI 1 of Supplementary information.

2.1. *Life cycle inventory (LCI) modelling*

2.1.1. *Biomass supply chain*

Norway spruce wood chips sourced from forest stands with 75% above ground forest residue extraction are assumed as the fuel source for each energy generation system. Stressors and indicators for seedling and fertiliser production and transport, seedling planting, pre-commercial thinning, round wood sawing, loading and forwarding to the closest road to the forest are quantified and aggregated in the system area called biomass production. Fertiliser requirements are based on the information provided by Ecoinvent 2.2 (2010) and the amount of seedlings cultivated per hectare has been reported by Vennesland et al. (2013). It is assumed that the distance between the seedling production plant and the forest is 200 km. Infrastructure and energy requirements for other processes are based on the Ecoinvent 2.2 (2010) database input values. Once forwarded, the harvested round wood is transported 10 km from forest road to a mobile chipper. The chipping site is assumed to be located 60 km from the energy generation plant.

2.1.2. *Energy generation*

Three energy plants are analysed in this work: a biomass gasification plant based on the currently operating Gussing CHP plant

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