International Journal of Greenhouse Gas Control 49 (2016) 330–342

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Carbon-negative emissions: Systemic impacts of biomass conversion A case study on CO_2 capture and storage options

Jens Hetland[a,*], Ping Yowargana[b], Sylvain Leduc[b], Florian Kraxner[b]

[a] SINTEF Energy Research, Trondheim, Norway
[b] Ecosystems Services and Management (ESM), International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

ARTICLE INFO

Article history:
Received 7 January 2016
Received in revised form 15 February 2016
Accepted 14 March 2016

Keywords:
Biopower
Bioenergy
BECCS
CO_2 capture
CCS
Co-firing
Efficiency
CO_2 mitigation
Negative emissions

ABSTRACT

This paper is a contribution to the ongoing debate on carbon-negative energy solutions. It deals with biomass conversion in dedicated biopower plants equipped with CCS (BECCS), or co-fired plants retrofitted with CCS in order to generate negative CO_2-emissions. In this context, bioenergy refers to the use of biomass to generate electricity (i.e. biopower) in compliance with the needs of nations and regions without seasonal space heating demand. In this paper, direct-fired and co-fired systems will be addressed, combined mainly with post-combustion flue gas cleaning. The question is which CCS alternative should be preferred in order to obtain negative emissions: either building multiple smaller biopower units, or employing co-firing of biomass and coal in existing large coal power plants. Based on efficacy and the potential for mitigating greenhouse gas emissions as key indicators, some major differences between the alternatives are shown. In the event that a coal power plant equipped with CCS is readily available, more net electric energy (in MWh) can be provided from the feedstock of biomass than would be obtainable from an independent BECCS plant, although the amount of CO_2 captured and stored from the biomass (per tonne) will be essentially the same. Further case-specific cost-benefit analyses will be required to determine the feasibility of carbon-negative energy solutions. Although the study is carried out from the perspective of actual biomass sources as regards biomass composition and available technology (i.e. expected efficiency levels) using Indonesian agricultural residues, its main conclusion is fairly general.

1. Introduction

The paper summarises a case-based study aimed at estimating the efficacy of biomass conversion into electric power given the chemical composition of candidate feedstocks. Emphasis is placed on (a) net electricity, i.e. electric power and electric energy supplied to the grid (in MW_e and MWh), and (b) the resulting greenhouse gas emissions, as to how the atmosphere is eventually affected. In this endeavour, two principles apply: one co-firing biomass and coal in large coal power plants, the other firing biomass in dedicated biopower plants (BECCS). Both principles employ absorption techniques cleaning the flue gas (CCS). This includes compression to supercritical pressure of the CO_2 to reach dense phase, consistent with realistic pipeline specifications for transport and injection of the CO_2 into deep geological formations. Whereas the base plant is defined by its operating capabilities (without CCS), the assessment of the capture and compression system, as well as the environmental impacts, require further details of the flue gas, in particular flow rate and chemical composition.

In 2013, the global generation of electricity from biomass reached 405 TWh, assuming an average capacity factor of over 50% (Renewables, 2014). This corresponds to 1.75% of the global electricity production (i.e. 23.127 PWh in 2013, (BP, 2014)). Today, most biopower plants are fairly small units, usually in the tens of MW_e, ranging typically from 1 to 100 MW_e. The small size is mainly due to limited availability of local feedstock combined with high transportation cost (IEA, 2007). For this reason, biopower plants are often deployed in geographical areas with substantial biomass crops, aimed at harnessing biomass sustainably at a rate consistent with natural growth.

Negative emissions, resulting from the combining of bioenergy with carbon dioxide capture and storage (BECCS), have become an issue of growing interest. According to the 5th assessment report of the IPCC (Working Group 3), about half of the scenarios needed to limit the atmospheric concentration of greenhouse gases at 430–480 ppm CO_2 equivalents feature BECCS. As these options jointly account for more than 5% of the global primary energy supply (Fuss et al., 2014), it is necessary to further assess the potential

---

[*] Corresponding author.
E-mail address: jens.hetland@sintef.no (J. Hetland).

http://dx.doi.org/10.1016/j.ijggc.2016.03.017

for CO_2 mitigation from a systemic perspective. Essential components are, on the one hand, the localisation and size of the plant vis-à-vis the biomass feedstock, the possible grid connection, and, on the other hand, life-cycle emissions. Relevant studies must be case specific, mainly conducted from the perspective of biomass (availability and inherent properties), as well as technology selection pursuant to local and regional demand for electricity combined with affordable pricing, and, last but not least, opportunities for CO_2 storage. In this respect, it must be recognised that biomass sources are often located far from plausible storage sites (Status and prospects of BIO-CCS, 2015).

As no BECCS demonstration project has been realised so far (confer GCCSI database (Large Scale CCS Projects, 2016)), relevant studies anywhere in the world are based on assumptions or experiences from related projects (Status and prospects of BIO-CCS, 2015). Without CCS, typical parameters of a high-pressure and high-performance biopower plant converting agricultural residues may be as high as 88–90/535–540 (bar/°C), reaching a plant efficiency up to 32% (LHV) (cf. Fig. 1, left). The given steam parameters are taken as the upper limits of efficiency used in the parametric study. Likewise, a medium-pressure and medium-performance plant, with steam parameters of 49/450 (bar/°C), may reach typically 27% efficiency (LHV) provided the same feedstock (Brendstrup, 2012).

Today, 600–800 MW_e has become a common unit size for modern coal power plants (e.g. in China) with efficiency typically around 44% (LHV) (Hetland and Liu, 2013). Even larger plants are built to benefit from the higher efficiency, for instance the 1070 MW_e Maasvlakte MPP3 power plant in the Netherlands, with 46% efficiency (MPP3, 2015). This plant, fuelled essentially with coal, is capable of receiving up to 30% biomass. The plant became operational in 2015, ready to be swiftly retrofitted with CCS, subject to commercial decision (cf. the Dutch ROAD project, Rotterdam Opslag en Afvang Demonstratieproject (ROAD, 2015)). If realised, 90% of the CO_2 will be captured from a slip stream of flue gas equivalent to 250 MW_e, and permanently stored in a depleted gas field off the coast of Rotterdam (Fig. 2).

2. Co-firing biomass with coal

Compliant with many hot geographical regions the utilisation of low-quality heat is prone to attract marginal interest, if any. Therefore, electricity-only conversion has been used in all cases considered in a parametric study.

In modern coal-fired power plants, co-firing with biomass offers a substantially higher net efficiency than is usually obtainable in dedicated biopower plants (cf. Fig. 1, left). To the extent that coal-fired power plants are readily available and operational, co-firing represents a true option. By replacing a portion of coal with biomass, co-firing seems to be the most economic near-term solution for employing biopower at large. In general, modern coal power plants can usually accept up to 15% biomass without modifying the steam boiler system (except for the solid-fuel feed system). Because the existing environmental control equipment can be used even at a higher percentage of biomass without major modifications, co-firing is a far less expensive option than building a new biopower plant on a green field (IEA, 2007).

If for instance a modern 660 MW_e pulverised-coal power plant is at hand, it makes probably more sense to apply co-firing with 15% biomass, than building an entirely new biopower plant in the 100 MW_e class to make use of the available biomass. The former will also generate more electric energy from the biomass. If both plants include CCS, the difference becomes even more pronounced, simply because the BECCS will sacrifice far more power on relative terms. The implication is that the BECCS alternative offers significantly less net electric energy to the grid.

Fuel flexibility implies i.a. that the plant can be adjusted to make use of different fuels in a way that ensures optimal performance, even with co-firing. Compared with the amount of replaced coal, biomass will contribute to reducing the amounts of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and other emissions. In this way, co-firing allows the biomass to be converted to electricity with low local pollution whilst benefitting from the elevated efficiency of modern coal power plants. Thus, adding biomass to the coal is considered an effective greening measure. After adjusting the boiler for peak performance, little or no loss in efficiency will occur by feeding moderate amounts of biomass to the coal (Hetland et al., 2014). This is generally referred to as fuel flexibility. Co-firing also offers options for CCS, thus reducing the overall emission of CO_2 by typically up to 90% with an efficiency penalty of roughly 10%-points (cf. Fig. 1, taking the difference between the left-hand and the right-hand trajectories).

3. BECCS

Conceptually, biopower systems may employ either of the following primary conversion principles: *direct-firing*, *co-firing*, *gasification*, *pyrolysis* and *anaerobic digestion* of biomass (Biopower, 2014). These principles align with the major concepts for CO_2 capture of bioenergy solutions (BECCS): *pre-combustion*, *oxy-combustion*, and *post-combustion*. Whereas the former concept involves gasification (and/or pyrolysis), concepts for oxy-combustion and post-combustion CO_2 capture (i.e. flue gas scrubbing) are relevant for the remaining conversion principles.

The efficiency of basic biopower plants disposing of large amounts of agricultural residues is usually around 30% (LHV), depending on technology and plant size. With high-quality wood chips one may consider advanced biopower in hundreds of MW_e. If electricity is the only yield, such units may exceed 40% efficiency (LHV) (IEA, 2007). However, at this high efficiency level capital expenses are likely to become prohibitive. Therefore, in order to cut cost, an efficiency level well below 40% seems viable, although the availability of suitable high-quality wood chips within a reasonable distance from the plant appears to be a limiting factor. Assume for instance a 800 MW_e biopower plant with 40% efficiency: in order for such a plant to operate at full capacity, over 500 t biomass must be provided each hour.[1] This is equivalent to 17 lorries per hour carrying 30 t each. Aggregated over the year, almost 150 000 deliveries of biomass would be required.

As this example signifies a logistical challenge, a more realistic approach is to assess the size of biopower from a perspective of dedicated biopower units, viable in a range from roughly 25 to 100 MW_e. In contrast, coal-fired power plants for optional co-firing of biomass are significantly larger (i.e. 600–800 MW_e). Depending on the rate of biomass-firing, the dedicated biopower plant and the co-fired plant can handle essentially the same amount of biomass.

Fig. 1 depicts the generalised concepts for the BECCS system (left) and for the co-fired power system (right), as used to form the cases of the present study. Although these power cycles appear rather similar with the same type of flue-gas scrubbing, they will generally differ significantly in size, performance, complexity and technical solutions. Due to inadequate technology and lacking economic assessments, the cost of BECCS is not well understood (Status and prospects of BIO-CCS, 2015).[2]

---

[1] Dry biomass from rice straw with [C,H,O,N,S,moisture,ash,CO_2] = [0.3888,0.0476,0.3551,0.0052,0.0005,0.0000,0.2028,0.0000] resulting in a lower heating value of 14.137 MJ/kg

[2] The cost of biopower varies widely because of the many feedstocks and processes. The cost will vary even more when it comes to BECCS, because CCS will have