Applied Energy 190 (2017) 481–489

Contents lists available at ScienceDirect

Applied Energy

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

Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO_2 targets

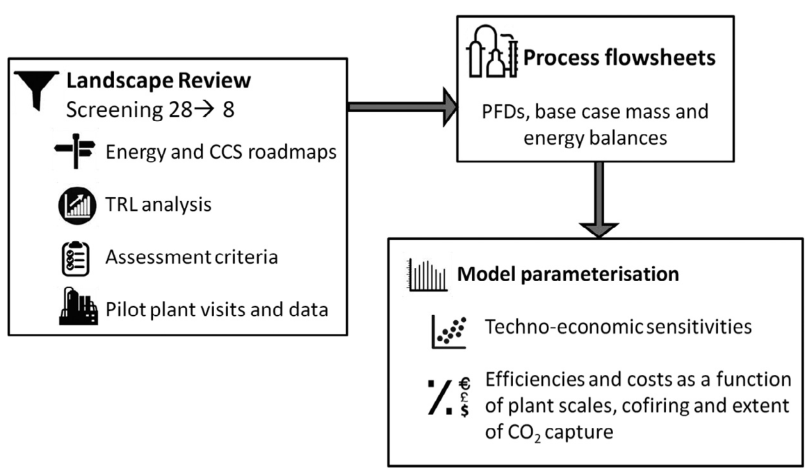
Amit Bhave [a], Richard H.S. Taylor [b], Paul Fennell [c], William R. Livingston [d], Nilay Shah [c], Niall Mac Dowell [c], John Dennis [e], Markus Kraft [e,j,*], Mohammed Pourkashanian [f], Mathieu Insa [g], Jenny Jones [f], Nigel Burdett [h], Ausilio Bauen [b], Corinne Beal [i], Andrew Smallbone [a], Jethro Akroyd [a]

[a] CMCL Innovations, UK
[b] E4tech, UK
[c] Imperial College London, UK
[d] Doosan Power Systems, UK
[e] Department of Chemical Engineering and Biotechnology, University of Cambridge, UK
[f] Faculty of Engineering, University of Leeds, UK
[g] EDF Energy, France
[h] Drax Power, UK
[i] Alstom Boiler France, France
[j] Nanyang Technological University, Singapore

HIGHLIGHTS

- Techno-economics of 8 Biopower CCS technologies ranging from TRL 4 to TRL 6-7.
- Net efficiency penalty due to CO_2 capture varied between 0 and 15 percentage points.
- Specific investment costs increased in the range 45–130% with CO_2 capture.
- Co-firing percentage, i.e. weighted feedstock cost, a key driver of LCOE.
- Lack of financial incentives for electricity generation with *negative* CO_2 emissions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form 24 December 2016
Accepted 26 December 2016
Available online 7 January 2017

Keywords:
Biomass
Biopower

ABSTRACT

Biomass-based power generation combined with CO_2 capture and storage (Biopower CCS) currently represents one of the few practical and economic means of removing large quantities of CO_2 from the atmosphere, and the only approach that involves the generation of electricity at the same time. We present the results of the *Techno-Economic Study of Biomass to Power with CO_2 capture (TESBiC)* project, that entailed desk-based review and analysis, process engineering, optimisation as well as primary data collection from some of the leading pilot demonstration plants. From the perspective of being able to deploy Biopower CCS by 2050, twenty-eight Biopower CCS technology combinations involving combustion or gasification of biomass (either dedicated or co-fired with coal) together with pre-, oxy- or post-combustion CO_2 capture

* Corresponding author at: Department of Chemical Engineering and Biotechnology, University of Cambridge, UK.
E-mail address: mk306@cam.ac.uk (M. Kraft).

http://dx.doi.org/10.1016/j.apenergy.2016.12.120

Bioenergy
Power generation
Carbon capture and storage (CCS)
Scenarios and forecasting
Techno-economics

were identified and assessed. In addition to the capital and operating costs, techno-economic characteristics such as electrical efficiencies (LHV% basis), Levelised Cost of Electricity (LCOE), costs of CO_2 captured and CO_2 avoided were modelled over time assuming technology improvements from today to 2050. Many of the Biopower CCS technologies gave relatively similar techno-economic results when analysed at the same scale, with the plant scale (MW_e) observed to be the principal driver of CAPEX (£/MW_e) and the cofiring % (i.e. the weighted feedstock cost) a key driver of LCOE. The data collected during the TESBiC project also highlighted the lack of financial incentives for generation of electricity with negative CO_2 emissions.

1. Introduction

The International Energy Agency (IEA) has warned that the door to limiting global average temperature rises to only 2°C (over pre-industrial levels) is closing, and the International Panel on Climate Change (IPCC) has highlighted the urgency of taking immediate mitigation actions in terms of technological changes [1,2]. This means that technologies that can rapidly remove vast amounts of CO_2 from the atmosphere may therefore need to be deployed, if other mitigation measures fail to rapidly reduce global emissions - a fact emphasised in the recent IPCC report which also placed an unprecedented emphasis explicitly on Bio-energy with carbon capture and storage (BECCS) [3].

BECCS or BioCCS as a concept can be achieved via multiple applications, i.e. through power generation (Biopower), biofuels production, hydrogen plants, bio-synthetic natural gas, heating, and industrial processes (steel, cement and paper) [4–8]. In case of BECCS, the emissions reduction potential is largely dependent on the scale of the installation and the upstream biomass emissions, which is in turn dictated by the available scale of the component technologies and the availability of biomass feedstock. Despite potential risks of over-reliance on as yet unproven technology, due to its large-scale negative emissions potential, BECCS presents a high value option that persistently features in majority of recent cost-effective scenarios or pathways aimed at decarbonising global energy use and achieving climate change targets [9–16]. The global technical potential of negative CO_2 emissions from BECCS, if deployed, has been estimated to be in the range of 3.2–10.4 $GtCO_{2e}$/yr [17,18]. BECCS has been reviewed at a systems-level in order to assess its role in stabilising CO_2 concentrations [19]. Based on an assumption of a global biomass potential of 100 EJ/yr, the review [19] stated a technical potential for BECCS at 10 $GtCO_2$/yr in 2050, with an economic potential of around 3.5 $GtCO_2$/yr. In another study, an energy system optimisation approach has been adopted to analyse the role of BECCS in meeting various global mean temperature limits [20]. Given its negative carbon emissions potential, BECCS allowed for lower temperature targets to become attainable and also at lower costs. At the same time, the uncertainties and knowledge gaps with respect to BECCS as a mitigation technology have also been highlighted. Some of the uncertainties include the sustainability of large scale deployment relative to other land and biomass needs (with significant concerns over land-use implications), the availability of suitable and secure CO_2 sequestration sites globally, the response of natural land and ocean carbon sinks to negative emissions, plus the costs, financing, legal liabilities and public acceptance [19–22].

Currently, four BioCCS projects are in operation around the world - mostly focused on CO_2 capture from ethanol production, with three of the projects using the CO_2 for enhanced oil recovery [19]. Recently, a spatially explicit optimisation framework was developed to characterise the optimal sizing (scale) for potential BECCS facilities located in Illinois, USA [23]. It was assessed that the biomass supply, technology cost and cost scaling have a strong effect on the optimal capacity, however the levelised cost and the cost of avoided CO_2 were observed to be relatively insensitive to deviations from the scaled size.

The present paper focuses on the assessment of the application of BECCS specifically in the biopower generation industry. As well as exploring dedicated biopower applications, coupling CCS technology with a co-fired (biomass and coal) power plant offers a practical option with moderate investment costs to evaluate these BECCS technology combinations. The significant research, development and innovation efforts in the field of CCS have already been reviewed in detail elsewhere [24–28]. The strong potential of *Biopower CCS* for carbon abatement has also been recognised in several studies, while highlighting the dearth of comprehensive data and techno-economic uncertainties associated with Biopower CCS [29,14,17–19,30–34]. In the context of UK, the significance of including Biopower CCS within the energy mix in order to achieve the UK target of a 80% reduction in greenhouse gas emissions by 2050 in a cost-effective manner, has been emphasised by the Committee on Climate Change and the Energy Technologies Institute [35,36].

In this paper, we discuss some of the key results from a study that was commissioned by the Energy Technologies Institute (ETI) in the UK, to assess the techno-economics of a wide range of technology combinations involving biomass fuelled power generation combined with CO_2 capture. This *Techno-Economic Study of Biomass to Power with CO_2 capture (TESBiC)* study entailed desk-based review and analysis, numerical modelling, optimisation as well as data collection at some of the leading pilot demonstration plants in Europe. Twenty-eight Biopower CCS technology combinations were identified and assessed as part of the TESBiC study. The paper is organised as follows: First, a short overview of the work performed in the field of Biopower CCS is given. Then the technical approach adopted in the TESBiC project is presented, followed by one workflow example of a specific Biopower CCS technology. The results of the techno-economic analysis of the eight short-listed Biopower CCS technology combinations are then discussed before drawing final conclusions.

2. Overview of biopower CCS

From the perspective of deployment of Biopower CCS by 2050, numerous technology combinations involving combustion or gasification of biomass (either dedicated or co-fired with coal) together with pre-, oxy- or post-combustion CO_2 capture currently exist. In a recent life cycle assessment (LCA) study of biomass co-firing power plants with CCS, a supercritical pulverised coal (PC) with post-combustion CO_2 capture and an integrated gasification plant with pre-combustion capture were analysed at a common capacity of 550 MW_e and the gains made in terms of reduction of CO_2 and SO_2 emissions were weighed against the efficiency drop and increased infrastructure demand [33]. For co-firing fixed at 30% (energy basis) and the extent of CO_2 capture set at 90%, net negative emissions in the range of 67-85 g/kWh were reported. In a separate techno-economic analysis [37], the potential of dedicated biomass with integrated gasification combined cycle (IGCC) coupled with CCS was proposed as the main bionergy conversion