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

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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)* study, 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 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.

Keywords: Biomass, biopower, bioenergy, power generation, carbon capture and storage (CCS), scenarios and forecasting, techno-economics

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, 5, 6, 7, 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 of 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, 10, 11, 12, 13, 14, 15]. Recently, linear programming was applied to conduct global modelling of various renewable technologies, including BECCS over the period 2010 to 2050 [16]. For the zero emissions scenario, BECCS was concluded to play a vital role in satisfying the demand in the heat sector. Elsewhere, the global technical potential of negative CO_2 emissions from BECCS, if deployed, has been estimated to be in the range of 3.2 to 10.4 Gt CO_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 [20, 19, 21, 22].

Currently, four BioCCS projects are in operation around the world - mostly focused on CO_2 capture from ethanol production, and three of the projects use 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. For a biopower application, coupling CCS technology with a co-fired (biomass and coal) power plant offers a practical option with moderate investment costs to evaluate these technology combinations. The significant research, development and innovation efforts in the field of CCS have already been reviewed in detail elsewhere [24, 25, 26, 27, 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, 18, 19, 30, 31, 32, 33, 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 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 MWe 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 a fixed co-firing of 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 conducted [37], the potential of dedicated biomass with integrated gasification combined cycle (IGCC) coupled with CCS was proposed as the main bionergy conversion technology for the long term, representing 33% of the global mitigation potential by 2100. An integrated gasification facility that combined electricity generation (combined cycle) and an option to produce Fischer Tropsch Diesel, with and without CCS has also been assessed in another study [38]. Torrefied biomass was proposed as a feedstock for the facility and specific direct CO_2 emissions were estimated to be -0.93 kg CO_2/kWh. A cofired (80% coal and 20 biomass) IGCC based on entrained-flow gasifier designs combined with oxy-, pre- and post-combustion CO_2 capture at a fixed rate of 90% has also been modelled [39]. It was concluded that the iron-based chemical looping was significantly more energy efficient than the post- and pre-combustion capture systems. Furthermore, the study also indicated that pre-combustion capture using either physical or chemical solvents was more energy efficient than post-combustion capture using chemical solvents.

Elsewhere, a mixed integer nonlinear programming (MINLP) approach was adopted to emphasise the need for operating biomass co-fired power plants at a high load factor and at high levels of the extent of CO_2 capture to ensure commercial feasibility [40]. Under the conditions of constrained supply of indigenous biomass, a price range threshold of 120-175 £/t of CO_2 was reported to incentivise the generation of carbon negative electricity. Recently, biomass conversion has also been considered in large scale (660 MWe) co-fired biomass plants retrofitted with post-combustion CO_2 capture and relatively smaller scale (100 MWe) dedicated biomass plants equipped with CO_2 capture [41]. For a 90% CO_2 capture, the power generation efficiency drop with CCS was estimated to be 10% points. For such efficiency penalty with CCS, the importance of ensuring a sufficiently high initial net efficiency of the basic biopower plant was highlighted and the advantages offered by the large scale co-fired power plant with super critical steam power cycles were also emphasised.

3. Approach

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 were examined based on the following assessment criteria over the period 2010 to 2050:

- Techno-economic characteristics such as nameplate capacities, capacity factors, LHV% electrical efficiencies, extent of co-firing and of CO_2 capture;

- CO_2, SO_2 and NO_x emissions;
- capital and operating costs (CAPEX and OPEX);
- Levelised costs of electricity (LCOE), costs of CO_2 captured and avoided;
- Flexibility and load-following capabilities;
- Technology Readiness Level (TRL) progressions;
- Feedstock characteristics;
- Gaps in the current understanding, resulting technical and commercial risks and corresponding potential mitigation strategies;
- UK development prospects; and
- Intellectual property and UK deployment potentials.

Bearing in mind the challenges arising from the lack of Biopower CCS data in the public domain and the large variances in the technology readiness levels (TRLs) of the various CO_2 capture technologies (Figure 1), significant consideration was given to the approach adopted in terms of the technology landscape review, screening, model development and the ensuing analysis phases.

[Figure 1 about here.]

Furthermore, to help ensure that the overall economic parameters could be compared across the technology combinations, harmonised estimates for a number of the more common cost items of equipment and utilities were prepared for use in this work. For example, the additional capital costs in terms of operations and utilities were assumed to be 5% of the total installed CAPEX, with civils and land set at 10%, project development at 5% and contingency at 10%. Several pieces of common equipment (compressors, air separation, turbines) also had their costs harmonised. Feedstock prices (2010 basis) were set throughout at 7 £/MWh for bituminous coal, 27 £/MWh for traded wood pellets and 10 £/MWh for domestic wood chip, with plant utilisation factors all set to 85%. Note that it was assumed that Biopower CCS will take the role of providing baseload power and will not play a role in balancing UK power grid with high penetration of renewables. The fixed operating costs were assumed to be 5% of the total installed CAPEX (based on 4% labour and maintenance and 1% for insurance). Most importantly, all costs are presented as "Nth-of-a-kind" (as if the technology were already at TRL 9), and not prototype costs (e.g. current lower TRLs).

A schematic of the approach used within the TESBiC project is presented in Figure 2. A landscape review of twenty eight technology combinations was performed based on data from the project partners and from literature, plus a review of existing roadmaps in the energy and CCS fields. Note that only those options able to reach TRL 5 (pilot scale) by 2020 were considered likely to be advanced enough to be able to contribute to mass deployment in the UK by 2050. This screening criterion was based on typical industry lead times and assuming that no major concerted focused effort in terms of research, development and deployment was made in advancing specific technology. Note that waste-to-energy plants were not considered, given their significantly lower efficiency and limited future deployment potential as compared to dedicated or cofiring biomass plants, thus weakening the case for adding efficiency-penalising capture [41, 42]. Fuel cells offer another power generation option compared to combined cycle hydrogen turbines, but as they would use the same biomass gasification and pre-combustion capture technologies as a dedicated biomass integration gasification combined cycle (bio IGCC) plant, these were not focused upon within the TESBiC study. Biomass integrated gasification fuel cell (BIGFC) technology is currently around TRL 4-5, but combined with CCS the whole system TRL is below TRL4 [43, 44].

As a consequence of the landscape review and screening, the following eight technology combinations were selected for further more detailed analysis:

1. Biomass-coal co-firing combustion, with post-combustion amine scrubbing (*cofire amine*)
2. Dedicated biomass combustion with post-combustion amine scrubbing (*bio amine*)
3. Biomass-coal co-firing combustion, with post-combustion carbonate looping (*cofire carb loop*)
4. Biomass-coal co-firing oxy-combustion, with cryogenic O_2 separation (*cofire oxy*)
5. Dedicated biomass oxy-combustion, with cryogenic O_2 separation (*bio oxy*)

6. Dedicated biomass chemical-looping-combustion using solid oxygen carriers (*bio chem loop*)
7. Biomass-coal co-firing IGCC (Integrated Gasification Combined Cycle), with physical absorption (*cofire IGCC*)
8. Dedicated biomass IGCC, with physical absorption (*bio IGCC*).

[Figure 2 about here.]

The eight technology combinations represented a wide range of current TRLs i.e. from TRL4 (bench-scale test rig) to TRL6-7 (demonstration). Base case process flowsheet models were developed for each of the eight technology combinations by employing a high-level process flow description and the associated mass and energy balances. Process efficiencies based on low heating values (LHV), the CAPEX and OPEX estimates, the costs for CO_2 captured and avoided and the LCOE were calculated for each of the base case models.

As plant performance and cost are known to be highly sensitive to plant scale, fast-response meta models were formulated on the basis of the base case values provided by the flowsheet models. In particular, output variables such as CAPEX, non-fuel OPEX, generation efficiency, CO_2, SO_2 and NO_x emissions were developed as functions of the four input parameters, namely, co-firing levels, extent of carbon capture, nameplate and operating capacities. Lastly, the main performance parameters for the eight TESBiC technologies were benchmarked at common plant scales (a small scale of 50 MW_e and an intermediate scale of 250 MW_e). The aforementioned techno-economic estimates based on the current state-of-the-art were then evolved for the years

2020, 2030, 2040 and 2050 for all eight technology combinations. Significant increases in the electricity generation efficiencies and reductions in the capital costs of all of the technologies were projected for the period 2010 to 2050. By their nature, these projections have large uncertainties attached, although the level of optimism assumed within the TESBiC project was consistent with that in other industry data sources used.

4. A work-flow example

In this section, the technical work-flow employed during the assessment of the Biopower CCS technologies is described with the help of a specific technology combination, chosen as an example. Given the paucity of published data on low TRL (TRL4) technology options, dedicated biomass chemical looping (bio chem loop) has been considered here.

Figure 3 shows a high-level process flow description for bio chem loop at a base capacity of 268.3 MW_e. Mass and energy balance calculations were used to evaluate the techno-economic output metrics (e.g. LHV efficiency, CAPEX, OPEX, etc.) at a number of operating points, termed as base cases.

[Figure 3 about here.]

The base case models were then used to populate data for the formulation of computational surrogates or meta models. The meta-model utilised was of the form, as given in Equation (1):

$$y_m = \bar{y}_m + A_{mn}(x_n - \bar{x}_n) \tag{1}$$

where the output vector y_m is related to an input vector x_n through a coefficient matrix A_{mn} in a piecewise linear fashion by difference from a base input vector $\bar{x}_n$ and a base output vector $\bar{y}_m = f(\bar{x}_n)$, and where m indicates the output index and n, the input index. Parameter estimation was performed with the Model Development Suite (MoDS) software [45] to calibrate the meta models via the coefficient matrix A_{mn} to base case evaluations obtained from the detailed models. The MoDS software has been previously applied for various digital engineering tasks that include parameter estimation and uncertainty quantification [46], Design of Experiments (DoE) [47], surrogates or meta model generation [48] and global sensitivity analysis [49, 50].

5. Results and discussion

Biopower CCS technologies currently represent one of the very few practical and economic means of removing large quantities of CO_2 from the atmosphere, and uniquely involves the generation of electricity at the same time. This would appear to make this approach to power generation very attractive given that many industrialised countries have stringent targets for the reduction of CO_2 emissions. It is clear, however that the available Biopower CCS technologies are relatively expensive in terms of both capital and operating costs (thus requiring financial incentives) as compared to fossil fuel based or other renewable power generation. Presently, there are no specific financial incentives anywhere in the world for the generation of electricity specifically with negative CO_2 emissions. Overall, the data collected during the TESBiC project indicated that the most significant barriers to the deployment of Biopower CCS technologies will be economic and regulatory in nature, rather than technical, provided that fossil CCS technology is deployed at commercial scale.

Key performance parameters in terms of the generation efficiency (LHV% basis) and the specific investment costs (CAPEX) for the eight Biopower CCS technology combinations were benchmarked at common plant scales (of 50 MW_e and 250 MW_e). Figure 4 gives the efficiency and CAPEX results at 50 MW_e plant capacity.

[Figure 4 about here.]

Bio amine and bio oxy technologies were the least efficient options, whereas cofire and bio IGCC showed the potential to reach the highest efficiencies by 2050. Although the efficiency of cofire carb loop remained competitive, the CAPEX was relatively high. Alongside the cofire amine and cofire oxy options, bio chem loop yielded the relatively lowest CAPEX range at a moderately high efficiency.

Wherever a direct comparison was feasible (for plants with an unabated equivalent), it was observed that the net efficiency penalty due to carbon capture varied in the range of 6 to 15 percentage points, whereas the specific investment costs (CAPEX) increased significantly in the range 45% to 130%, with annual operating and maintenance costs growing by 4% to 60%. In case of dedicated bio chem loop, however, there is no efficiency loss or comparator given that both power generation and CO_2 capture are intrinsic to the operation of the technology. At 250 MW_e, the technologies were observed to be tightly grouped, almost lying completely within each other's uncertainty bounds. These observations confirm that within the current uncertainty bounds of the available data, the plant scale (MW_e) is the principal driver of CAPEX (£/MW_e), rather than the choice of technology, with larger plants having lower specific capital costs.

[Figure 5 about here.]

The LCOE was calculated using a discounted cost of capital (at 10% discount rate, and a plant technical/economic lifetime of 30 years), adding the annual fixed and variable operating costs, and finally adding the feedstock costs divided by the plant electricity generation efficiency. Figure 5 presents the potential evolution of the LCOE at a 50 MW_e scale for the eight technologies covering the period up to 2050. Three distinct groupings can be observed, with low efficiency bio amine and bio oxy with the highest LCOE, then the higher efficiency bio IGCC, bio chem loop and cofire carb loop options in the middle, and lastly, the cofire amine, cofire oxy and cofire IGCC with the lowest LCOE (attributed to cheap coal prices). Since this is a small-scale plant, either biomass pellets or chips could realistically be used, however Figure 5 shows the LCOE results when the biomass feedstock used is in the form of imported pellets. The switch to using chips instead of pellets dramatically lowers the LCOE, with many options having very similar LCOE (80-100 £/MWhe) in 2050, since the price of UK locally sourced biomass chips (10 £/MWh) is much closer to the price of coal (7 £/MWh).

[Figure 6 about here.]

The cost of CO_2 captured was calculated by multiplying the LCOE (£/MWhe) by the annual electricity output (MWhe/yr), then dividing by the annual

CO_2 emissions captured (tCO_2/yr). However, this varied very little over time, since improved capital costs and plant efficiencies meant that both the LCOE and the amount of CO_2 captured per year decreased in step, if it is assumed that the plant power output remains constant. Alternatively, if the plant feedstock input remains constant, then the amount of CO_2 captured will be fixed, but the LCOE will fall as the annual electricity output rises again, giving little change in the cost of CO_2 captured. As the cost of CO_2 captured varied only slightly over time; average 2010-2050 values have been presented in Figure 6.

Given the dependency between LCOE and the cost of CO_2 captured, Figure 6 shows several similarities to the trends in LCOE across the eight technology combinations. The co-firing options exhibited the cheapest cost of CO_2 captured (due to coal vs. pellet prices), with the switch between biomass pellets and chips noticeably reducing the cost of CO_2 captured for the other options. Interestingly, the 50 MW_e case with chips yielded very similar cost of CO_2 captured across the board (range of 100-130 £/tCO_2), since the slight differences in LCOE were balanced by the different amounts of CO_2 captured (with lower efficiency plants capturing more CO_2 whilst they generated the target 50 MW_e).

[Figure 7 about here.]

In order to evaluate the cost of CO_2 avoided, the comparator technology was chosen to be an unabated coal power plant (from the relevant decade) for the benchmarking exercise. The cost, efficiency and emissions data for unabated coal combustion power plants were used from previous published data [51]. The choice of a different comparator technology such as a coal power plant with CCS or a dedicated biomass power plant (without CCS), both more expensive options, would further reduce the cost of CO_2 avoided reported in the TESBiC study.

The cost of CO_2 avoided only dropped slightly over time; hence again only average 2010-2050 values were presented. Figure 7 shows a tight grouping when using a common scale of 50MWe, with costs of avoided CO_2 between 60-90 £/tCO_2 when using pellets (30-65 £/tCO_2 were obtained when using chips). The feedstock costs dominate, so those technologies that maximise the use of low-cost chips (i.e. the dedicated biomass technologies) were able to achieve the lowest costs of CO_2 avoided. Bio chem loop appears to potentially be the most attractive technology in both cases (by quite some distance), although the uncertainty bars are large for this earlier stage technology.

From a TRL perspective, the eight shortlisted Biopower CCS technologies (out of twenty eight in total) represent a wide range of current TRLs (Technology Readiness Levels) i.e. from TRL4 (bench-scale test rig) to TRL6-7 (demonstration). *Second generation* capture technologies such as cofire carb loop and bio chem loop currently have low TRLs (4 to 5), as is evident from the limited (fewer than 10) number of bench scale and pilot scale plants, with a maximum plant capacity of 3 MW_{th}. These technologies (a majority of which are operated with coal feedstocks at present) yielded higher uncertainties in their techno-economic estimates as compared to the *first generation* capture technologies such as amine scrubbing and oxyfuel combustion with higher TRLs of 6 to 7. For lower current TRL technology options, the TESBiC data from existing pilot plants and demonstrations helped in identifying the key technical and commercial gaps and challenges that exist for the selected Biopower CCS technologies. To present an example, for dedicated biomass chemical looping combustion (bio chem loop), some of the unknowns associated with the identification of an optimal oxygen carrier material suited for biomass feedstocks, the stability and lifetime of the carrier, the attrition rates at large scales and achieving higher gas conversion efficiency were highlighted. These factors were classified as having 'high uncertainty', whereas factors such as incompleteness of the flowsheet at large scales and high temperature solid circulation rates were identified as having 'medium uncertainty'.

An outline development roadmap for each of the technologies were also prepared as part of the TESBiC study. In the case of the more developed Biopower CCS technologies, the route to further development after demonstration of the capture technology on a coal-fired plant would involve deployment of the capture technology at a commercial scale on a coal plant cofiring biomass, or demonstration on a dedicatd biomass plant. The roadmaps for many of the Biopower CCS technologies are closely tied to the development of fossil CCS technology. For the less well developed capture technologies (chemical and carbonate looping), fairly conventional development roadmaps, involving component testing, small and large pilot scale testing, and larger scale demonstration activities have been defined.

6. Conclusions

The TESBiC study focused on assessing twenty eight technology combinations involving biomass fuelled power generation combined with CO_2 capture (Biopower CCS). Based on their deployment potential by 2050 and the system-level TRL (Technology Readiness Level) progression criteria, technologies were short-listed for further analysis. These eight options represented a wide range of current TRLs i.e. from TRL4 (bench-scale test rig) to TRL6-7 (demonstration). Base case process flowsheet models (mass and energy balances) were developed for each of the eight technology combinations by employing a high-level process description for Nth-of-a-kind plants. The base case models were then utilised to generate fast-response surrogates or meta models for techno-economic outputs (CAPEX, non-fuel OPEX, generation efficiency, LCOE, cost of CO_2 captured and avoided) as functions of the four input parameters (co-firing levels, extent of carbon capture, nameplate and operating capacities).

Wherever a direct comparison was feasible (for plants with an unabated equivalent), it was observed that the net efficiency penalty due to carbon capture varied in the range of 6 to 15 percentage points, whereas the specific investment costs (CAPEX) increased in the range 45% to 130%, with annual operating and maintenance costs growing by 4% to 60%. At 250 MW_e, the technology combinations were observed to be tightly grouped, almost lying completely within each other's uncertainty bounds. In general terms, the plant scale (MW_e), rather than the choice of technology is the principal driver of CAPEX (£/MW_e). The co-firing %, i.e. the weighted feedstock cost, is one of the key drivers of LCOE, with dedicated biomass options using expensive pellets always having significantly higher LCOE than co-firing with cheap coal. At 50 MW_e, the LCOE results over the period 2010 to 2050 exhibited three distinct groupings: the first with low efficiency bio amine and bio oxy with the highest LCOE, then the higher efficiency bio IGCC, bio chem loop and cofire carb loop options with a moderate LCOE, and the cofiring options with amine, oxy and IGCC with the lowest LCOE on account of the cheap coal prices. Although the dedicated biomass technologies yield higher LCOE values and costs per tonne of CO_2 captured, the major advantages of these technology combinations, however, are that they do not involve fossil fuel utilisation and that they offer very significant negative CO_2 emissions per kWh generated at relatively modest scales. Using biomass pellets for the cofiring and dedicated technology options at 50 MW_e capacity, the average values over the period 2010 to 2050 for the costs of CO_2 captured were observed to be in the range of 100-190 £/tCO_2 and for the costs of CO_2 avoided to be in the range of 60-90 £/tCO_2.

Presently, there are also no financial incentives available (anywhere in the world) specifically for the generation of electricity with negative CO_2 emissions - current policies either only penalise positive emissions, or incentivise zero emissions. The data collected during the TESBiC project indicates that the most significant barriers to the deployment of Biopower CCS technologies will be economic and regulatory in nature, rather than technical, assuming fossil CCS technologies are successfully proven at scale. Furthermore, establishing sustainable biomass supply chains with low upstream emissions (and few indirect impacts on existing land use and carbon stocks) and availability and suitability of CO_2 sequestration sites are important issues that would need to be considered for the development and deployment of Biopower CCS. More detailed engineering studies are recommended to help reduce the uncertainties in the cost estimates across the eight technology combinations. Such studies followed by pilot and demonstration activities involving BioPower CCS technologies naturally form the next step towards rapidly reducing CO_2 emissions from the power sector, whilst keeping open the option of developing low-cost, scalable negative emissions technologies in case of lack of mitigation action and climate change overshoot.

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[1] International Energy Agency, Model Energy Outlook (2011).

[2] IPCC, Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, 2007.

[3] IPCC, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the 5th Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, 2014.

[4] A. Arasto, K. Onarheim, E. Tsupari, J. Kaerki, Bio-CCS: feasibility comparison of large scale carbon-negative solutions, Energy Procedia 63 (2014) 6756–6769.

[5] M. C. Carbo, R. Smit, B. van der Drift, D. Jansen, Bio energy with CCS (BECCS): Large potential for bioSNG at low CO_2 avoidance cost, Energy Procedia 4 (2011) 2950–2954.

[6] Q. Chen, A. Rao, S. Samuelsen, Coproduction of transportation fuels in advanced IGCC via coal and biomass mixtures, Applied Energy 157 (2015) 851–860.

[7] J. R. Moreira, V. Romeiro, S. Fuss, F. Kraxner, S. A. Pacca, A mixed integer nonlinear programming (MINLP) supply chain optimisation frmaework for carbon negative electricity egenration using biomass to energy with ccs BECCS in the UK, Applied Energy 179 (2016) 55–63.

[8] J. S. Rhodes, D. W. Keith, Engineering economic analysis of biomass IGCC with carbon capture and storage, Biomass and Bioenergy 29 (2005) 440–450.

[9] D. Klein, G. Luderer, E. Kriegler, J. Strefler, N. Bauer, M. Leimbach, A. Popp, J. P. Dietrich, F. Humpenoeder, H. Lotze-Campen, O. Edenhofer, The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE, Climate Change 123 (2014) 705–718.

[10] D. P. van Vuuren, S. Deetman, J. van Vliet, M. van den Berg, B. J. van Ruijven, B. Koelbl, The role of negative CO_2 emissions for reaching 2°C - insights from integrated assessment modelling, Climate Change 118 (2013) 15–27.

[11] O. Dessens, G. Anadrajan, A. Gambhir, Avoid2 wpc1 report: Review

of existing emissions pathways and evaluation of decarbonisation rates (2014).

[12] S. Selosse, O. Ricci, Achieving negative emissions with BECCS (bioenergy with carbon capture and storage) in the power sector: New insights from the TIAM-FR (times integrated assessment model france) model, Energy 76 (2014) 967–975.

[13] N. McGlashan, N. Shah, B. Caldecott, M. Workman, High-level techno-economic assessment of negative emissions technologies, Process Safety and Environmental Protection 90 (2012) 501–510.

[14] European Biofuels Technology Platform for Zero Emission Fossil Fuel Power Plants, Biomass with CO_2 capture and storage (Bio-CCS): The way forward for Europe (2012).

[15] C. Gough, P. Upham, Biomass energy with carbon capture and storage (BECCS): a review (2010).

[16] K. Tokimatsu, S. Konishi, T. Tezuka, R. Yasuka, M. Nishio, Role of innovative technologies under the global zero emissions scenarios, Applied Energy 162 (2016) 1483–1493.

[17] IEAGHG, Potential for biomass and carbon dioxide capture and storage (2011).

[18] J. Koornneef, P. van Breevoort, C. Hamelinck, C. Hendriks, M. Hoogwijk, K. Koop, M. Kopel, A. Camps, Global potential for biomass and carbon dioxide capture, transport and storage up to 2050, Int. J. Greenhouse Gas Control 11 (2012) 117–132.

[19] J. Kemper, Biomass and carbon dioxide capture and storage: A review, Int. J. Greenhouse Gas Control 40 (2016) 401–430.

[20] C. Azar, K. Lindgren, M. Obersteiner, K. Riahi, D. P. van Vuuren, K. M. G. J. den Elzen, K. Moellersten, E. D. Larson, The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS), Climatic Change 100 (2010) 195–202.

[21] S. Fuss, J. G. Canadell, G. P. Peters, M. Tavoni, R. M. Andrew, P. C. abd R. B. Jackson, C. D. Jones, F. Kraxner, N. Nakicenovic, C. L. Quere, M. R. Raupach, A. Sharifi, P. Smith, Y. Yamagata, Betting on negative emissions, Nature Climate Change 4 (2014) 850–853.

[22] E. Kato, Y. Yamagata, BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting negative carbon emissions, Earth's Future 2 (2014) 421–439.

[23] D. L. Sanchez, D. S. Callaway, Optimal scale of carbon-negative energy facilities, Applied Energy 170 (2016) 437–444.

[24] N. MacDowell, N. Florin, A. Buchard, J. Jallett, A. Galindo, G. Jackson, C. S. Adjiman, C. K. Williams, N. Shah, P. Fennell, An overview of CO_2 capture technologies, Energy and Environmental Science 3 (11) (2010) 1645–1669.

[25] J. Yan, Carbon capture and storage, Applied Energy 148 (2015) A1–A6.

[26] D. Y. C. Leung, G. Caramanna, M. M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, Renewable and Sustainable Energy Reviews 39 (2014) 426–443.

[27] J. Gibbins, H. Chalmers, Carbon capture and storage, Energy Policy 36 (2008) 4317–4322.

[28] M. Kanniche, R. Gros-Bonnivard, P. Jaud, J. Valle-Marcos, J.-M. Amann, C. Bouallou, Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO_2 capture, Applied Thermal Engineering 30 (2010) 53–62.

[29] IEAGHG, Biomass CCS study 2009/9 (2009).

[30] D. McLaren, A comparitive global assessment of potential negative emissions technologies, Process Safety and Environmental Protection 90 (2012) 489–500.

[31] G. Lomax, T. M. Lenton, A. Adeosun, M. Workman, Investing in negative emissions, Nature Climate Change 5 (2015) 498–500.

[32] J. Laude, C. Jonen, Biomass and CCS: The influence of technical change, Energy Policy 60 (2013) 916–924.

[33] W. Schakel, H. Meerman, A. Talaei, A. Ramirez, A. Faaji, Comparitive life cycle assessment of biomass co-firing plants with carbon capture and storage, Applied Energy 131 (2014) 441–467.

[34] P. J. Vrgragt, N. Markusson, H. Karlsson, Carbon capture and storage, bio-energy with carbon capture and stoprage, and the escape from the fossil-fuel lock-in, Global Environmental Change 21 (2011) 282–292.

[35] Committee on Climate Change, Bioenergy review (2011).

[36] C. Heaton, Modelling low-carbon energy system designs with the ETI ESME model, ETI Paper.
URL www.eti.co.uk

[37] D. Klein, N. Bauer, B. Bodirsky, J. P. Dietrich, A. Popp, Bio-IGCC with CCS as a long term mitigation option in a coupled energy system and land use model, Energy Procedia 4 (2011) 2933–2940.

[38] J. C. Meerman, M. M. J. Knoope, A. Ramirez, W. C. Turkenburg, A. P. C. Faaij, Technical and economic prospects of coal- and biomass-fired integrated gasification facilities equipped with CCS over time, Int. J. Greenhouse Gas Control 16 (2013) 311–323.

[39] C.-C. Cormos, A. Padurean, P. S. Agachi, Technical evaluations of carbon capture options for power generation from coal and biomass based on integrated gasification combined cycle scheme, Energy Procedia 2 (2011) 1861–1868.

[40] O. Akgul, N. M. Dowell, L. G. Papageorgious, N. Shah, A mixed integer nonlinear programming (MINLP) supply chain optimisation frmaework for carbon negative electricity egenration using biomass to energy with ccs BECCS in the UK, Int. J. Greenhouse Gas Control 28 (2014) 189–202.

[41] J. Hetland, P. Yowargana, S. Leduc, F. Kraxner, Carbon negative emissions: Systemic impacts of biomass conversion - a case study on CO_2 capture and storage options, Int. J. Greenhouse Gas Control 49 (2016) 330–342.

[42] IEA-ETE03, Biomass for power generation and CHP (2007).

[43] J. Sadhukhan, Y. Zhao, N. Shah, N. P. Brandon, Performance analysis of integrated biomass gasification fuel cell (BGFC) and biomass gasification combined cycle (BGCC) systems, Chem. Eng. Sci 65 (2010) 1942–1954.

[44] F. P. Nagel, S. Ghosh, C. Pitta, T. J. Schildhauer, S. Biollaz, Biomass integrated gasification fuel cell systems - concept development and experimental results, Biomass and Bioenergy 35 (2011) 354–362.

[45] Model Development Suite (MoDS) software user's manual, CMCL Innovations, Cambridge, UK (2011).

[46] S. Mosbach, J. H. Hong, G. P. E. Brownbridge, M. Kraft, S. Gudiyella, K. Brezinsky, Bayesian error propagation for a kinetic model of n-propylbenzene oxidation in a shock tube, Int. J. Chemical Kinetics 46 (7) (2014) 389–404.

[47] S. Mosbach, A. Braumann, P. L. W. Man, C. Kastner, G. P. E. Brownbridge, M. Kraft, Iterative improvement of bayesian parameter estimates for an engine model by means of experimental design, Combustion and Flame 159 (3) (2012) 1303–1313.

[48] G. P. E. Brownbridge, P. Azadi, A. Smallbone, A. Bhave, B. Taylor, M. Kraft, The future viability of algae-derived biodiesel under eonomic and technical uncertainties, Journal of Aerosol Science 151 (2014) 166–173.

[49] P. Azadi, G. P. E. Brownbridge, S. Mosbach, A. Smallbone, A. Bhave, O. Inderwildi, M. Kraft, The carbon footprint and non-renewable energy demand of algae-derived biodiesel, Applied Energy 113 (2014) 1632–1644.

[50] W. Menz, G. P. E. Brownbridge, M. Kraft, Bayesian error propagation for a kinetic model of n-propylbenzene oxidation in a shock tube, Journal of Aerosol Science 76 (2014) 188–199.

[51] M. Finkenrath, Cost and performance of carbon dioxide capture from power generation, IEA.

List of Figures

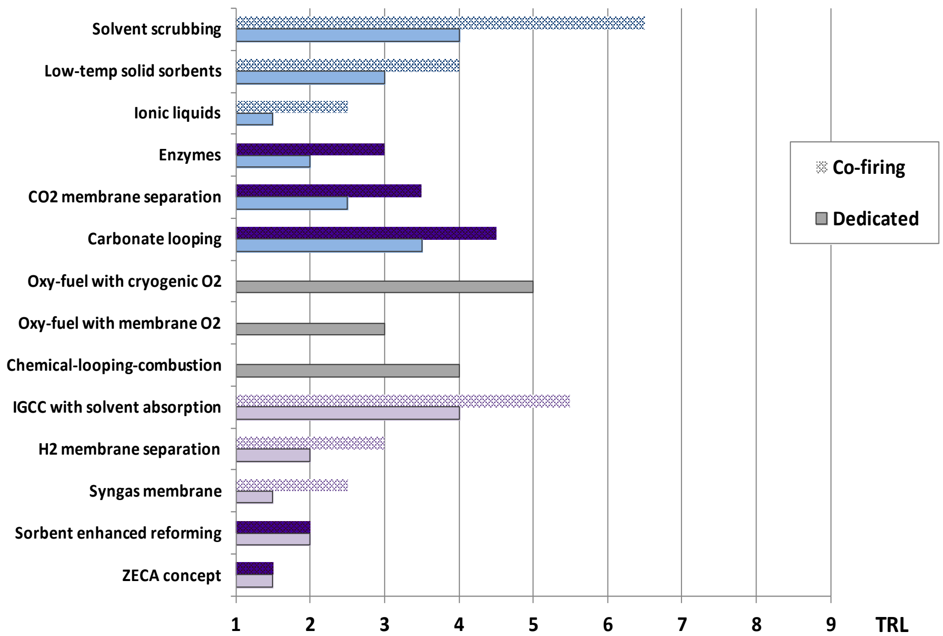

Figure 1: *Current technology readiness levels (TRL) for CCS technologies.*

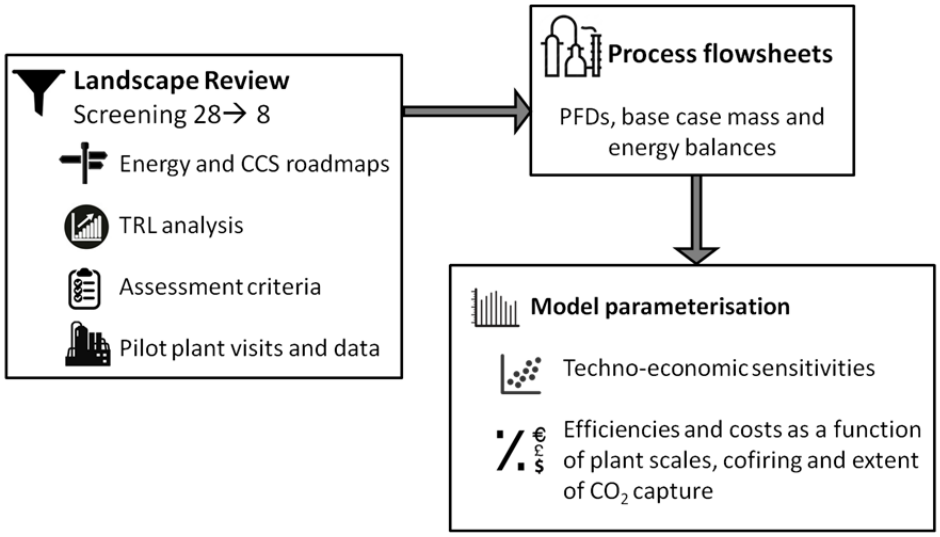

Figure 2: *TESBiC work-flow.*

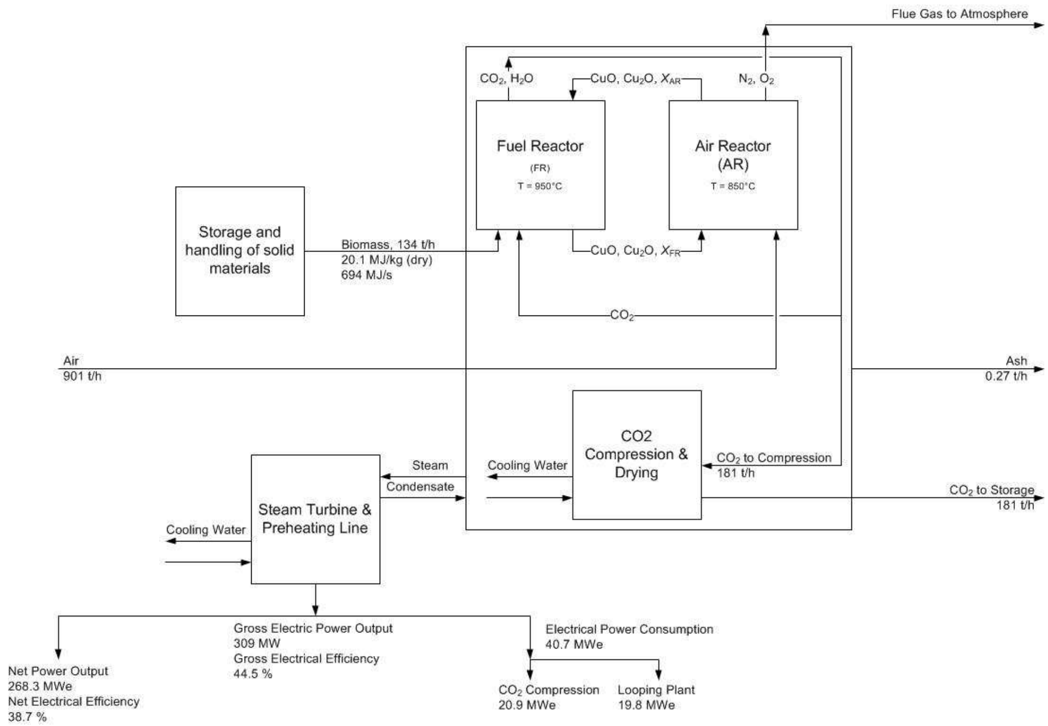

Figure 3: *A high-level process flow diagram for dedicated biomass chemical looping combustion (bio chem loop).*

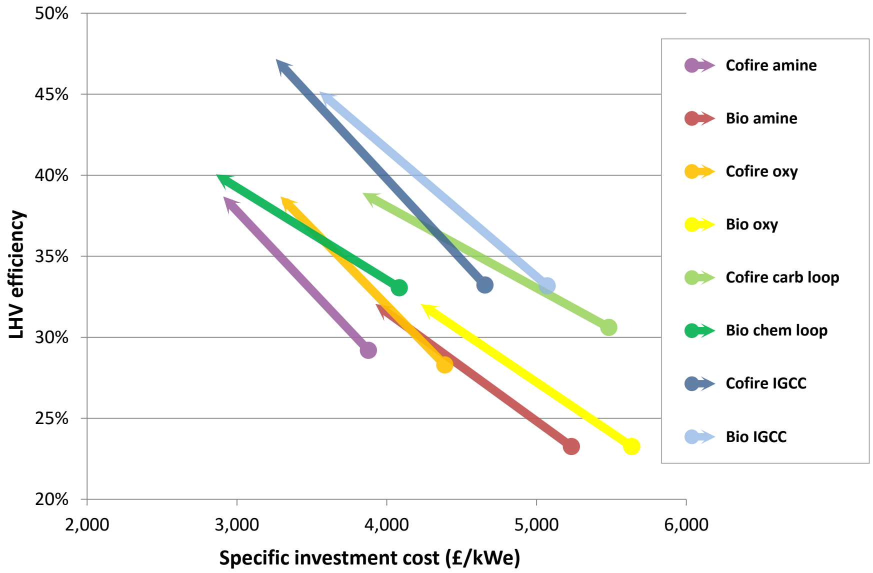

Figure 4: *LHV efficiency vs. "Nth-of-a-kind" specific investment costs for eight Biopower CCS technology options (dots indicate 2010 values and arrow heads indicate estimates for 2050).*

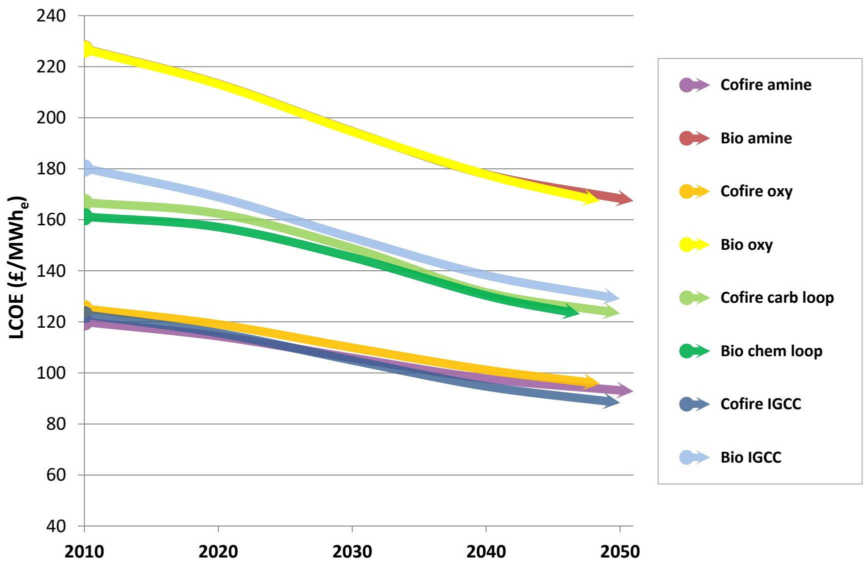

Figure 5: *LCOE for the eight Biopower CCS technology options up to 2050, at 50* MW_e.

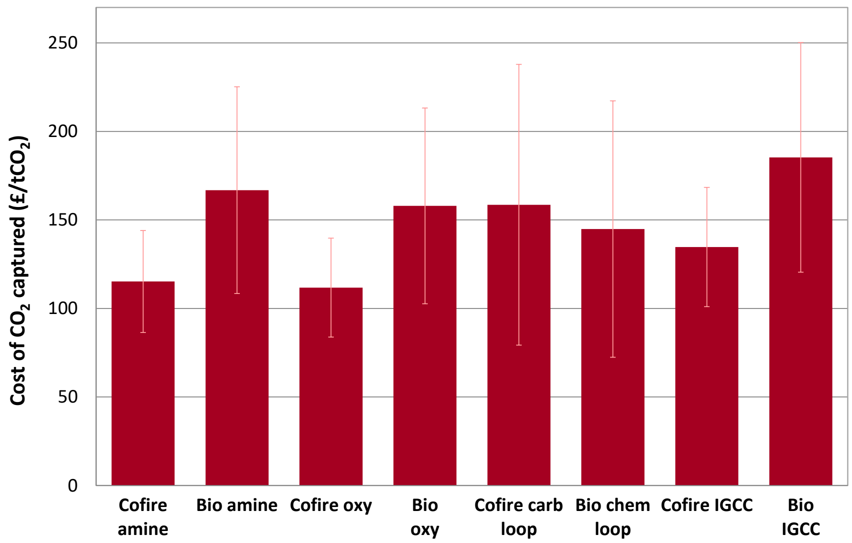

Figure 6: *Cost of CO_2 captured for the eight Biopower CCS technology options at 50 MW_e.*

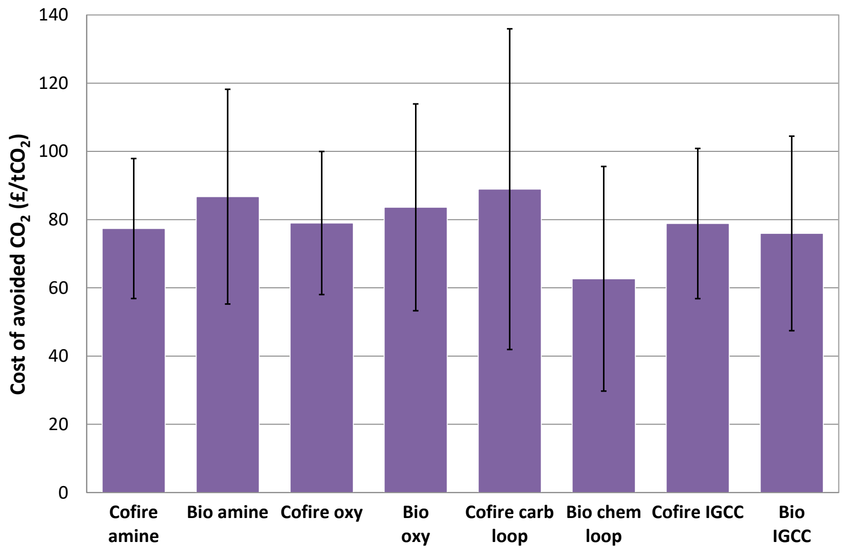

Figure 7: *Cost of CO_2 avoided for the eight Biopower CCS technology options at 50 MW_e.*