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 very 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. Despite its attractiveness, there exists a dearth of comprehensive data and analyses of the numerous Biopower CCS technology options available. We present the results of a first-of-a-kind analysis, the "Techno-Economic Study of Biomass to Power with CO_2 capture" (TESBIC) study, commissioned by the Energy Technologies Institute and performed by a multi-partner consor-

tium. The TESBiC project entailed desk-based review and analysis, process engineering, optimisation as well as primary data collection from some of the leading pilot demonstration plants in Europe, from the perspective of deployment of 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. Techno-economic characteristics such as capital and operating costs, LHV% electrical efficiencies as well as CO_2, SO_2 and NO_x emissions were modelled as a function of nameplate capacities, extent of co-firing and of CO_2 capture, covering the critical period up to 2050. 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 by 2050, given industry lead times and without a focused research development and deployment effort for particular technologies. For technology routes that allow a direct comparison between ”with-” and ”without-CCS” plants, 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 chemical looping combustion, however, there is no efficiency loss since both power generation and CO_2 capture are intrinsic to the operation of the technology. The plant scale (MW_e) was observed to be the principal driver of CAPEX (£/MW_e), rather than the choice of technology, with larger plants having lower specific capital costs. The co-firing %, i.e. the weighted feedstock cost, is one of the key drivers of Levelised Costs Of Electricity (LCOE), with

dedicated biomass options using expensive pellets always having significantly higher LCOE than co-firing with cheap coal. The data collected during the TESBiC project highlighted the lack of financial incentives for generation of electricity with negative CO_2 emissions, and also indicated that the most significant barriers to the deployment of Biopower CCS technologies will be economic and regulatory in nature, rather than technical.

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

1. Introduction

Due to its large-scale negative emissions potential, biomass-based power generation combined with CO_2 capture capture and storage (Biopower CCS) presents a high value option that persistently features in most cost-effective scenarios or pathways aimed at decarbonising global energy use and achieving climate change targets [1, 2, 3, 4]. The global technical potential of negative CO_2 emissions from Biopower CCS, if deployed, has been estimated to be of the order of 3.2 to 10.4 Gt CO_2e/yr [5, 6]. The International Energy Agency (IEA) 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 change [7, 8]. This means that technologies that can rapidly remove vast amounts of CO_2 from the atmosphere may therefore need to become a significant part of the energy mix, if other mitigation measures fail to keep the world on track to meet their emissions targets - a fact emphasised in the recent IPCC report which placed an unprecedented emphasis explicitly on Bio-energy CCS [9]. Both the IEAGHG and EBTP-ZEP have recognised the strong potential of Biopower CCS for carbon abatement, but the dearth of comprehensive data and analyses on Bio-energy CCS in general has also been highlighted [4, 5, 6, 10].

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 recognised by the Committee on Climate Change and the Energy Technologies Institute [11, 12]. We present some of the results from a study that was commissioned by the Energy Technologies Institute (ETI) in the UK, to assess the 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) was performed by a multi-partner consortium comprising some of the leading industrials, SMEs and academic researchers in the fields of biomass, power generation, CO_2 capture and numerical modelling. The TESBiC project team consisted of large industrials (Drax Power: leading the UK efforts in conversion of 4000 MW_e capacity from coal to biomass, EDF: one of the largest producers of low-carbon electricity in Europe), engineering services companies (Doosan Power systems and Alstom Boiler France), leading academic research groups (University of Cambridge, Imperial College London, University of Leeds) and specialised small to medium enterprises (SMEs) namely, E4tech and CMCL Innovations.

The TESBiC project entailed desk-based review and analysis [13, 14, 15, 16, 17, 18], numerical modelling, optimisation as well as data collection and interviews at some of the leading pilot demonstration plants in Europe. 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. Twenty eight such Biopower CCS technology combinations were identified and assessed by the TESBiC consortium.

Note that the TESBiC study did not consider waste-to-energy plants, 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 [19].

In this paper, we present a short summary of the TESBiC study and some of its findings.

2. Approach

Twenty eight Biopower CCS technology combinations were examined based on the following assessment criteria covering the critical period up 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.

Given the lack of Biopower CCS data in the public domain, and the large variance between the technology readiness levels of the various technology combinations involving biomass for power production and CCS (Figure 1), the unique composition of the TESBiC consortium therefore proved extremely beneficial during the landscape review, screening, model development and the ensuing analysis phases.

[Figure 1 about here.]

Furthermore, to help ensure that the overall economic parameters can 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 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%. 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. Landscape review and screening of twenty eight technology combinations were performed based on data from the project partners and from literature, the TRL analysis, and a review of existing roadmaps in the energy and CCS space. As a result, the following eight technology combinations were selected for further 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 routes represented a wide range of current TRLs (Technology Readiness Levels) i.e. from TRL4 (bench-scale test rig) to TRL7 (full scale demonstration). 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 RD&D effort was made in advancing specific technology routes.

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 BIGCC plant, they were not focused upon with the TESBiC study. Biomass integrated gasification fuel cell (BIGFC) technology is currently around TRL 4-5, but without CCS [20, 21].

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 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 $\mathrm{MW_e}$ and an intermediate scale of 250 $\mathrm{MW_e}$). The aforementioned techno-economic estimates based on the current state-of-the-art were then evolved through 2030, 2040 up to 2050 timescales for all eight technology combinations.

3. A work-flow example

In this section, the technical work-flow employed during the assessment is described with respect to a specific technology combination, as an example. Given the dearth 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 capacity of 268.3 $\mathrm{MW_e}$. 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 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 $\bar{y}_m = f(\bar{x}_n)$. Parameter estimation was performed with Model Development Suite (MoDS) software [22] to calibrate the meta models via the coefficient matrix A_{mn} to base case evaluations obtained from the detailed models.

4. 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 the only approach that 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 power generation. Presently, there are also 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.

Figure 4 gives the efficiency and CAPEX results for a common small scale of 50 MW_e plant capacity.

[Figure 4 about here.]

For lower current TRL technology options, the TESBiC data from existing pilot plants and demonstrations also helped in identifying the key technical and commercial gaps and challenges that exist for the selected Biopower CCS technologies. To present an example, in case of relatively lower current TRL technology options such as dedicated biomass chemical looping combustion, 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'.

5. Summary

The TESBiC study marked the completion of a first-of-a-kind assessment of a wide range of technology combinations involving biomass fuelled power generation combined with CO_2 capture. The key findings from the TESBiC study are summarised as follows:

1. 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 TRL7 (full scale demonstration). Only those options able to reach TRL 5 (pilot scale) by 2020 are considered likely to be advanced enough to be able to contribute to mass deployment in the UK by 2050, given industry lead

times (and without a major focused concerted RD&D effort on particular technologies).

2. 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 given that both power generation and CO_2 capture are intrinsic to the operation of the technology.
3. "Second generation" 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) yielded higher uncertainties in their techno-economic estimates as compared to the "first generation" technology combinations such as cofire amine and cofire oxy (TRLs 6 to 7).
4. Key performance parameters for the eight TESBiC technologies were benchmarked at common plant scales (of 50 MW_e and 250 MW_e). The large-scale biomass co-firing technologies using solvent scrubbing, oxy-fuel and IGCC with physical absorption (cofire amine/oxy/IGCC, respectively) have low capital costs and similar overall generation efficiencies (with future upside potential for cofire IGCC). These similarities, and low coal costs, are expected to yield low LCOE (Levelised Cost Of

Electricity) and low costs per tonne of CO_2 captured and avoided for these technologies.

5. The dedicated biomass technologies (bio amine/oxy/IGCC) typically have higher specific investment costs, when benchmarked at the same scale. The combustion technologies (bio amine & oxy) also have relatively low generation efficiencies. Although these facts are expected to yield higher LCOE values and costs per tonne of CO_2 captured, the major advantages of the dedicated biomass technologies, however, are that they do not involve fossil fuel utilisation and that they offer very significant negative CO_2 emissions per kWh generated at small-scale.
6. Bio chem loop shows potential to provide relatively high generation efficiencies and low capital costs across a range of scales, and could offer attractive negative CO_2 emissions. However, compared to the other six options, there are much higher technical risks attached to the development of bio chem loop and cofire carb loop technologies. In the case of bio chem loop major uncertainties around the selection of an optimal oxygen carrier material suitable for biomass feedstocks, its stability and lifecycle, and the carrier attrition rates at large scales, were highlighted during the course of this study.
7. In general terms, 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. 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.

8. Significant increases in the electricity generation efficiencies and reductions in the capital costs of all of the technologies have been 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.
9. An outline development roadmap for each of the technologies has also been prepared. In the case of the more developed capture technologies, the route to further development after demonstration of the capture technology on coal-fired plant would involve demonstration of the technology at commercial scale on a dedicated biomass plant or a coal plant co-firing biomass. The roadmaps for many of the biomass CCS technologies are closely tied to the development of coal 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 have been defined.
10. 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.
11. Lastly, establishing sustainable biomass supply chains with low up-

stream emissions (and few indirect impacts on existing land use and carbon stocks) is an important issue 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 footprint while producing power.

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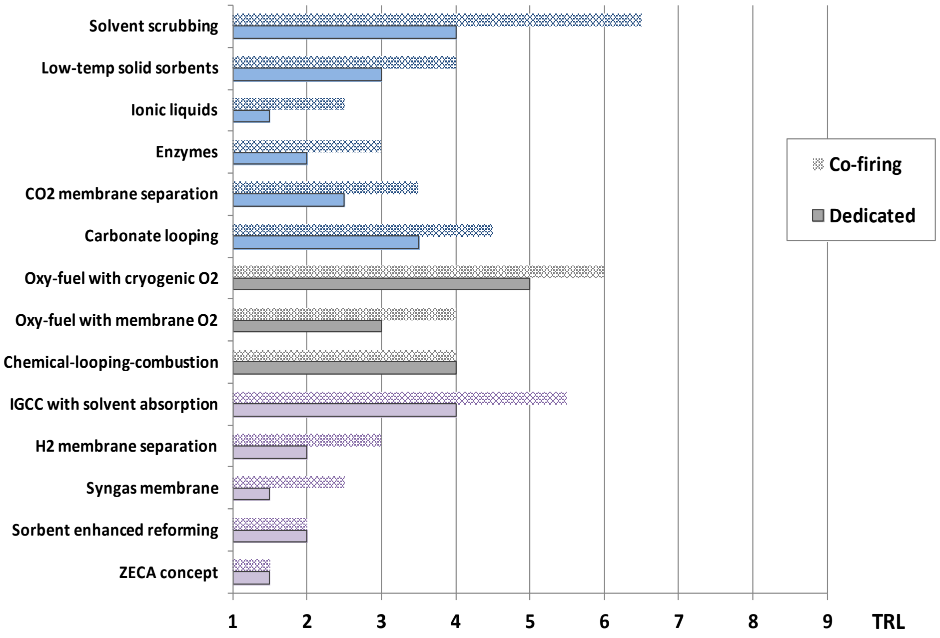

Figure 1: *Current technology readiness levels (TRL) for CCS technologies.*

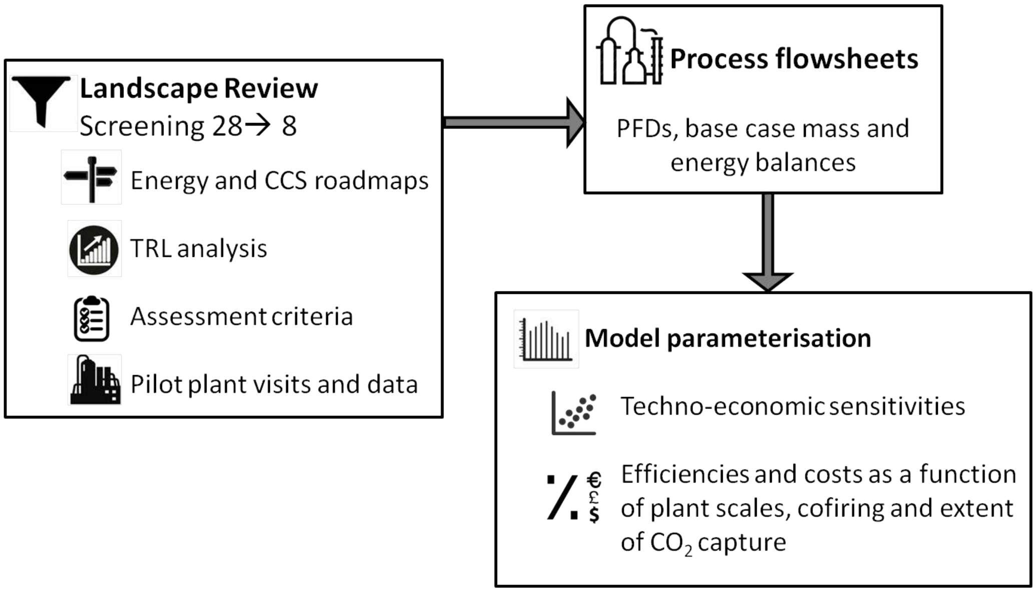

Figure 2: *TESBiC work-flow.*

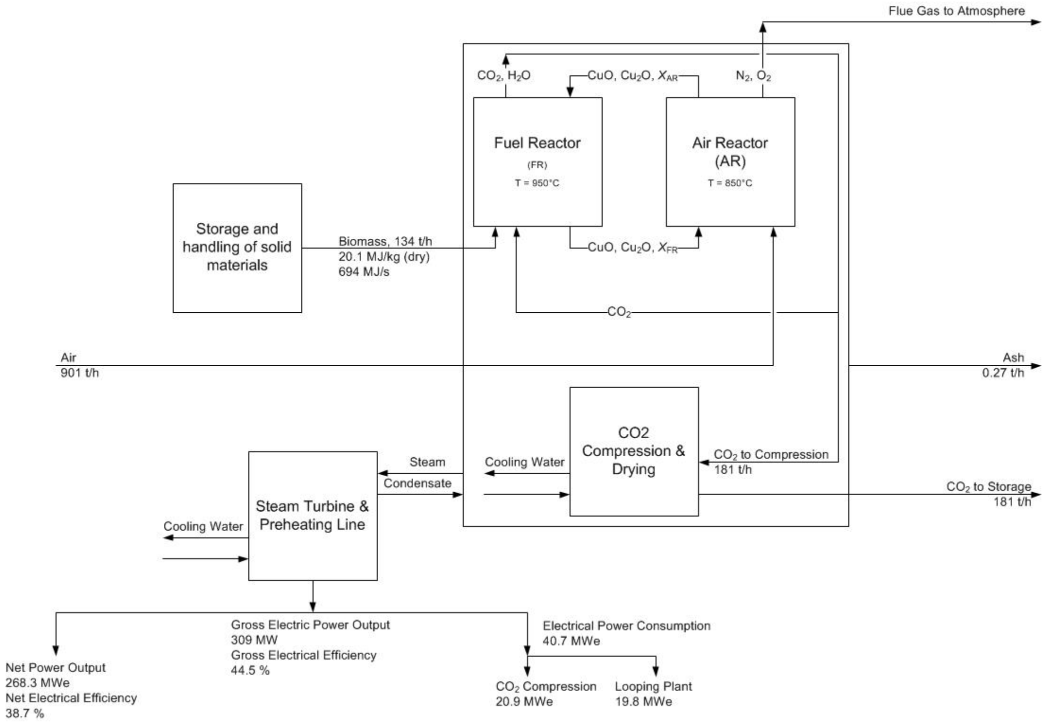

Figure 3: *A high-level process flow diagram for dedicated biomass chemical looping combustion (bio chem loop).*

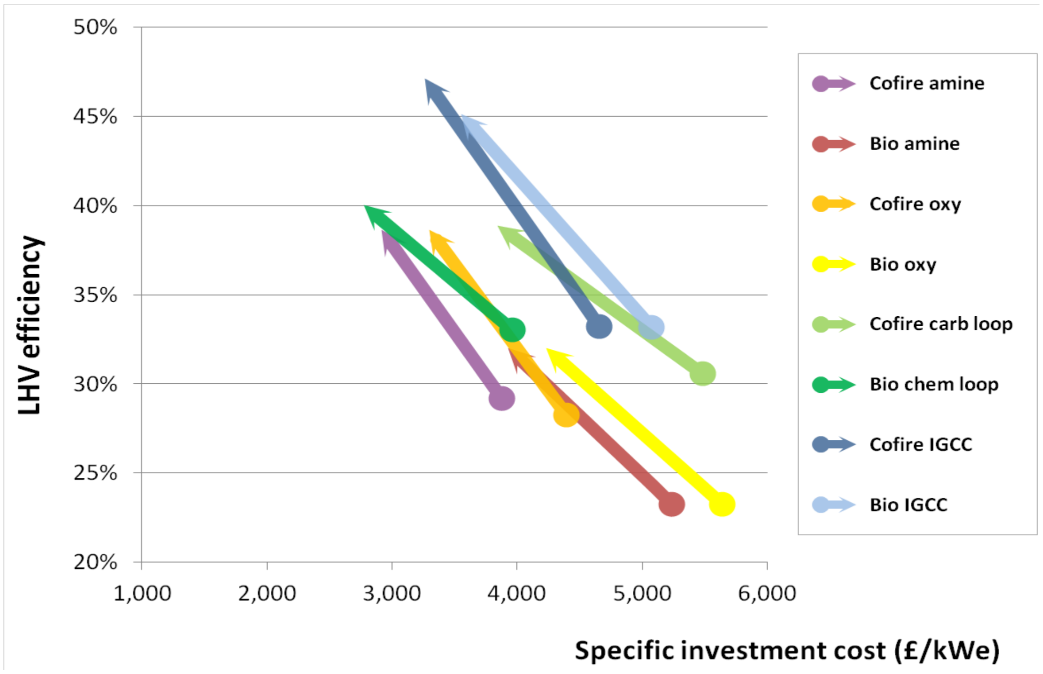

Figure 4: *LHV efficiency vs. "Nth-of-a-kind" specific investment costs for eight Biopower CCS technology options (dots indicate 2010 values and arrow heads indicate estimates for 2050).*