University of Sheffield | Energy Innovation Centre

Optimised Solvent Plant Configurations

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Key Knowledge Deliverable Cover Sheet

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UK BECCS-MCFC: Next Generation CCUS Technology for Net-Zero 2050

Baseline Test Work: Optimisation - Reporting Optimised solvent/plant configurations.

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Optimised solvent plant configurations for comparison with BECCS MCFC options

The purpose of this report is to describe the plant configurations using conventional amine post-combustion capture and other conventional technologies that best match the proposed novel molten carbonate fuel cell (MCFC) BECCS configurations.

Novel MCFC technology is being proposed for biomass energy with carbon capture and storage (BECCS) applications in the UK. To assess its technical and economic viability, as part of this project test work on a pilot scale MCFC will be used to underpin techno-economic analysis (TEA) of future commercial plants. This TEA will be contrasted with comparable values for the conventional amine post-combustion capture options described in this report.

Two possible MCFC BECCS configurations are described first, then their nearest conventional plant analogues. It is assumed that the reader is familiar with the basic features of the following types of plant, some example reference sources are also indicated in the footnotes: MCFC[1], biomass steam boiler and combined cycle gas turbine power plants with CCS[2] and methane reformers[3] for hydrogen production.

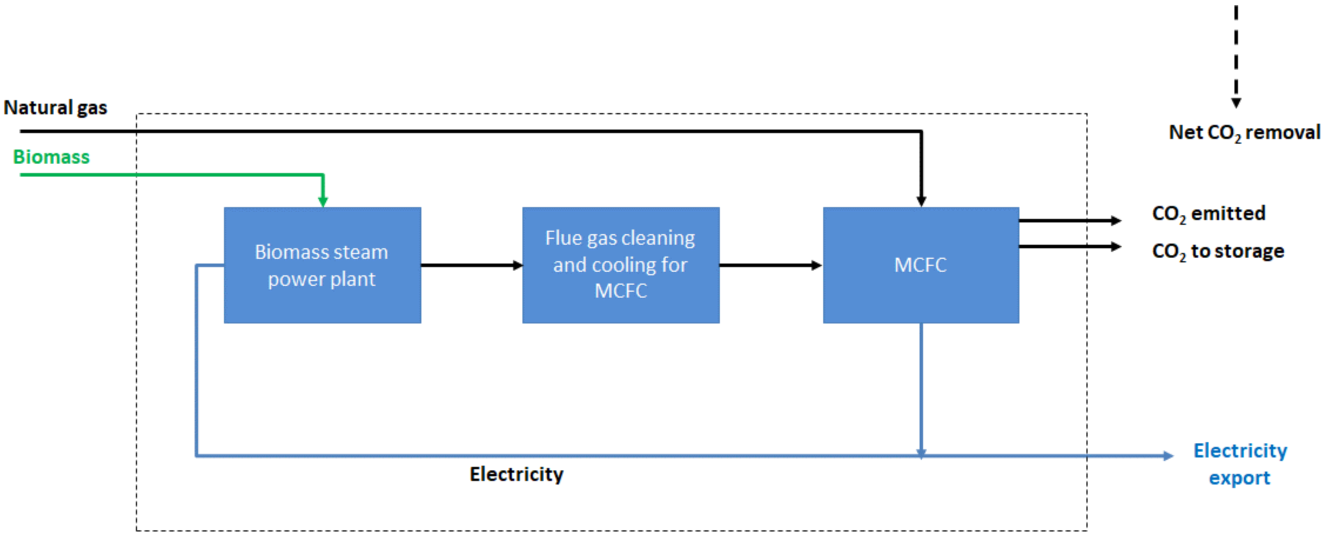
Both sets of BECCS options (MCFC and conventional) are based on biomass combustion only, since large-scale biomass gasifiers capable of producing either a syngas for conventional hydrogen production or a fuel gas for MCFC are not commercially proven.

Because different plant configurations contain common elements and individual sections want to be readable as stand-alone items, there is some repetition of text on the same issues.

[1] https://www.gov.uk/government/publications/review-of-next-generation-carbon-capture-technology-for-industrial-waste-and-power-sectors
[2] https://ukccsrc.ac.uk/wp-content/uploads/2023/01/BAT-for-PCC_v2_EfW_web-1.pdf
[3] https://www.gov.uk/government/publications/review-of-emerging-techniques-for-hydrogen-production-from-methane-and-refinery-fuel-gas-with-carbon-capture

MCFC BECCS configurations

MCFC fuelled by natural gas and producing electricity integrated with a biomass combustion steam plant



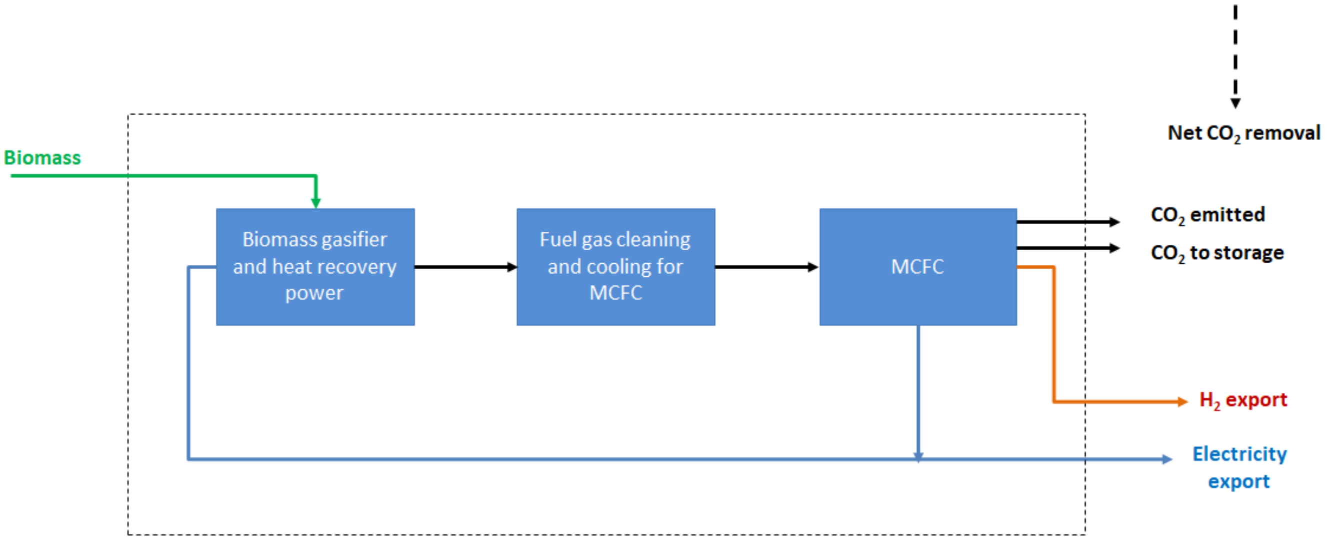
MCFC fuelled by natural gas and producing electricity integrated with a biomass combustion steam plant

This configuration is based on a conventional biomass combustion power plant that burns biomass to generate steam that is then used in a steam turbine to generate electricity. A range of plant sizes and boiler types might be used, but all have the same basic inputs/outputs. The flue gas is then cleaned to the high standard required and passed to a MCFC (possibly several MCFC units, via a manifold system) for CO2 capture. To make the MCFC work, natural gas fuel is supplied directly to it and, in this case, the MCFC converts as much as possible of the energy in the fuel to electricity. The overall capture rate expected for the carbon dioxide from natural gas is up to 100%[4]. The overall capture rate expected for the CO2 in the flue gas from the biomass plant is up to ~95%. Note that the transfer system for flue gas to the MCFC may also involve an open stack, to avoid the potential for over-pressurisation if the induced draft fan on the boiler plant and the forced draft fan on the MCFC plant fail to match flows exactly. In this case any leakage out from the open stack will obviously also adversely affect the biomass flue gas capture rate.

The electricity produced by this configuration will vary in value in future UK electricity generation mixes dominated by variable renewable electricity (VRE) sources, principally wind and solar. In particular, at times when VRE generation exceeds demand, especially demand that is already net of peak electricity balancing uses such as charging storage, generating electrolytic hydrogen etc., the electricity production from both the biomass power plant and the MCFC may be valueless.

[4] https://www.sciencedirect.com/science/article/pii/S0306261922000393?via%3Dihub
T. A. Barckholtz, K. M. Taylor, S. Narayanan, S. Jolly and H. Ghezel-Ayagh, “Molten carbonate fuel cells for simultaneous CO2 capture, power generation, and H2 generation,” Applied Energy, vol. 313, 2022.

MCFC fuelled by natural gas and producing as little electricity and as much hydrogen as possible integrated with a biomass combustion steam plant



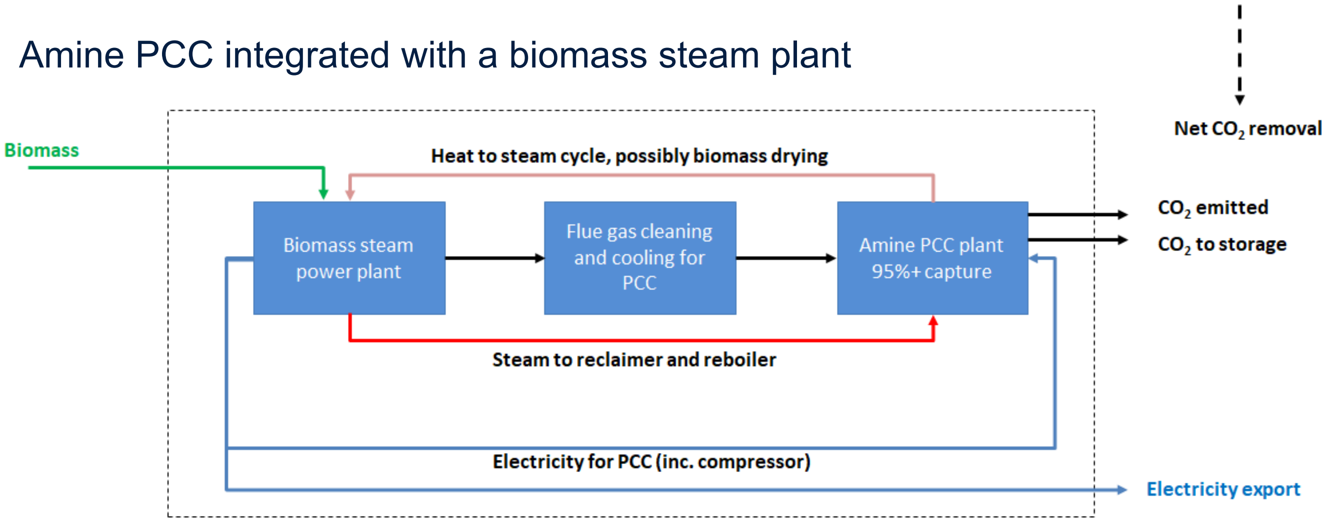
MCFC fuelled by natural gas and producing as much hydrogen as possible electricity integrated with a biomass combustion steam plant

This configuration is similar to the previous one, but the MCFC is operated to minimise electricity production and maximise hydrogen production from conversion of the natural gas feed. It is possible that there is always a demand for the hydrogen because it can be stored if not required at the time. It is also possible, however, that factors such as the demand for hydrogen in the UK being seasonal, the variability in electrolytic hydrogen production from VRE and limitations on hydrogen storage capacity make this assumption invalid.

As before, the overall capture rate expected for the carbon dioxide from natural gas is up to 100% and from the biomass flue gas is expected to be up to ~95%, subject to any leakage during the flue gas transfer.

Solvent BECCS configurations

Amine PCC integrated with a biomass steam plant



Best Available Technology amine PCC integrated with a biomass steam plant

This configuration is based on a conventional biomass combustion power plant that burns biomass to generate steam that is then used in a steam turbine to generate electricity. A range of plant sizes and boiler types might be used, but all have the same basic inputs/outputs. The flue gas is then cleaned as necessary and passed to an amine post-combustion capture (PCC) plant. Steam and electricity for the PCC plant are provided from the biomass plant, reducing the amount of electricity available for export. Capture rates of 95% are the current expected standard for PCC on biomass power plants in UK guidance[5] and even higher capture rates may be achieved in practice[6]. Note, though, that the transfer system for flue gas to the PCC plant may also involve an open stack, to avoid the potential for over-pressurisation if the induced draft fan on the boiler plant and the forced draft fan on the PCC plant fail to match flows exactly. In this case any leakage out from the open stack will obviously also adversely affect the biomass flue gas capture rate.

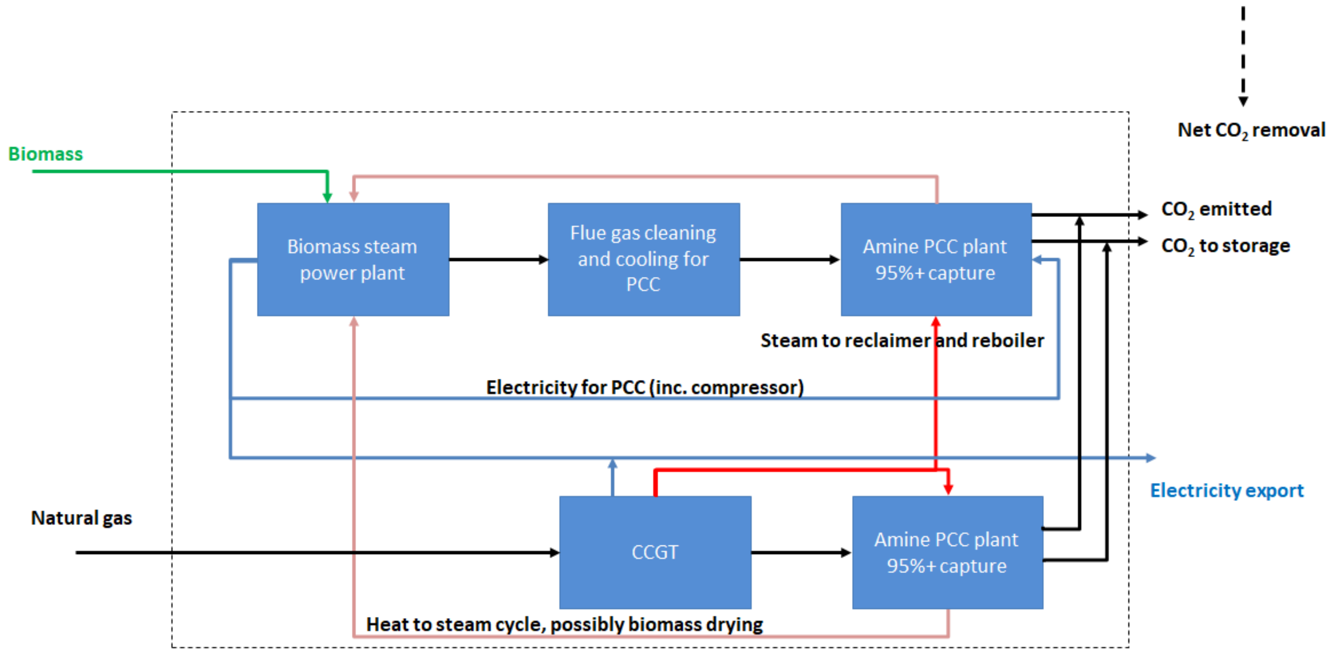
The electricity produced by this configuration will vary in value in future UK electricity generation mixes dominated by variable renewable electricity (VRE) sources, principally wind and solar. In particular, at times when VRE generation exceeds demand, especially demand that is already net of peak electricity balancing uses such as charging storage, generating electrolytic hydrogen etc., additional electricity production from the biomass power plant may be valueless. To take advantage of this varying value for exported electricity rich and lean solvent storage tanks can be used so that at least some of the electricity output penalty can be taken during periods of low electricity value, with a consequent increase in net plant electricity output at times of high electricity value[7].

[5] https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat

[6] https://ukccsrc.ac.uk/wp-content/uploads/2023/01/BAT-for-PCC_v2_EfW_web-1.pdf

[7] Chalmers, H., Gibbins, J. & Leach, M. (2012) *Valuing power plant flexibility with CCS: the case of post-combustion capture retrofits*, Mitigation and Adaptation Strategies for Global Change, vol. 17, no. 6, pp. 621-649. https://doi.org/10.1007/s11027-011-9327-5

Amine PCC combined with a biomass steam plant and a CCGT+PCC



Amine PCC integrated with a biomass steam plant and a CCGT+PCC

If baseload, mainly gas fired, electricity output, as with the ‘MCFC fuelled by natural gas and producing electricity integrated with a biomass combustion steam plant’ configuration is, however, valuable then a gas-fired combine cycle gas turbine (CCGT) + PCC plant might be integrated with a biomass PCC plant. Various integration options are possible, in the one shown above steam is supplied for the biomass PCC unit from the CCGT heat recovery steam generator (HRSG) and surplus low grade heat (at temperatures below the low-pressure (LP) pinch in the HRSG) is also sent to the biomass steam plant.

This approach gives the greatest possible output from the biomass steam plant and would therefore attract greater revenues if a premium price was paid for BECCS electricity – and measures were not in place to avoid some natural gas energy also being rewarded for appearing as output from the BECCS plant.

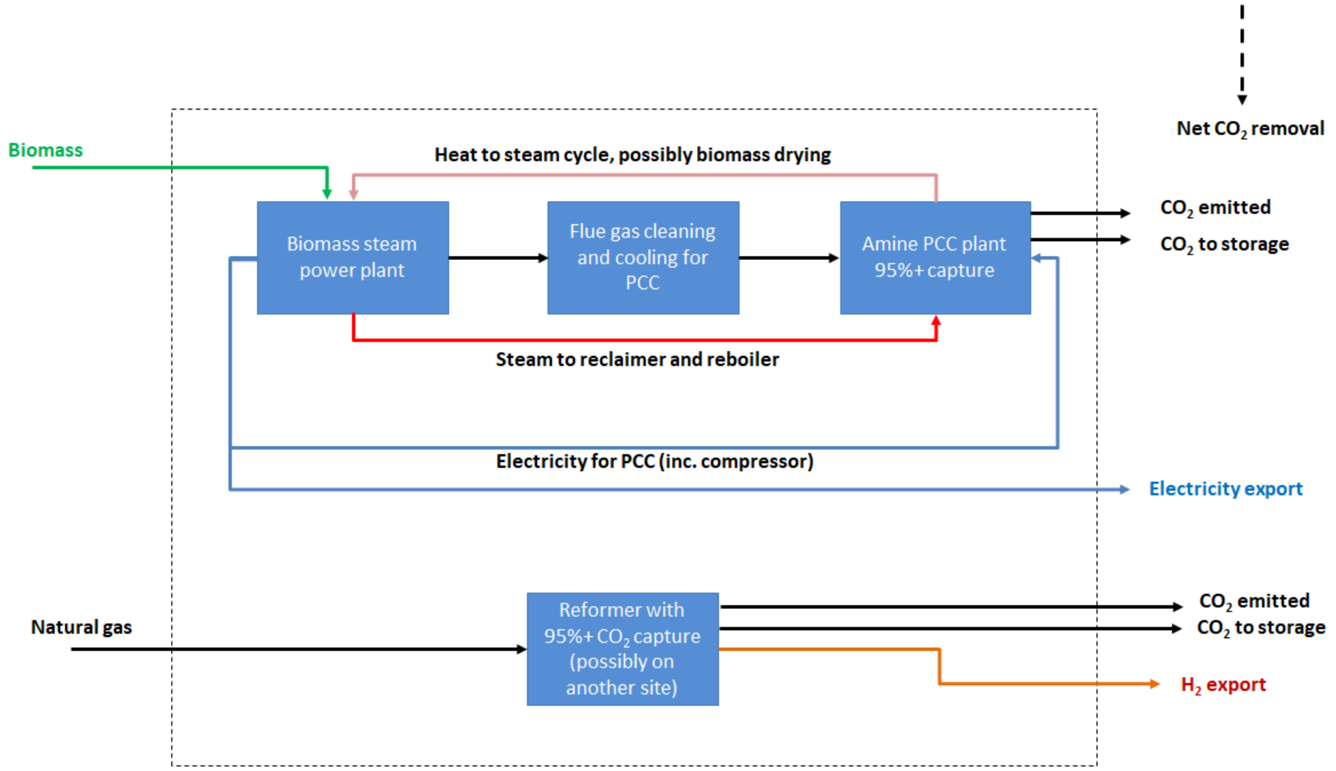
More extreme integration, particularly with small size units, might theoretically see a shared absorber, more likely a shared stripper. Sequential combustion, where the GT flue gas is sent to the biomass boiler to recover heat and, in the context of PCC to raise the CO2 content, is also possible but not likely.

If the natural gas CCGT+PCC plant was not integrated, and possibly even sited elsewhere, with the BECCS plant configured as in the previous case and providing its own steam and electricity for the PCC unit, then the confusion over electricity source would not occur. A slight reduction in aggregate electricity production might appear to result, due to the inability to use heat below the LP pinch in the HRSG but, for smaller BECCS applications, the separate CCGT could in effect be a part of a much larger conventionally-sized CCGT power plant, with very significant cost and efficiency improvements.

The greatest benefit of separate operation (and possibly siting) of the CCGT+PCC and BECCS plant is, however, the CCGT+PCC plant can be shut down at periods when its electricity was not required due to surplus VRE and would be essentially valueless, saving unnecessary natural gas consumption.

As before, the overall capture rate expected for the carbon dioxide from natural gas and from the biomass flue gas is expected to be 95% or greater, subject to any leakage during the flue gas transfer.

Amine PCC integrated with a biomass steam plant and a separate natural gas reformer



Amine PCC integrated with a biomass steam plant and a separate natural gas reformer

This combination minimises the amount of baseload electricity production and maximises the hydrogen production from natural gas with CCS, for comparison with the ‘MCFC fuelled by natural gas and producing as little electricity and as much hydrogen as possible’ case. It is possible that an electricity supply is also required for the natural gas reformer unit; this could be provided from the BECCS plant but this would not constitute a genuine baseload demand in most cases (i.e. unless grid connections were infeasible), since it could be more cheaply supplied from the grid at times when VRE generation is plentiful.

A conventional biomass combustion power plant burns biomass to generate steam that is then used in a steam turbine to generate electricity. A range of plant sizes and boiler types might be used, but all have the same basic inputs/outputs. The flue gas is then cleaned as necessary and passed to an amine post-combustion capture (PCC) plant. Steam and electricity for the

PCC plant are provided from the biomass plant, reducing the amount of electricity available for export. Capture rates of 95% are the current expected standard for PCC on biomass power plants in UK guidance[8] and even higher capture rates may be achieved in practice[9], subject to any leakage during the flue gas transfer.

For comparison with the high-hydrogen MCFC case, a natural gas reformer is assumed to be used to generate hydrogen. This reformer could be a range of types; all achieve similar conversion efficiencies from natural gas to hydrogen and can capture 95% or more of the CO2 produced[10].

Feed-through into the TEA

The amine capture plant baseline TEA for this Work Package will always use the optimised full-integrated amine plant, optionally with solvent storage.

The additional CCGT+PCC plant for power and a natural gas reformer for hydrogen production will be assumed to be independent from the amine BECCS plant, since this is likely to be the norm and so independent plants will be the electricity and hydrogen market price-setters.

Estimated values for dispatchable gas-fired electricity and hydrogen production with CCS will then be produced based on published data for the characteristics of these plants plus the key variables being considered for the amine capture plant baseline, principally natural gas price and the fraction of time that available generation is in excess of demand.

The amine capture plant will be assumed to be penalised by extra costs for the ‘lost’ electricity output at the value of alternative electricity sources.

Similarly, the MCFC configurations can be assumed to be rewarded by revenues at the value of alternative electricity and hydrogen sources in the techno-economic analysis, to offset the additional cost for the natural gas fuel supply to the fuel cell.

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[8] https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat

[9] https://ukccsrc.ac.uk/wp-content/uploads/2023/01/BAT-for-PCC_v2_EfW_web-1.pdf

[10] https://www.gov.uk/government/publications/review-of-emerging-techniques-for-hydrogen-production-from-methane-and-refinery-fuel-gas-with-carbon-capture

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