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Modelling and optimisation

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Key Knowledge Deliverable Cover Sheet

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

BECCS techno-economic analysis for solvent post-combustion capture using concentrated MEA and an advanced amine blend to compare with MCFC configurations

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Abbreviations

AC	Alternating current
ACC	Amortized Capital Cost
BECCS	Biomass Energy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
COE	Cost of electricity
DC	Direct Current
DESNZ	Department for Energy Security & Net Zero
FGD	Flue Gas Desulphurisation plant
H_2	Hydrogen
IC	Indirect Cost
LHV	Lower Heating Value (also known as net calorific value)
MEA	Monoethanolamine
MCFC	Molten-carbonate fuel cell
NG	Natural Gas
NH_3	Ammonia
NOx	Oxides of Nitrogen
O_2	Oxygen
O&M	Operation and Maintenance
Pa	Pascal, unit of pressure, 1N/m2
ppm	parts per million
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide (with water, forms sulphuric acid)
SOx	Oxides of Sulphur (unspecified mix of SO2 and SO3)
TCC	Total capital cost
TEA	Techno-Economic Analysis
TERC	Translational Energy Research Centre
Uc	Carbon utilisation
Uf	Fuel utilisation ratio
UK	United Kingdom

Introduction

Bioenergy with Carbon Capture and Storage (BECCS)

BECCS is a technology that combines biomass-based energy generation with carbon capture and storage (CCS) methods [1], [2]. It consists of converting biomass, such as agricultural wastes, forestry waste, or specific energy crops, into biofuels or biogas via gasification [3], or fermentation [4] or generating heat/power via combustion[5], [6]. The CO_2 produced during biomass combustion, gasification/or fermentation is caught and stored, keeping it from being released into the environment and contributing to global warming [7]. BECCS has emerged as a potential strategy for climate change mitigation since it not only generates renewable energy but also actively removes CO_2 from the environment, thereby lowering greenhouse gas emissions [8].

Molten Carbonate Fuel Cell (MCFC)

Molten Carbonate Fuel Cell (MCFC) technology employs a molten carbonate electrolyte and operates at high temperatures. Primarily, MCFC technology generates electricity. However, it indirectly facilitates CO_2 concentration. During electrochemical reactions, CO_2 entering the cathode side of the cell (a combustion flue gas) is transferred to the anode (which is fed with hydrogen fuel from an integrated reformer), where it becomes more concentrated [9], [10], [11], [12], [13], [14], [15]. MCFCs have several benefits, including their high efficiency, fuel flexibility (they can run on a range of fuels, including biogas and natural gas), and ability to extract CO2 emissions straight from the input streams [16]. Owing to these features, MCFCs are seen as a potential technology for producing electricity with less of an adverse effect on the environment compared to current state-of-the-art solvent technology [13], [17], [18].

Objectives of the Study

This research aim for Task 4.1 is to provide a comprehensive techno-economic analysis (feasibility analysis) of an MCFC pilot plant with the potential of being considered as a scalable BECCS configuration for sustainable power generation. The goal of the project is to create a process simulation model that will allow researchers to evaluate the system’s efficiency and cost-effectiveness across a range of optimisation techniques and operating scenarios.

Literature Review

The technologies of Molten Carbonate Fuel Cells (MCFC) [19], [20] and Bioenergy with Carbon Capture and Storage (BECCS) have gained significant attention owing to their ability to mitigate climate change and offer sustainable energy alternatives [8]. The environmental benefits, economic viability, and technical feasibility of combining BECCS and MCFC systems have all been examined in several studies as shown in Table 1.

Table 1: Literature review for many configurations of MCFC integrated with BECC

Process	%CO_2 recovery	Size (MW)	OpEx (M$)	CapEx (M$)	COE $/MWh	$/t CO_2 avoided cost	Ref
Biomass plant +MCFC	74.8	40.29	-	-	80.95	-	[21]
Syngas (from biodiesel plant) +MCFC		0.303				-	[22]
NG+ MCFC-CCS cycles	75					-	[23]
Biomass+MCFC		1		2.125		-	[2]
(biogas /bioethanol)*+MCFC		0.013					[24]

*Reference [24] does not include details of costs

The material that is currently available on BECCS highlights how it may be used to combine carbon capture and storage methods with bioenergy production to achieve zero emissions [2], [3], [21], [25], [26]. To maximise BECCS performance and lower costs [27], [28], several researchers have looked at different biomass feedstocks [2], conversion technologies [23], and carbon capture strategies [21]. Furthermore, the effects of BECCS deployment on biodiversity, land use change [29], and net greenhouse gas emissions [30] have all been studied by academics.

Comparably, the goals of MCFC technology research have been to lower system costs, increase fuel flexibility, and improve cell performance [20], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40]. To increase efficiency [23], [41], [42] and reduce environmental impact [18], [19], [20], various MCFC and operating conditions have been investigated in several modelling and optimisation studies. Cell lifetime and reliability have been improved due to research into MCFC stack design [43], materials development, and degradation mechanisms [44]. The majority of studies are for natural gas combustion rather than for biomass-based flue gas.

Even with the significant research efforts in the MCFC and BECCS areas, the integration of these two activities is a major gap in the literature which calls for more research into Integrational Challenges:

- No previous studies have simulated BECCS systems integrated with MCFCs at the specific size of 30 kW (see Table 1). The primary objective is to fill this gap by conducting a simulation study of a MCFC system with the potential to be converted into a BECCS configuration at the scale of 30 kW.

- The study aims to bridge the gap between simulation-based research and practical implementation. This study will contribute to the advancement of BECCS-MCFC technology by providing insights into its performance and scalability beyond 30 kW. The validated model will be used to develop the scaling-up strategy and will serve as a valuable resource for future research and practical implementation of BECCS-MCFC systems.

Due to its ability to work as both an energy generation and CCS system, recent approaches have suggested the possibility of using MCFC as a negative emissions technology within a bioenergy with carbon capture and storage (BECCS) configuration. For this, the oxidant gas (an inlet of the cathode side) must be generated from a biogenic source, such as a biomass power plant, or through any other configuration that involves the generation of biogenic CO_2. There have been some studies concerning integration of coal plant with MCFC [35], [41], [45] and the impact of contaminents. Biomass types have different mixes of inorganics compared to coal, which could result in the presence of different pollutants in the flue gas generated during its combustion process. On the other hand, under the same idea of biogenic-based feedstock, the carbon footprint of the operation of the MCFC could be reduced by using biofuels, such as biomethane as the reagent gas (anode side), however, this configuration cannot be considered as a BECCS configuration.

As discussed above, much of the research has focussed on analysing scenarios where cathode and anode inlets receive fossil-based inputs. Few scenarios have tried to analyse the feasibility of an MCFC operating with biobased inlets. While the use of biogas as anode input has been assessed, there is a gap in the research about the use of oxidant gas with biogenic origin, such as from the combustion of biogenic feedstock. It is in this sense, that this study aims to fill this gap in the scientific literature by analysing an MCFC system that receives flue gas from the combustion of wood chips. The challenges associated with the system's integration and scalability will be discussed. This study intends to address gaps in the literature to increase our knowledge of the possible synergies between MCFC and BECCS technologies and make it easier for them to be integrated into future sustainable energy systems. This project aims to offer practical insights for industry stakeholders, policymakers, and researchers working towards a low-carbon energy transition through extensive modelling, optimisation, and analysis.

Gas cleaning in the context of an MCFC system operation

Given the wide and varied presence of contaminants in biogenic feedstock, the analysis of the potential presence of contaminants in both the fuel source and the oxidant gas is of major importance. Several studies have reviewed this issue, specifically when it comes to the anode side contaminants [46], [47], [48], [49], [50], however, there is still a lot of uncertainty about the effect of pollutants found in the cathode side, with few studies approaching this issue [49], [50], [51], [52]. Given that this work will propose a MCFC system with an innovative arrangement, based on the concentration of oxidant gas coming from a biomass-burning system, most of the interest in gas decontamination and adjustment is focused on the oxidant gas. Based on this concern, a summary of the available information is collected and summarized in Table 2:

Table 2: Contaminants effect on MCFC performance: cathode side

Contaminant	Effects	Source
SO_2	Corrosion of metallic parts, primary (2) and secondary (1) poisoning. Loss of electrolyte due to reaction 2, poisoning from H_2S. $H_2S + 1.5O_2 \rightarrow H_2O + SO_2$ (1) $CO_3^{2-} + SO_2 + 0.5O_2 \rightarrow CO_2 + SO_4^{2-}$ (2)	[49]
NO_x	Cell performance drops, triggers step-by-step increase of internal resistance. Effect decreases with increasing operating times.	[50]
Particulates	Dust contamination does not result in a sudden drop in electric parameters. Observed pressure difference between inlet and outlet.	[51]
Inorganic Aerosols	Possible metal salts deposition, unlikely to be able to regenerate electrolyte.	[53]

Methodology

Process simulation model development

The MCFC process plant simulation is carried out on Aspen Plus 14, using the Peng Robinson thermodynamic tool for the representation of the chemical and physical equilibrium between and within the different process streams. The composition of the gases exiting the MCFC unit is calculated using an in-house tool that, based on electrochemistry, fuel utilisation, and chemical equilibrium, can predict the composition of the output gases. This model was validated by the manufacturer and is therefore considered reliable for the scope of this work. The resulting exiting gas compositions are then supplied to the Aspen Plus model, which is shown in Figure 1 and Figure 2. Figure 1 describes the inlet of the anode side, in addition to its pre-heating system, while Figure 2 describing the same, but for the cathode side.

The system follows a typical configuration in which the inlet of the reformer/anode is natural gas, while the inlet of the cathode is the flue gas resulting from the grate boiler at TERC that is fed by biomass. The system is composed of an MCFC unit, for which both inlets should be fed at a specific temperature. To achieve these temperatures, both inlet trains are composed of a series of heat exchangers. At the same time, humidifiers are also present to achieve the required humidity demanded for the operation of the MCFC unit. The resulting unit produces a cathode outlet that has a lower CO_2 concentration when compared to the input. On the other hand, the anode outlet possesses greater importance as the CO_2 lost in the cathode is transferred there, but additionally, H_2, CO, and residual CH_4 are found in this stream. This creates various opportunities for increased technical and economic performance of the system, and it will be discussed in the following sections.

Figure 1. Aspen Plus process flow diagram of the anode and anode train of the MCFC.

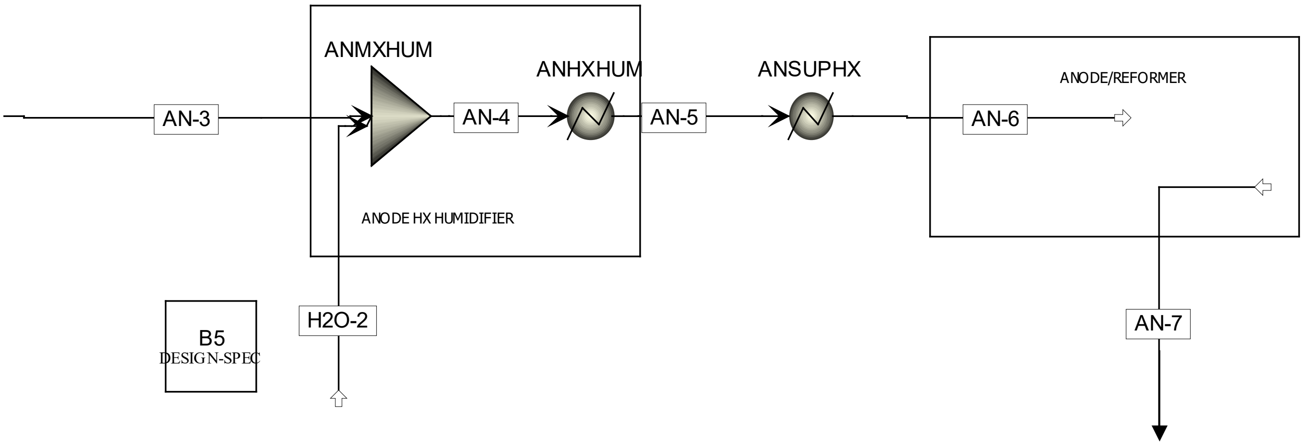
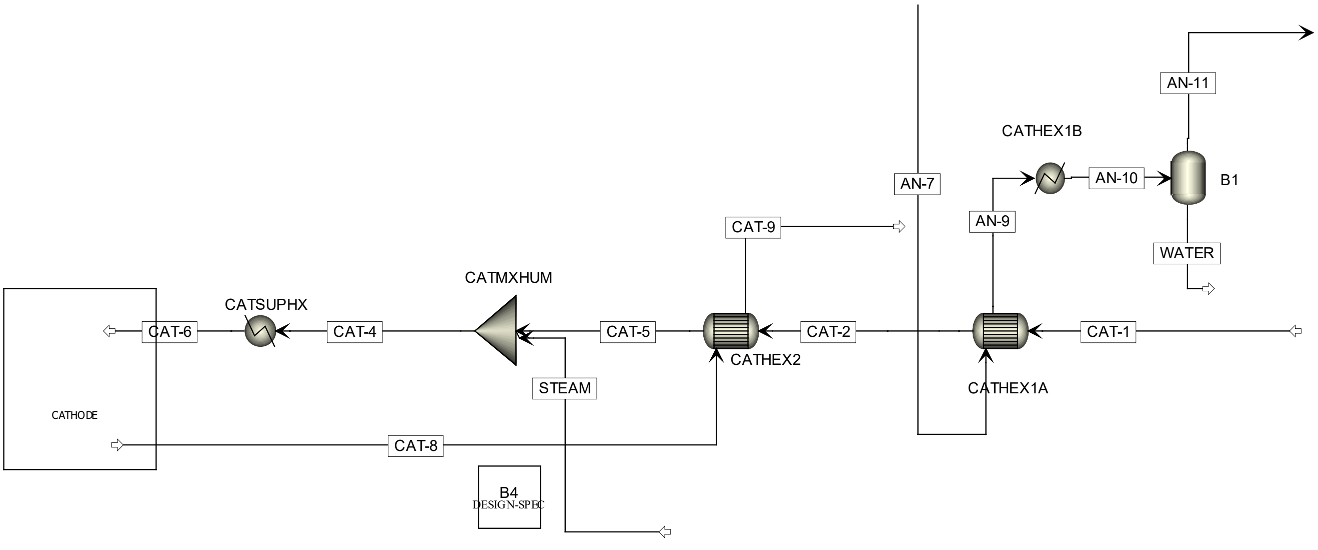


Figure 2. Aspen Plus process flow diagram of the cathode and cathode train of the MCFC.



Important variables include the inputs of both anode and cathode. For the anode, natural gas is used, with a molar composition of 20% H_2, 72% CH_4 and 8% CO_2). On the other hand, the cathode inlet is the flue gas of a grate boiler that uses wood chips for the combustion, and which molar composition is 10% CO_2, 12% H_2O, 70% N_2 and 8% O_2. Other MCFC-specific operating variables include temperature (590°C -605°C), pressure (101.3 kPa), fuel utilisation ratio (Uf) of

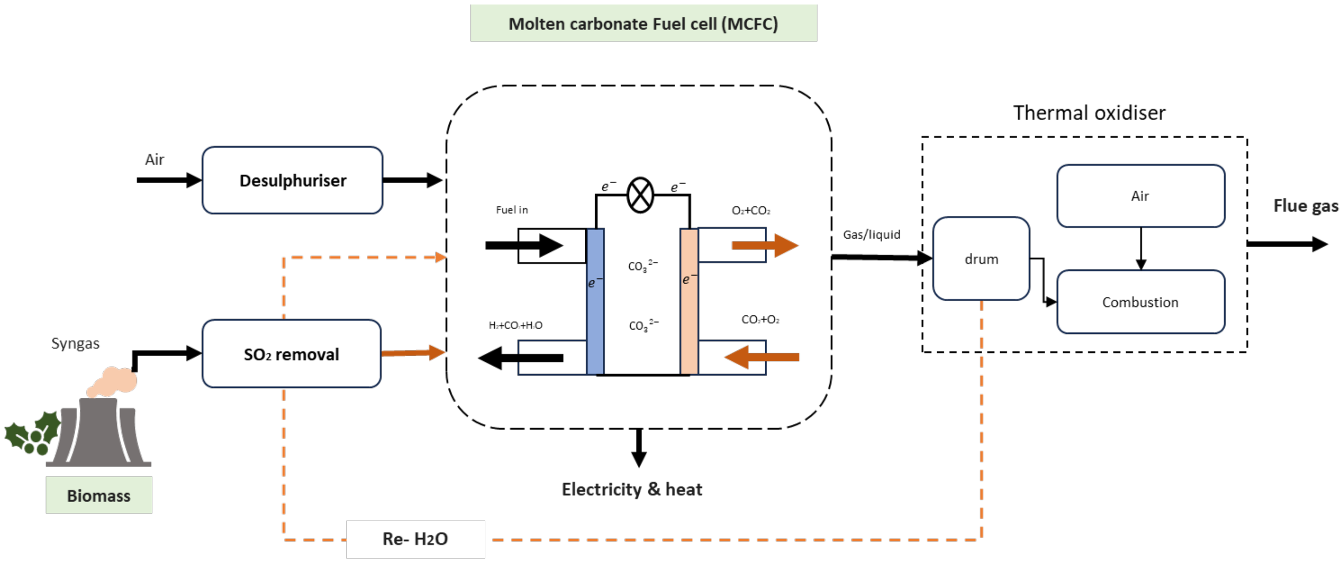
68%, carbon utilisation (Uc) of 86%, steam-to-carbon ratio (2.01). The overall chemistry conversion happening inside the MCFC unit is as shown in Eq. 1.

$$CH_4 + CO_2 + 2O_2 \rightarrow 5CO_2 + 4H_2O + Heat + electricity \qquad \textbf{Eq. 1}$$

It is pertinent to clarify that the system boundaries of the Aspen model omit the inclusion of the cleaning system model, owing to its incompatibility with the process software. It is assumed that the cleaning system will efficiently reduce impurities to a level where they cease to pose a substantive risk to the system. Due to the high sensitivity of the system to sulphur, a reduction in the sulphur content of the natural gas used on the anode side is necessary to prevent potential operational challenges that may produce a decrease in fuel cell performance. Following the meticulous cleaning process of the inlet streams to conform to the stringent standards for the anode and cathode inlet gases of the MCFC, which are tailored to match the cell's tolerance levels (sulphur <1ppm and particles <1ppm [54]), the electrochemical reactions commence within the MCFC. These reactions facilitate the conversion of chemical energy into both heat and electricity.

Upon exiting the MCFC anode and passing through a series of heat exchangers, both gaseous and liquid components are directed to a drum for further processing. The outlet water undergoes treatment for reuse, while the gas is routed to a combustor for thermal oxidising. In the thermal oxidiser, the gas is treated with air to ensure the release of flue gas into the environment excludes hydrogen (H_2) or carbon monoxide (CO), to meet environmental standards, see Figure 3. Future activities will consider scenarios where separation of hydrogen adds attractive flexibility of operation.

Figure 3 : pilot plant MCFC layout



Results and discussion

Process Simulation and Optimization

Validation of the Model

To guarantee the correctness and dependability of simulation findings, the model was compared with that of previously published elsewhere in the literature when MCFC was integrated with a biofuel-based source [24], which is based on some similar simulation parameters, and shown in Table 3.

Table 3: Simulation results of [24] **and MCFC model in this work.**

	This work	Ref [24]
Cell Number	30	30
Stack active area (cm^2)	7825	3000
Cell density (mA/cm^2)	172	180
Fuel utilisation (%)	68	-
CO_2 utilisation(%)	68	-
Steam-to-carbon ratio	2.01	2.5-4.5
Voltage (V)	0.747	0.45-0.63 @(550-650°C)
MCFC output electricity (kW)	30	13
Cathode inlet compositions (mol %)	10% CO_2, 12% H_2O,70% N_2 and 8% O_2	35% CO_2,65% CH_4

For illustrative purposes, Figure 4 depicts the key streams that were simulated in the Aspen Plus model. Their details are presented in Table 4.

Figure 4: The flowsheet of MCFC

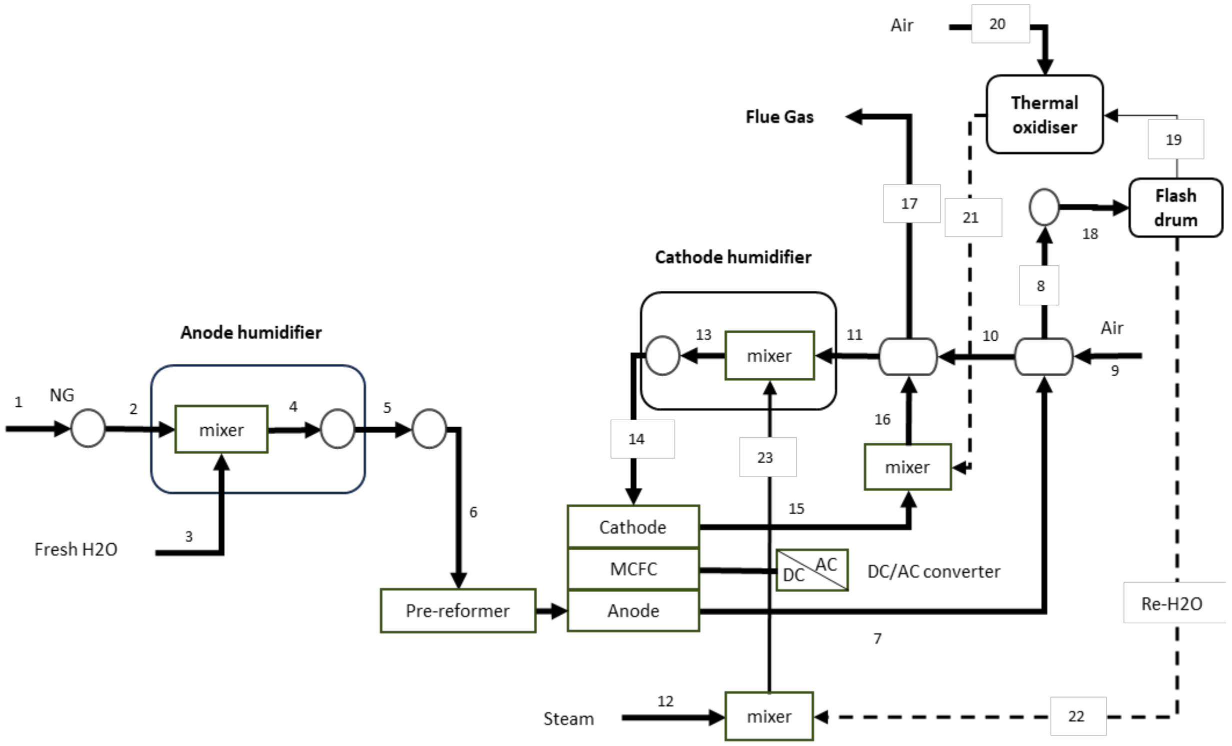


Table 4: The detailed data for relevant streams of the MCFC system

	T (°C)	P (bar)	M (kg/hr)	Mole Flow (Nm3/hr)	Molar compositions (%) H_2	CH_4	CO_2	CO	H_2O	N_2	O_2
1	15	1.13	5.511	8.0	19.96	72.09	7.95				
2	15	1.01	5.511	8.0	19.96	72.09	7.95				
3	15	1.13	9.29	11.5					1.00		
4	15	1.13	14.80	19.5	8.00	29.00	3.00		59.00		
5	150	1.03	14.8	19.5	8.00	29.00	3.00		59.00		
6	605	1.03	14.8	19.5	8.00	29.00	3.00		59.00		
7	590	1.03	59.35	47.5	10.37		43.00	5.47	41.00		
8	180	1.03	59.35	47.5	10.37		43.00	5.47	41.00		
9	15	1.05	292.03	216.7			11.36			79.20	9.43
10	135.3	1.05	292.03	216.7			11.36			79.20	9.43
11	601.8	1.05	292.03	216.7			11.36			79.20	9.43
12	105	1.05	8.54	10.6					1.00		
13	538.7	1.05	315.82	246.2			9.99		12.00	69.68	8.30
14	590	1.05	315.82	246.2			9.99		12.00	69.68	8.30
15	610	1.02	270.95	221.1			3.56		13.36	77.62	5.46
16	611.8	1.00	345.85	269.8			11.46		13.00	70.63	4.86
17	251.6	1.00	345.85	269.8			11.46		13.00	70.63	4.86
18	20	1.03	59.35	47.5	10.37	0.24	42.80	5.47	41.09		
19	20	1.03	44.10	28.5	17.28	0.40	71.35	9.11	1.84		
20	170	3.00	30.80	23.9						79.00	21.00

21	618.2	1.00	74.899	48.7			47.30		11.67	38.85	2.13
22	20	1.03	15.25	19.0	0.00	0.00	0.00	0.00	99.99		
23	15	1.01	23.79	29.6					1		

Explanation of the Optimisation Process:

Finding the best system configurations and operating conditions to maximise energy efficiency, reduce carbon emissions, and improve economic performance is the goal of the optimisation process. To explore the solution space and find the best-performing situations, mathematical optimisation procedures are used. The cost of electricity (COE) as an economic indicator is calculated based on the assumptions proposed in Table 5.

Table 5: main assumption to calculate COE

Discount rate (%)	7	[55]
Annual operating hours (hr)	8000	[55]
Operating lifetime (years)	35	assumed
Natural gas cost (£/GJ)	6.7	assumed
LHV of Natural gas (kJ/kg)	49,152.58	[55]

Sensitivity studies (± 20%) are performed to evaluate how resilient optimisation outcomes are to modifications in important factors (operating and maintenance cost (O&M), amortized cost, Fuel cost) offering insights into the uncertainties and trade-offs related to various optimisation techniques. By doing this, the research hopes to give decision-makers useful information about how to build and run BECCS-MCFC systems that will ensure the production of sustainable energy while efficiently controlling the economy (cost of electricity (COE)) for the produced energy.

Economic performance of the proposed scenario

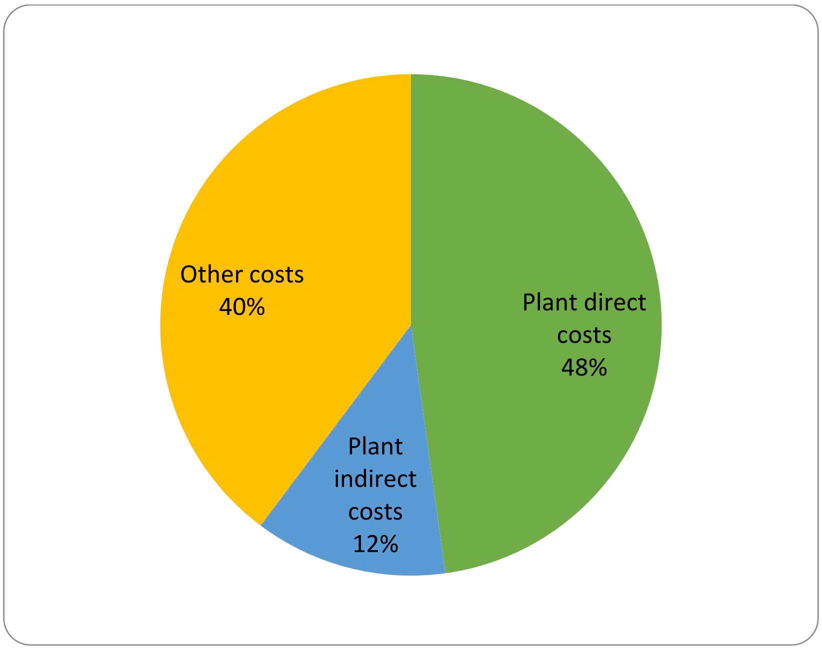
Techno-economic analysis (TEA), including key performance indicators and economic metrics, was performed by calculating the total capital cost, operating and annual cost, from which the COE was calculated. The total capital cost was based on the equipment purchase cost (**1.1396 M£**) of the current pilot plant MCFC with a capacity of 30 kW.

Table 6: Calculations of total capital cost

Plant direct costs			
Equipment purchase (PC)			1,139,631.00
Piping, installed	0.47	x PC	£535,626.57
Instrumentation &control	0.36	x PC	£410,267.16
Insulation	0.68	x PC	£774,949.08
Electrical facilities	0.11	x PC	£125,359.41
Buildings	0.18	x PC	£205,133.58
Yard improvements(service facility cost)	0.10	x PC	£113,963.10
Auxiliary facilities (site development cost)	0.10	x PC	£113,963.10
Total plant direct costs (DC)			£3,418,893.00
Engineering and supervision	0.33	x PC	£376,078.23
Construction expense	0.41	x PC	£467,248.71
Legal expenses	0.04	x PC	£45,585.24
Total plant indirect costs (IC)			£888,912.18
Contractor's fee	0.22	x (DC+IC)	£947,717.14
Contingency	0.44	x (DC+IC)	£1,895,434.28
Total other cost			£2,843,151.42
Total capital cost (TCC)			£7,150,956.60
Specific capital cost ($/kW)			172,979.11

The above total capital cost (TCC) calculations show that the majority of cost 48% comes from plant direct cost, while indirect and other costs represent 52% altogether as shown in Figure 5.

Figure 5: Total capital cost



Based on mass balance, approximately 30 kW of electricity is generated, assuming a 100% efficiency of the AC/DC converter. Additionally, 11.34 kW of heat is generated, resulting in a total net energy output of the system of 49.93 kW. The calculated cost of electricity in Table 7 is based on the generation of 49.93 kW total energy, totalling around 2.15 £/kWh. This figure is higher than the average value of renewable electricity in the UK, which is expected considering the pilot plant level of operation. With optimization and scale-up scenarios, a significant decline in the cost of electricity is anticipated.

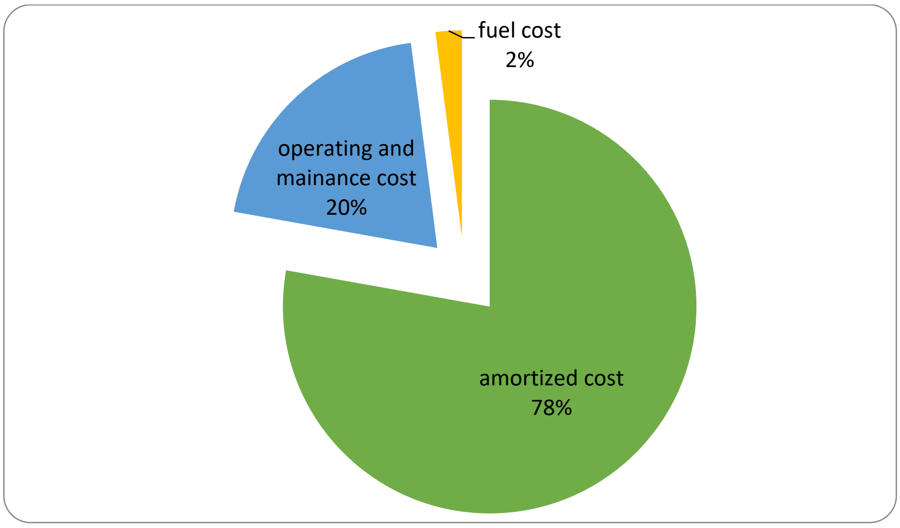
Table 7: Cost of electricity (COE) calculations

Total capital cost (M£)	7.15
Amortized cost (M£)	**0.55**
Operating and maintenance cost (O&M) (M£)	**0.14**
Total fuel input (MW, LHV)	0.08
Total fuel input (Gt/year)	2166.93
Fuel cost (M£), (6.7£/GJ)	**0.01**
Total annual cost (M$)	**0.71**
COE (£/kWh)	2.15

The total annual cost comes mainly from amortised costs (78%) and operating and maintenance costs (20%), which is assumed to be 2% of total capital costs [55] and only 2% of fuel costs as shown in Figure 6.

$$ACC = TCC * \frac{discount\ rate}{1 - (1 + discount\ rate)^{-(operating\ life\ time)}}$$ **Eq 2** [14]

Figure 6: Total annual cost



Sensitivity analysis.

Assume that the MCFC stack cost is about 85% of the total equipment purchase cost [55]. The sensitivity analysis was made based on variations in the cost of MCFC to get corresponding specific capital costs and COE see Figure 7 and Figure 8. The analysis revealed that by optimizing the cost of MCFC, it is possible to achieve a COE as low as 1£.

Figure 7 : Sensitivity analysis of MCFC & Specific capital cost

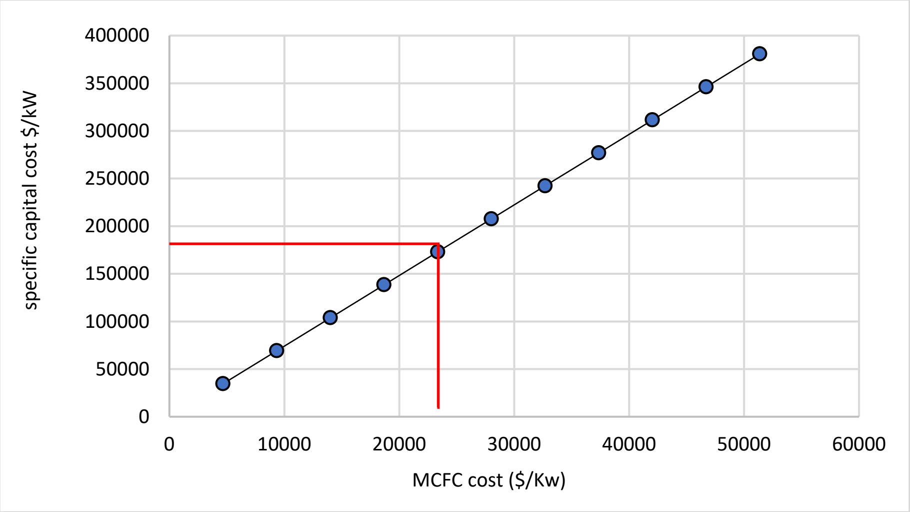
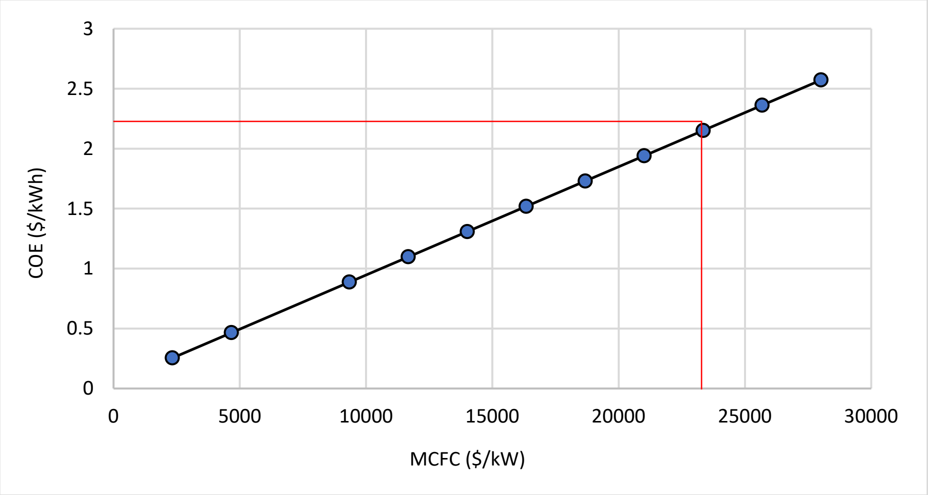
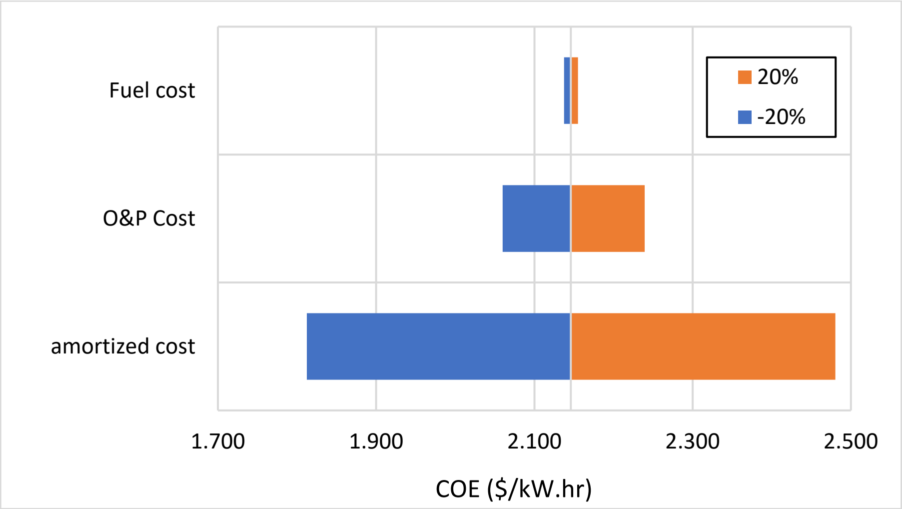


Figure 8: Sensitivity analysis of MCFC and COE.



The Tornado diagram illustrating the variation in input factors such as Fuel cost, O&M cost, and amortized cost by (±20%) is depicted in Figure 9. Notably, the amortized cost of electricity exhibits a significant influence, whereas the fuel cost demonstrates the lowest impact. Remarkably, the COE can be minimized to 1.8 £/kW.hr if the amortized cost is reduced by 20%.

Figure 9: Tornado diagram for COE calculations



Comprehensive sensitivity analyses were conducted, involving variations of annual cost factors by up to ±20%. The impact of these variations, as well as their interactions, on the Cost of Electricity (COE), is presented in the Table 8 - Table 10The results show how the change of each parameter affects the COE and what the minimum price can be obtained from the current scenario. 1.8£/kW.hr is the minimum price obtained, which is higher than the average UK electricity price suggesting that further optimisation (i.e. co-integration) needs to be considered in future work.

Table 8: Effect of amortised cost and fuel cost on COE

		amortized cost				
		0.442	0.4971	**0.552**	0.608	0.6628
Fuel cost	0.0116	1.804	1.971	2.138	2.305	2.472
	0.0123	1.806	1.973	2.140	2.307	2.474
	0.0131	1.808	1.975	2.142	2.309	2.476
	0.0145	1.812	1.979	**2.146**	2.313	2.480
	0.0160	1.817	1.984	2.151	2.318	2.485
	0.0167	1.819	1.986	2.153	2.320	2.487
	0.0174	1.821	1.988	2.155	2.322	2.489

Table 9: Effect of operating and maintenance cost and fuel cost on COE

		operating and maintenance cost				
		0.114	0.1287	**0.143**	0.1573	0.172
Fuel cost	0.01162	2.051	2.094	2.137	2.181	2.224
	0.01234	2.053	2.096	2.140	2.183	2.226
	0.01307	2.055	2.099	2.142	2.185	2.228
	0.01452	2.060	2.103	**2.146**	2.190	2.233

	0.01597	2.064	2.107	2.151	2.194	2.237
	0.01670	2.066	2.110	2.153	2.196	2.239
	0.01742	2.069	2.112	2.155	2.198	2.242

Table 10: Effect of operating and maintenance cost and amortised cost on COE.

		amortized cost				
		0.442	0.4971	0.552	0.608	0.6628
operating & maintenance cost	0.114	1.726	1.893	2.060	2.227	2.394
	0.122	1.747	1.914	2.081	2.248	2.415
	0.129	1.769	1.936	2.103	2.270	2.437
	0.143	1.812	1.979	**2.146**	2.313	2.480
	0.157	1.856	2.023	2.190	2.357	2.524
	0.164	1.877	2.044	2.211	2.378	2.545
	0.172	1.899	2.066	2.233	2.400	2.567

Conclusion:

This research has offered a thorough examination of the integration of MCFC and BECCS technologies for the production of sustainable energy. The techno-economic viability of this integrated system has been significantly enhanced by process optimisation and modelling.

Although the BECCS-MCFC system has the potential for CO_2 reduction and sustainable energy generation, several factors affect its economic feasibility. The COE is influenced by the amortised costs (78%), fuel prices (2%), and operating and maintenance expenses (20%). Sensitivity analysis showed how changes in these variables can affect the COE and pointed us to possible areas to optimise and save costs. The small effect of fuel cost is due to the small size of the plant, and this is expected to be more significant when scaled up to the largest size.

Although the present COE is higher than the average value of renewable power in the UK, this is to be anticipated at the pilot plant level of operation. Significant COE reductions are expected with optimisation and scale-up scenarios, making the BECCS-MCFC system more competitive and economically sustainable.

This study's findings provide useful insights for industry stakeholders, politicians, and researchers working towards a low-carbon energy transition. Further study and improvement of the modelling and optimisation technique are advised to improve the analysis's accuracy and robustness, opening the way for the actual deployment of BECC-MCFC systems on bigger sizes.

Recommendations for Future Work – next steps:

1. Complete a techno-economic study ((modelling and optimisation: contaminants), **WP4.2**): that takes into account a wider variety of elements, such as carbon pricing, governmental incentives, and market circumstances. This would provide a more detailed assessment of the BECCS-MCFC system's economic feasibility and competitiveness.
2. Environmental Impact Assessment (Modelling and Optimisation: TEA &LCA), **WP4.3**): Conduct a detailed evaluation of the BECCS-MCFC system's environmental implications, including carbon footprint, water consumption, and waste creation.
3. Integration with Renewable Energy Sources,((Modeling and optimisation: integration), **WP4.4**): study the integration of BECCS-MCFC systems with other renewable energy sources, such as H_2 and carbon capture. Evaluating the synergies between these technologies might result in more dependable and sustainable energy systems.
4. Comparison study, ((Modeling and optimisation: technology assessment), **WP4.5**): this part will include the comparison between previously suggested scenarios and selected optimised and more efficient models to scale for.
5. Scale-Up Studies (**WP5**): Conduct more research on the scalability of the BECCS-MCFC system by experimenting with different plant sizes and capacities. Scaling up the system might offer useful information on the performance, costs, and feasibility of large-scale deployments.

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