ACT NEWEST CCS Project No 299683

Deliverable D5.3

Report on the technical comparison of the investigated WtE CCUS technologies

Dissemination level	Internal	Date
Written By	Dan SU	18.07.2022
Checked by	Laura Herraiz	27.07.2022
Checked by WP5 Leader	Camilla Thomson	25.07.2022
Approved by the coordinator	Mathieu Lucquiaud	31/08/2022
Issue date	31.07.2022	

Executive Summary

This report, within WP 5.3, compiles and analyses key findings and results from WP 5.2.1, WP 5.2.2 , WP3.3 in order to conduct a comparative technical assessment among the investigated technologies in this project on the basis of several key performance indicators (KPIs), including energy consumption, carbon capture rate, cost analysis, operational availability and flexibility, capacity and versatility of feedstock, etc. The KPIs are categorized into quantitative and qualitative indicators in order to consider a broad range of factors affecting the feasibility of implementing carbon capture technologies in WtE facilities.

In this report, two municipal solid waste combustion technologies are considered: (i) an air-fired moving grate boiler and (ii) an oxy-fuel combustion circulating fluidised bed boiler, both equipped with heat recovery for steam generation and electricity production in the steam turbines. For the WtE facility with a moving grate boiler, two post-combustion capture technologies are investigated: (i) amine-based chemical absorption with an aqueous solution of monoethanolamine (MEA) and with 2nd generation solvents and (ii) Membrane assisted CO_2 liquefaction. The comparison of these technologies is reported in a three-level hierarchy. The first level establishes a comparison between the first and second-generation solvent-based CO_2 capture systems. The second level focuses on the two post-combustion CO_2 capture technologies, i.e. membrane and solvent-based CO_2 capture. The third level compares post-combustion capture with oxy-fuel combustion capture.

The comparative assessment in each level is conducted at different level of detail, based on the available data at the time of writing. In general, as a relatively well-developed technology, post-combustion MEA based CO_2 capture outperforms both Membrane and Oxy-fuel CO_2 capture, in terms of energy consumption and cost effectiveness. For the benchmark MEA cases, the effect of CO_2 capture rates from 90% to 95% to 99.72% on the energy performance of the CO_2 capture plant is marginal; however, this is awaiting validation from pilot scale studies.

The specific power consumption for membrane capture is approximately 1.4 to 1.7 times higher than that for MEA-based capture. It is affected by the targeted carbon capture rate and the feed gas CO_2 concentration and a further optimisation should be conducted. For the assumptions considered in this study, the LCOE of membrane-assisted CO_2 liquefaction is 6% to 26% higher than that of the 35 %wt MEA solvent capture. The CO_2 avoidance cost for Membrane based CO_2 capture is around 2.3 times higher than that of 35% MEA capture cases. Though there is the flexibility of electricity sources for

Membrane cases, this advantage is not adequate to guarantee a lower LCOE when the electricity-purchasing price is low, compared with benchmark MEA cases.

In terms of oxy-fuel CO_2 capture, the specific electricity consumption strongly depends on the technology used in the ASU, which is the main electricity consumer in the processes. Compared with amine-based CO_2 capture, an ASU energy consumption below 120 kWh/t CO_2 would be required in the oxy-fuel CFBC process to achieve an overall specific electricity consumption similar to the electricity output penalty of 311 kWh/t CO_2 evaluated for a 35 %wt MEA capture system at 95% capture rate. The pilot-scale test campaign has shown a promising performance for oxy-combustion of SRF in CFB boilers (key findings are available in *NEWEST_D5.2.2_USTUTT*), yet the TRL of this technology is relatively lower and it needs to be demonstrated at scale to reduce uncertainties.

An excel spreadsheet has been created and is attached to this document (Appendix B) to summarise the KPIs for the different carbon capture technologies considered in this work. It can be used as a tool ready to be updated once more data for each technology become available. This assessment presents some key metrics that are important and relevant for CCUS for WtE sector, policy makers, regulators and technology developers.

1 Introduction

Task 5.3 within NEWESTCCUS Project is an activity that gathers and analyses the existing results of WP 5.2, WP5.2.1 and WP5.2.2 to compare the investigated technologies in terms of key performance and technical parameters. The purpose of this work is to synthesise information available from different CO_2 capture technologies in the project, to present a balanced view of each technologies and to identify the potential modifications for future work to improve performance. A benchmark case is determined and the rest of the technologies are grouped into three levels for the comparative assessment, as shown in *Table 1*:

Table 1 Investigated CO_2 capture technologies and description of three levels of comparison

<table>
<tr><td colspan="4">Comparison levels of the investigated CO_2 capture technologies in this study</td></tr>
<tr><td>Benchmark: Amine based chemical absorption</td><td>2nd generation solvents</td><td rowspan="2">Membrane assisted liquefaction (two membranes)</td><td rowspan="3">Oxy-Fuel combustion with CO_2 capture and compression system</td></tr>
<tr><td colspan="2">Level 1: Post-combustion-Solvent based CO_2 capture: Base case solvent VS 2nd Generation Solvent</td></tr>
<tr><td colspan="3">Level 2: Post-combustion based CO_2 capture: Solvent VS Membrane</td></tr>
<tr><td colspan="4">Level 3: CO_2 capture technologies: Post-combustion VS Oxy-fuel CO_2 capture</td></tr>
</table>

For each comparison level, a set of Key performance indicators (KPIs) is created in an Excel spreadsheet (Appendix B. NEWEST-CCUS Task 5.3 the comparative techno-economic assessment_Spreadsheet_KPIs) in order to analyse a broad set of factors affecting the feasibility of carbon capture technologies in WtE sector. The KPIs are further categorized into quantitative and qualitative KPIs to report the findings. The spreadsheet summarized as much as data available at the time of the writing and will be updated alongside the progress of current and future assessment related study. The following sections in this report presents some of the key results based on the quantitative KPIs as listed in the Appendix B.

2 Description of the investigated CO_2 capture technologies

As mentioned in the previous section, this WP 5.3 report is based on the framework provided by WP 5.1, and gathers and analyses results from WP 5.2.1 & WP 5.2.2 & WP3.3 of the investigated technologies, as shown in *Figure 1*. The core data sources are mainly from the progressing of each technology from the responsible project partners. Additional literature review is necessarily performed to fill in the gap when data not available to complete the comparison. The description of each of the technologies is presented in the following chapters.

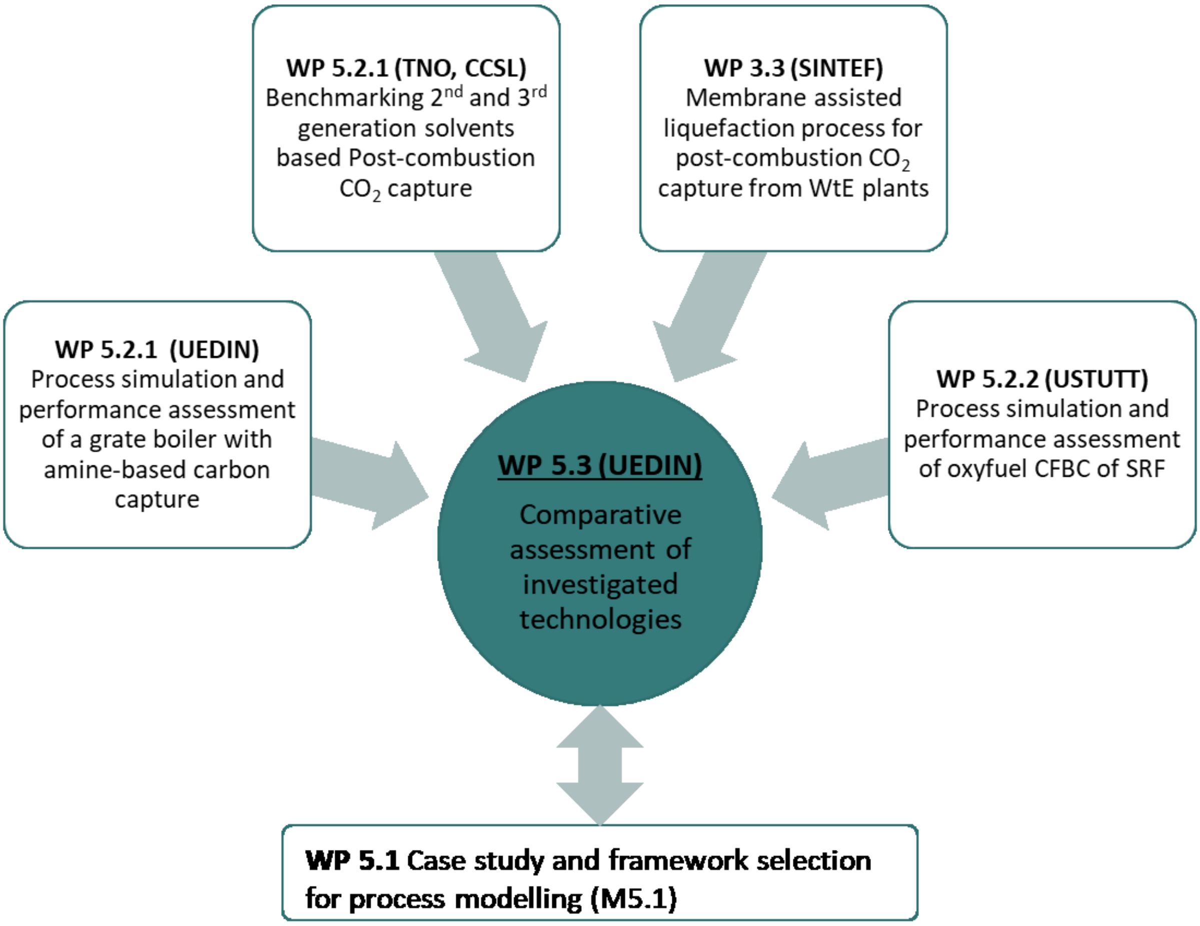

Figure 1 Resources of D5.3 report

2.1 Post-combustion CO_2 capture with monoethanolamine (MEA) aqueous solutions: Benchmark case

The benchmark post-combustion CO_2 capture process considered in this work consists of chemical absorption with a 35% w/w monoethanolamine (MEA) aqueous solution. It is the most established technology and has been used as the reference case for the next generation technologies investigated in this project. Heat required for solvent regeneration is extracted from the main steam cycle of the Power-only WtE plant at 4 bar. The CO_2 capture plant is separately modelled in Aspen-Plus V10 with the objective of sizing the absorber column and optimising the operating parameters that lead to the minimum specific reboiler duty (SRD) required to achieve a given CO_2 capture efficiency. An open-source steady-state model of a conventional solvent-based CO_2 capture plant using 35%wt MEA aqueous solution (developed by the U.S. Department of Energy's Carbon Capture Simulation Initiative at the National Carbon Capture Centre (NCCC)) is used as starting point (Josh Morgan, 2021). This model has been validated satisfactorily with NCCC pilot plant data from the 2014 campaign (Morgan et al., 2018; Soares Chinen et al., 2018). The PCC system in gProcess is modelled as a "grey box" which requires input parameters of the CO_2 capture efficiency and the SRD obtained from the CO_2 capture model in Aspen Plus. The Aspen Plus model requires input parameters of the flow rate and composition of the flue gas stream exiting the direct contact cooler (DCC).

In terms of CO_2 capture rate selected for the comparison, recent guidelines published by the UK Environmental Agency for permitting new post-combustion CO_2 capture plants for gas and biomass power plants require a design CO_2 capture rate of at least 95% to be achieved for an environmental permit to be approved (Gibbins & Lucquiaud, 2021). For base case MEA solvent-based CO_2 capture, design of a CO_2 capture process with 95% CO_2 capture efficiency is used as baseline CO_2 capture scenario.

2.2 Post-combustion CO_2 capture with advanced 2nd generation solvent

Comparing with 2nd generation solvent: Within the scope of the NEWESTCCUS project, Carbon Clean's proprietary solvent CCSL (2nd generation solvent in this report) will be tested at Twence, the WtE facility in Hengelo Netherlands. As these tests are ongoing at the time of writing, the performance of this solvent in comparison with other technologies will be included in future documentation and is outside of the scope of this report.

2.3 Post-combustion CO_2 capture with Membrane-assisted CO_2 liquefaction

The membrane-assisted CO_2 liquefaction is a hybrid, two-stage separation process for capturing CO_2 from flue gas. The first separation stage consists of a CO_2-selective polymeric membrane unit separating the bulk of CO_2 from the incoming flue gas. The resulting permeate on the vacuum side of the membrane is a crude CO_2 product, still containing a considerable fraction of diluents such as nitrogen, oxygen and water. Before entering the second CO_2 separation stage, the permeate is compressed and dehydrated before it is cooled to around -54°C by recuperative and auxiliary refrigeration. In two separation stages, the CO_2 gas is liquefied and purified for transport and storage. Energy input from electricity, rather than steam, reduces integration challenges when retrofitting to an existing industrial facility. This will be an advantage in any industry sector where large volumes of steam are not readily available. Where electricity is available, there is no reliance on natural gas or other chemical fuel.

The process flow diagrams of a 1-stage membrane+liquefaction and 2-stage membrane+liquefaction are presented in Figure 2 and Figure 3.

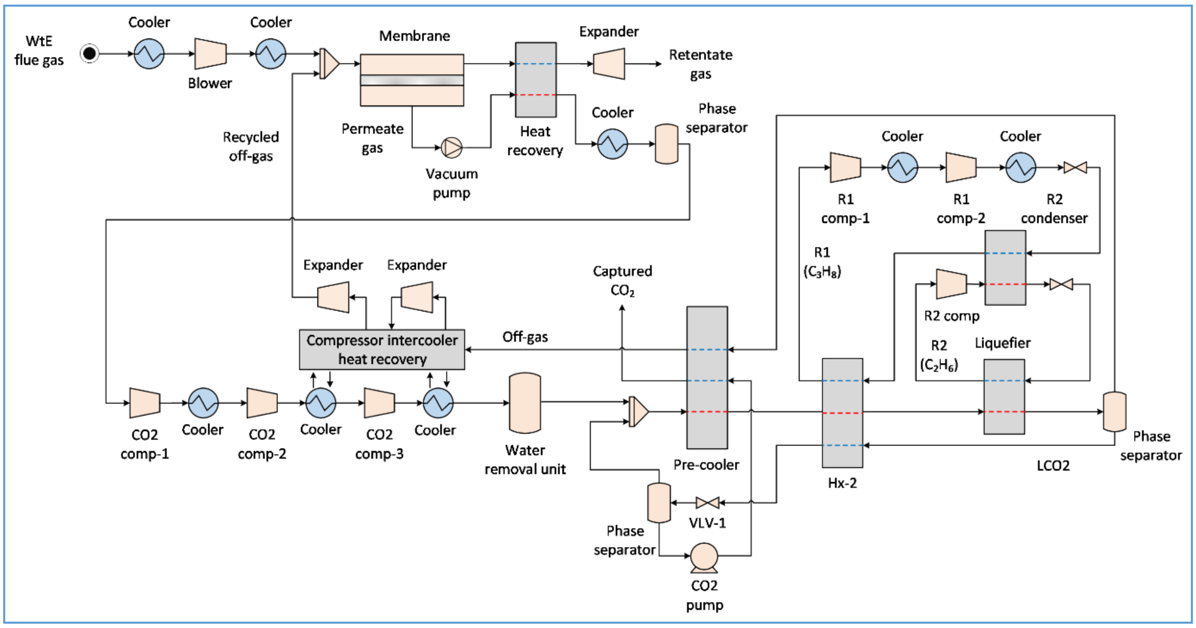

Figure 2 Process flow diagram of a 1-stage membrane+liquefaction (by Sintef)

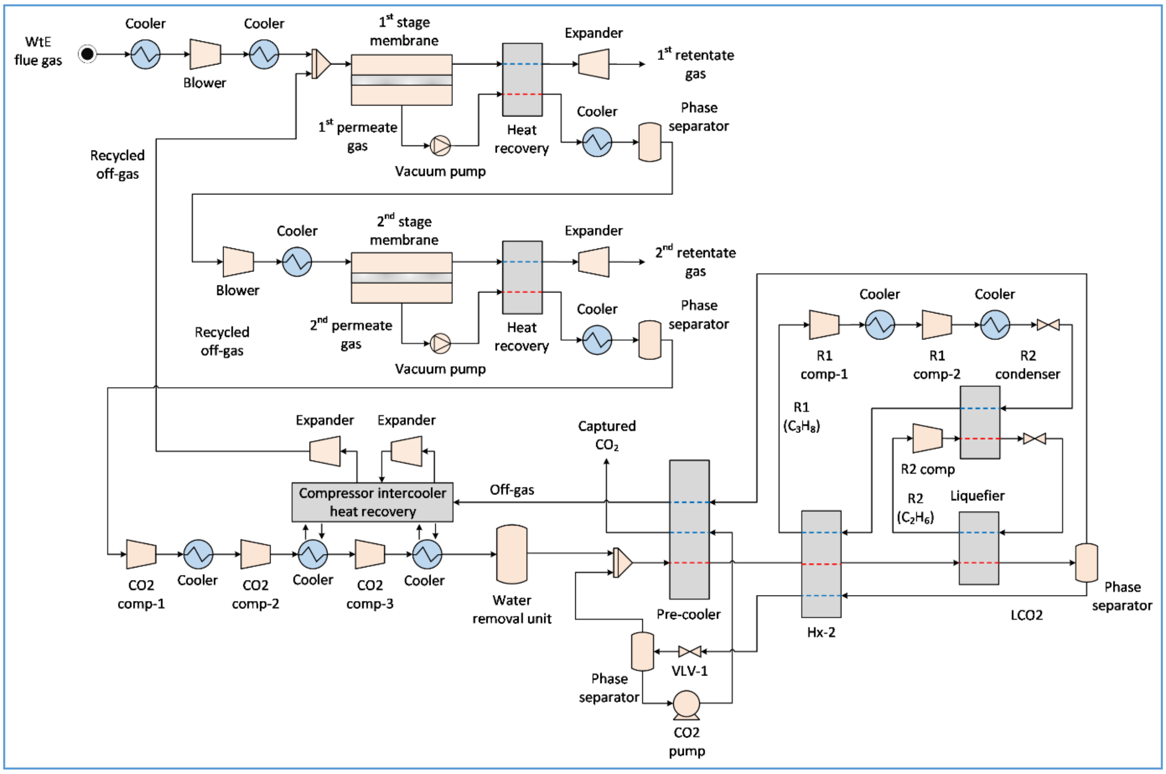

Figure 3 Process flow diagram of a 2stages membrane+liquefaction (by Sintef)

In this comparative assessment study, comparison of Membrane based CO_2 capture with the benchmark MEA cases represents the 2^{nd} level comparison for this study. Two Membrane-assisted liquefaction cases from WP3.3 are selected as comparing cases: they are Fixed Site Carrier (FSC) Case

3 and Polaris polymeric Case 3. A relative detailed cost analysis is conducted as part of KPIs included in this report.

2.4 Oxy-fired circulating fluidised beds using Solid Recovered Fuels

In the WtE sector, improvements in automatic waste sorting technology are allowing operators to divide waste into high-regulated waste such as Solid Recovered Fuel (SRF) and low/non-regulated waste (MSW in this study). The latter can be incinerated in grate-fired boilers, and the former allows for the use of fluidized bed boilers to maximise the energetic value of SRF.

Within the NEWEST-CCUS project, pilot scale testing of Oxy-fuel circulating fluidized bed oxy-combustor using solid recovered fuel (SRF) was performed at the Institute of Combustion and Power Plant Technology (IFK) of the University of Stuttgart. Performance data used in this report are referenced from the full-scale model of an Oxy-CFBC-SRF plant, using SBS®1, substitute fuel derived from municipal waste processing developed by REMONDIS(REMONDIS, 2014), as fuel input, which has been build up Aspen Plus® by the University of Stuttgart. The block flow diagram of the reference oxy-fuel WtE plant with a CFB boiler is presented in Figure 4.

Oxy-fuel combustion, different from Post-combustion CO_2 capture, highly dependent on the air separation unit (ASU) and its technology. The cryogenic separation unit is the most common separation method, whereas the other technologies, such as adsorption and membrane air separation, are less favorable and common due to the higher fabrication, integration, maintenance, and energy footprint that lead to the higher cost of O_2 production(Kheirinik, Ahmed, & Rahmanian, 2021). Oxy-fuel CO_2 capture benefits from higher concentration of CO_2 in the flue gas in relation to capturing CO_2 from the flue gas. The effective control of combustion process with heterogeneous fuel properties is required for application in the WtE sector. However, additional CO_2 separation equipment is still required to produce a pure stream of CO_2. In an oxy-fired system the benefits of a higher CO_2 concentration in the flue gas need to be balanced against the cost of modifying the plant and the energy cost associated with generating the oxygen required (AECOM, 2021).

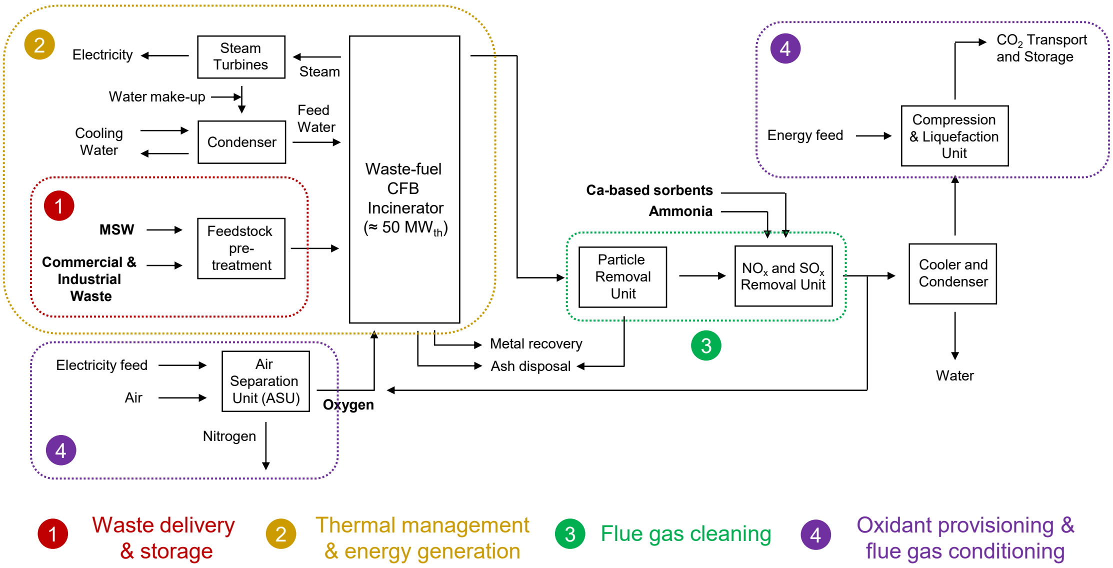

Figure 4 Block flow diagram of the reference oxy-fuel WtE plant with a CFB boiler(Joseba Moreno, 2022)

For more information on the characteristics and a full description of the Oxy- CFBC facility, the reader is referred to NEWEST-CCUS Project deliverable D5.2.2 (Joseba Moreno, 2022).

3 Level 1: Comparison with 2nd Generation Solvent

At the time of the writing, the experimental test campaign is being conducted at Twence and still need to be finalized to obtain results. The Level 1 comparison for the 2nd generation solvent is, therefore, outside of the scope of this document.

4 Level 2: Comparison with Membrane-assisted CO_2 liquefaction

In this comparison, two post-combustion based CO_2 capture technologies are included: solvent-based capture with 35% MEA aqueous solution, and membrane-based capture compared. Each technology is designed to be integrated into the same new-build WtE plant and to capture the same amount of CO_2 from the flue gas emitted from the plant. The main KPIs for each technology are shown in *Table 2* in the following section. For a full detailed set of KPIs, please refer to the attached Appendix B. NEWEST-CCUS Task 5.3 the comparative techno-economic assessment_Spreadsheet_KPIs.

4.1 Quantitative KPIs-Performance parameters

4.1.1 Specific energy consumption

Membrane-assisted CO_2 liquefaction is based on the principle of combining two different separation technologies, none of which are perfectly suited for stand-alone capture of CO_2 at low to medium concentration in flue gases, so that each can carry out a partial separation within its favorable regime of operation (Bouma et al., 2017). The main power requirements for membrane-assisted CO_2

liquefaction are flue gas compression, vacuum pumping and compression of crude CO_2 permeate, and auxiliary refrigeration. As can be seen from *Figure 5*, for the same referenced WtE plant, with the same feed CO_2 concentration of 11.1%vol in the input flue gas, the specific power consumption for membrane cases is around 1.4 to 1.7 times higher than the MEA cases in this study. The efficiency of the carbon capture with membrane assisted CO_2 liquefaction depends on the CO_2 concentration of the incoming flue gas. It is also reported that CO_2 concentration at the interface of the membrane unit and liquefaction unit is important, which affects the CO_2 capture ratio and membrane area and vacuum pump size and work. The CO_2 concentration at the interface depends on the membrane type, pressure differential across membrane, and membrane area (Rahul Anantharaman, 2020). Options for efficiency improvement should be evaluated through further pilot scale testing and process modelling of a full-scale plant.

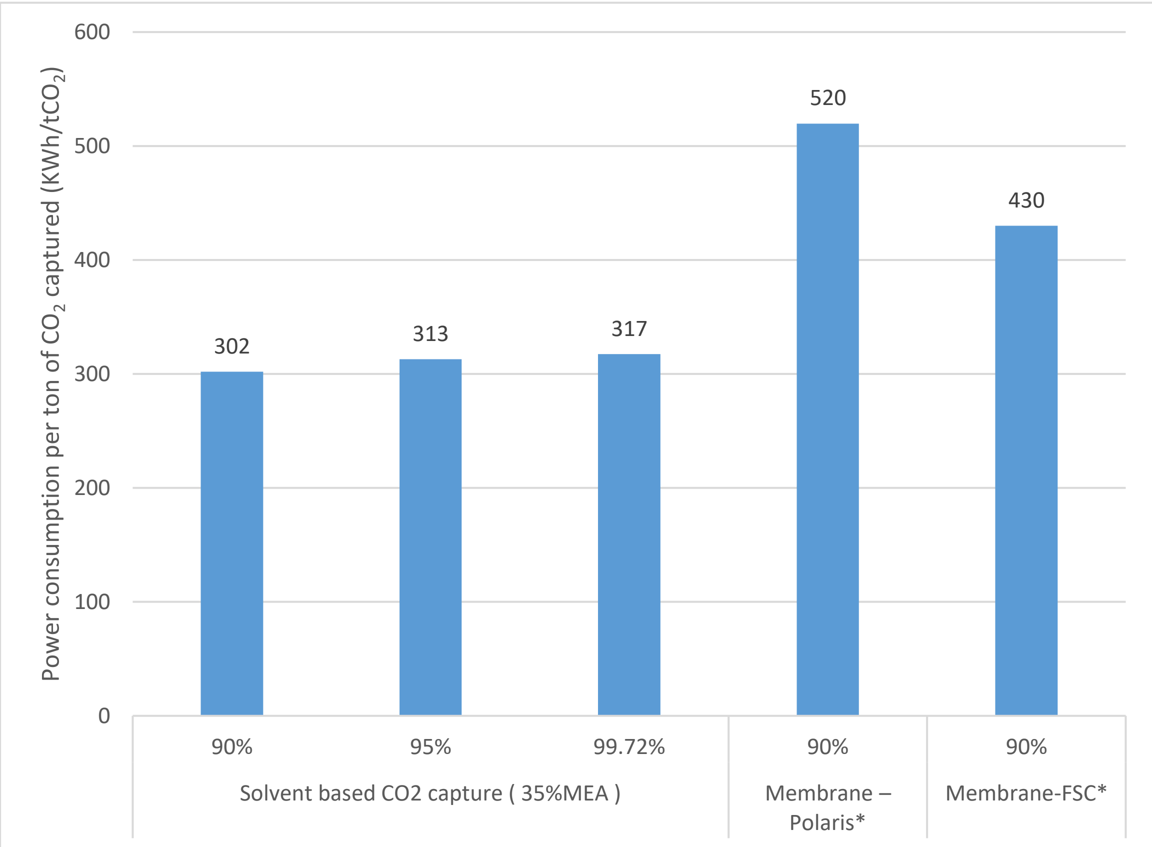

Figure 5 Comparison of the specific power consumption per ton of CO_2 captured for Membrane and MEA cases. Note: For MEA cases, the specific power consumption per ton of CO_2 captured is using electricity output penalty per ton of CO_2 captured, which is the difference of power output before and after CO_2 capture.

4.1.2 Carbon capture rate

For membrane-assisted CO_2 liquefaction, the optimal carbon capture rate considered in this project is 90%, while solvent-based CO_2 capture processes can achieve ultra-high CO_2 capture rates.

For 35%wt MEA case, a 95% CO_2 capture efficiency is chosen as the baseline CO_2 capture scenario, and an ultra-high capture level of 99.72% is chosen as comparison. Ultra-high CO_2 capture rates are possible with a relatively small increase in the specific reboiler duty from 3.52 to 3.72 MJ/kg CO_2. It is important to note that a 99.72% CO_2 capture rate represents zero-residual CO_2 emissions from the waste fuel, as the remaining 0.28% CO_2 corresponds to atmospheric CO_2 that enters the plant with combustion air.

In membrane-assisted CO_2 liquefaction, the CO_2 capture rate strongly depends on the separation pressure (typically 20 - 40 bar) and temperature (typically around -55°C). The energy- and/or cost-optimal CO_2 capture ratio is also highly dependent on the CO_2 concentration in the permeate gas from the membrane unit. The trade-off involved in the liquefaction process is thus between compression required prior to liquefaction and the refrigeration utility (Bouma et al., 2017).

Table 2. Performance parameters of Solvent and Membrane based CO_2 capture technologies investigated in this study

KPI	**Description / Units**	**Solvent based CO_2 capture (35%MEA)**			**Membrane – Polaris***	**Membrane-FSC***
CO_2 capture levels or CO_2 capture Ratio	Defined as the amount of CO_2 captured for compression relative to the amount of CO_2 generated in the combustion of waste (overall system capture levels for membrane)	90%	95%	99.72%	90%	90%
Feed gas						
Feed gas composition (dry basis)	**CO_2/N_2/H_2O/O_2 (mol%)**	11.11/75.23/6.95/6.72			11.11/75.23/6.95/6.72	
Feed gas flowrate	kg/s	30.71			33.6	
Feed gas temperature	°C	40			135	
Capture performance						
Amount of CO_2 captured from feed gas for transport/storage	kg/s	4.7	4.9	5.2	4.65	4.65
Power required for CO_2 capture	MW	5.11	5.52	5.94	8.70	7.20
Specific power consumption	KWhe/tCO_2 captured	305	312	320	519	430
Specific heat consumption	MJ/kgCO_2 captured	3.51	3.52	3.72	N/A	N/A

Note: *Membrane –Polaris: Polaris™ polymeric membrane developed by MTR *Membrane –FSC: Fixed Site Carrier (FSC) membrane developed by NTNU

4.2 Quantitative KPIs-Cost analysis

Substantial cost calculations is important in determining the economic feasibility of the selected carbon capture process for WtE plants. In this report, a detailed capital cost estimation (CAPEX) for both solvent-based CO_2 capture with 35%wt MEA and membrane-assisted CO_2 liquefaction is conducted in collaboration with project partner SINTEF. The methodology and key assumption for the CAPEX estimation is presented in Appendix A. At the time of writing, no standard business models are available from literature for WtE with CCS that could be used as reference. In the UK, the Waste Industrial Carbon Capture (ICC) Business Model is under developing by the government as part of business models to support for CCS. The Waste ICC model is supposed to be designed to incorporate payments for captured CO_2, without any distinction between biogenic and fossil CO_2 and is under drafting/consulting phase(BEIS, 2022). At the 4.2.3 Section, two business models are presented, with the Business model_1 represents business as usual scenario, the Business model_2 to predict the effect of future business models under which biogenic CO_2 emission is valued at certain negative emission credit.

4.2.1 Levelized cost of electricity (LCOE)

The levelized cost of electricity is an important parameter when carrying out an economic evaluation of CCS technologies. It allows the plant owners and decision makers to identify the price of electricity required for a WtE plant where the revenues equal costs, that is, how much money is required per MWh of electricity to recoup the lifetime costs involved in constructing and operating a power plant. In order to calculate the LCOE of a WtE plant with different CO_2 capture technologies, the CAPEX and OPEX of the investigated WtE plant should be calculated. The Chemical Engineering Plant Cost Index (CEPCI) of the corresponding year to adjust the cost from the reporting year to the reference year 2021.

First, the cost estimation of the reference WtE plant without CO_2 capture is estimated to be CAPEX: 1177£/t MSW, Fixed OPEX 13.4£/t MSW and Varible OPEX 25.8£/t MSW, referenced from a UK based WtE plant at similar operation scale (Wheeler, 2015). The CAPEX estimation methodology and key assumption of CO_2 capture process are described in detail in previous studies by the SINTEF and included in Appendix A. Table 3 is a short summary of the Capex for this study.

Table 3 Estimated Capex of the WtE plant and capture plant

	WtE plant w/o PCC	**Membrane**		**35% MEA**		
		FSC case	Polaris case	90% capture	95% capture	99.72% capture
Capex	188	95.6	81	35.9	36.5	37.9

(£million)						

The OPEX estimation for the membrane based CO_2 capture system is conducted directly by SINTEF, as can be seen in *Table 4*:

Table 4 Summary of Variable and Fixed Opex for the two Membrane based CO_2 capture

	Membrane FSC	**Membrane Polaris**
Fixed OPEX (M£/y)	**3.12**	**2.62**
Maintenance, labour, insurance, etc.	3.05	2.59
Membrane replacement	0.07	0.03
Variable OPEX (M£/y)	**0.46**	**0.42**
Cooling water	0.46	0.42
Total OPEX (M£/y)	**3.58**	**3.04**
Technical inputs		
Net power requirement (MW)	7.200	8.700
Cooling water requirement (t/h)	1817	1665
Cooling water cost (£/m^3)	0.031	

Note: Opex of electricity is not included here, in order to calculate the LCOE in the following sections.

The OPEX of MEA based CO_2 capture follows the methodology presented in (IEAGHG, August 2017) and the summary of Variable and Fixed OPEX for the three CO_2 capture rates as below:

Table 5 Summary of Variable and Fixed Opex for three CO_2 capture rates of MEA based CO_2 capture

	MEA 90% capture	**MEA 95% capture**	**MEA 99.72% capture**
	m£/y	m£/y	m£/y
Labour cost	0.24	0.24	0.24
Annual maintenance	0.83	0.84	0.87
Other	0.12	0.13	0.13
Annual fixed operating cost	**1.19**	**1.21**	**1.24**
MEA Solvent	0.17	0.20	0.27
Waste disposal	0.28	0.28	0.28
Annual variable operating cost	**0.44**	**0.48**	**0.54**
Total annual operating cost	**1.63**	**1.69**	**1.79**

The LCOE of a WtE plant without and with CO_2 capture is calculated according to Equations (1) to (4) (BEIS, 2020) :

$$NPV\ of\ Total\ Costs = \sum_n \frac{CAPEX_n + OPEX_n}{(1 + Discount\ Rate)^n} \quad (1)$$

$$NPV\ of\ Electricity\ Generation = \sum_n \frac{Net\ Electricity\ Generation_n}{(1 + Discount\ Rate)^n} \quad (2)$$

$$LCOE = \frac{NPV\ of\ Total\ Cost}{NPV\ of\ Electricity\ Generation} \tag{3}$$

$(n = time\ period)$

It should be noted that:

1) A constant gate fee of £100/tMSW (typical UK value) is assumed when evaluating the Opex of a WtE plant without and with CO_2 capture, for both CO_2 capture technologies. At this stage, it is therefore assumed that the integration of CO_2 capture doesn't affect the gate fee that customers should pay to the WtE plant.
2) For MEA based CO_2 capture, the thermal requirement for CO_2 regeneration and power consumption for CO_2 compression/auxiliary process is supplied by the WtE plant, which leads to an electricity output penalty to the WtE plant under consideration;
3) For Membrane based CO_2 capture, there is electricity consumption for the capture and compression process, which is modeled to be provided by the plant itself, that is, the integration of CO_2 capture will affect the electricity production of the WtE plant under consideration, in form of electricity revenue reduction.
4) No carbon cost is included in the LCOE calculation, neither before nor after the CO_2 capture system is added to the WtE plants.

Figure 6 shows the breakdown of the LCOE for MEA and Membrane based CO_2 capture. In this figure, both the membrane cases and the MEA solvent cases use the same reference WtE plant with the same gate fee of £100/tMSW. Carbon cost is not taken account in any of the scenarios. As can be seen from *Figure 6*, both MEA and Membrane based CO_2 capture will increase the LCOE generation in a WtE plant. With 35% MEA based CO_2 capture, the LCOE increases from 78£/MWh to 185£/MWh, 195£/MWh and 207£/MWh for 90%, 95% and 99.72% capture rate, respectively. With Membrane based CO_2 capture, the LCOEs increase from 78£/MWh to 364£/MWh and 407£/MWh for the FSC and the Polaris case, respectively. The overall net LCOE for membrane-based CO_2 capture is almost two times higher than that for MEA-based CO_2 capture. This is due to 1) the relatively higher Capex of carbon capture facility. The Capex of carbon capture and compression for MEA solvent case is £35.9 million, £36.5 million and £37.9 million for 90%, 95%, and 99.72% cases respectively; whereas for the Membrane cases, the Capex of carbon capture and compression facility are £95.6million and £81million for FSC and Polaris cases respectively, around 2.14 to 2.65 times higher than MEA solvent cases. 2) Difference in electricity output penalty. For Membrane cases, the electricity requirement is met from the WtE plant, in form of electricity output reduction of the plant; For the MEA solvent cases, solvent regeneration requires steam extraction from the main steam cycle that leads to an electricity output penalty in the WtE plant. For the same referenced WtE plant, the power output of the WtE plant are reduced from 15.3MW to 10.2MW, 9.75MW, 9.33MW under MEA solvent based 90%, 95%, and 99.72% cases; whereas the power output of the WtE plant are reduced from 15.3MW to 8.1MW, 6.6MW under the FSC and Polaris cases respectively. With the same gate fees assumed for all the cases, the higher Capex and lower power production under the Membrane cases leads to higher LCOE to make the plant break even. It has to be noted that 95% capture rate with MEA is considered the benchmark case in this study, yet 90% capture rate is included in *Figure 6* only for comparison purposes with membrane cases.

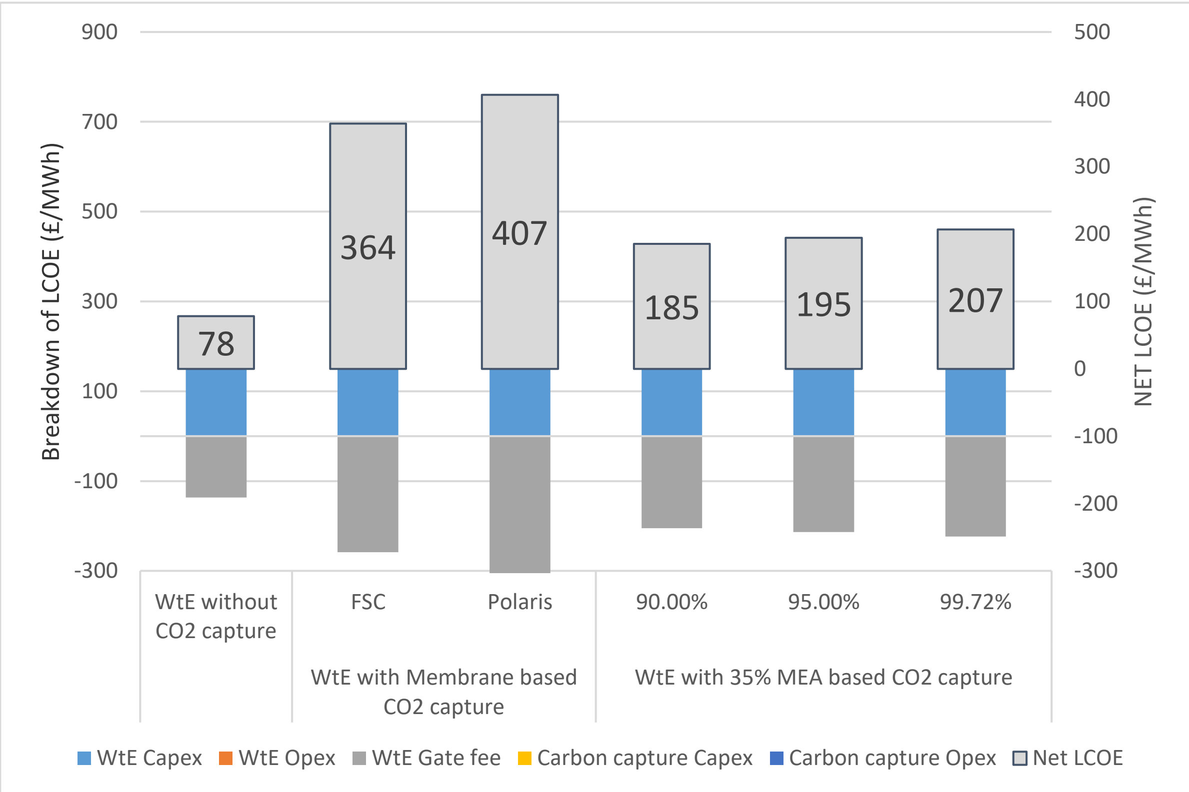

Figure 6 Breakdown of LCOE of WtE plant under Membrane cases 90% capture (FSC and Polaris) and 35% MEA cases for three CO2 capture rates (90%/95%/99.72%)

In *Figure 6*, the LCOE for the MEA cases represents a favourable scenario in terms of the cost of electricity from the grid, since the LCOE represents the price of electricity required for a WtE plant where the revenues equal costs.

As mentioned in section 2, one of the advantages of Membrane based CO_2 capture is in the flexibility of electricity sources. A sensitivity analysis is conducted to assess the effect of the electricity price, assuming the electricity is purchased from a 3rd party in range of £78/MWh to £250/MWh, as shown in Figure 7. It is seen that even the electricity-purchasing price is as low as the price equals to the LCOE under WtE without PCC case (£78/MWh), the LCOE of the integrated plant is still higher than that under the MEA solvent-based case (£185/MWh-£207/MWh). Though there is the flexibility of electricity sources for Membrane cases, this advantage is not adequate to guarantee a lower LCOE when the electricity-purchasing price is low, compared with benchmark MEA cases. The Membrane-Polaris case has lower Capex and higher power requirement than the FSC case. The Polaris case performs better in terms of LCOE than that of FSC case when the purchasing electricity price is below £170/MW. The difference of LCOE for the two cases is in range of £7/MWh to £10/MWh under purchasing electricity price from 78£/MW to £250/MW.

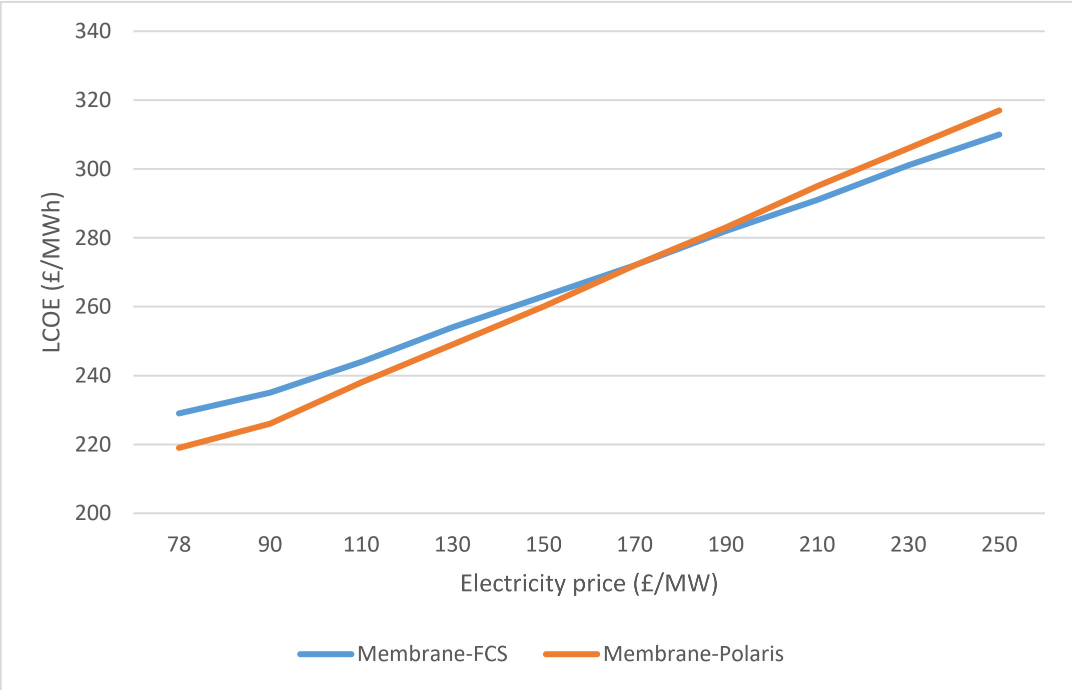

Figure 7 Sensitivity of electricity purchasing price for the LCOE under Membrane cases

4.2.2 Comparison of CO_2 avoidance Cost

The CO_2 avoidance cost is calculated based on the cost and emission intensity of the electricity generated with and without CCS as shown in Equation 5(Simon Roussanaly, 2019).

$$CO_2\ Avoidance\ Cost = \frac{LCOE_{CCS} - LCOE_{REF}}{\left({}^{tCO_2}/_{MWh}\right)_{\mathrm{ref}} - \left({}^{tCO_2}/_{MWh}\right)_{CCS}} \tag{5}$$

Where:

• $(LCOE)_{ref}$ is the levelised cost of electricity of the power plant without CCS

• $(LCOE)_{CCS}$ is the levelised cost of electricity of the power plant with CCS

• $(tCO_2/MWh)_{ref}$ is the CO_2 of electricity of the power plant without CCS emission intensity

• $(tCO_2/MWh)_{CCS}$ is the CO_2 of electricity of the power plant with CCS emission intensity

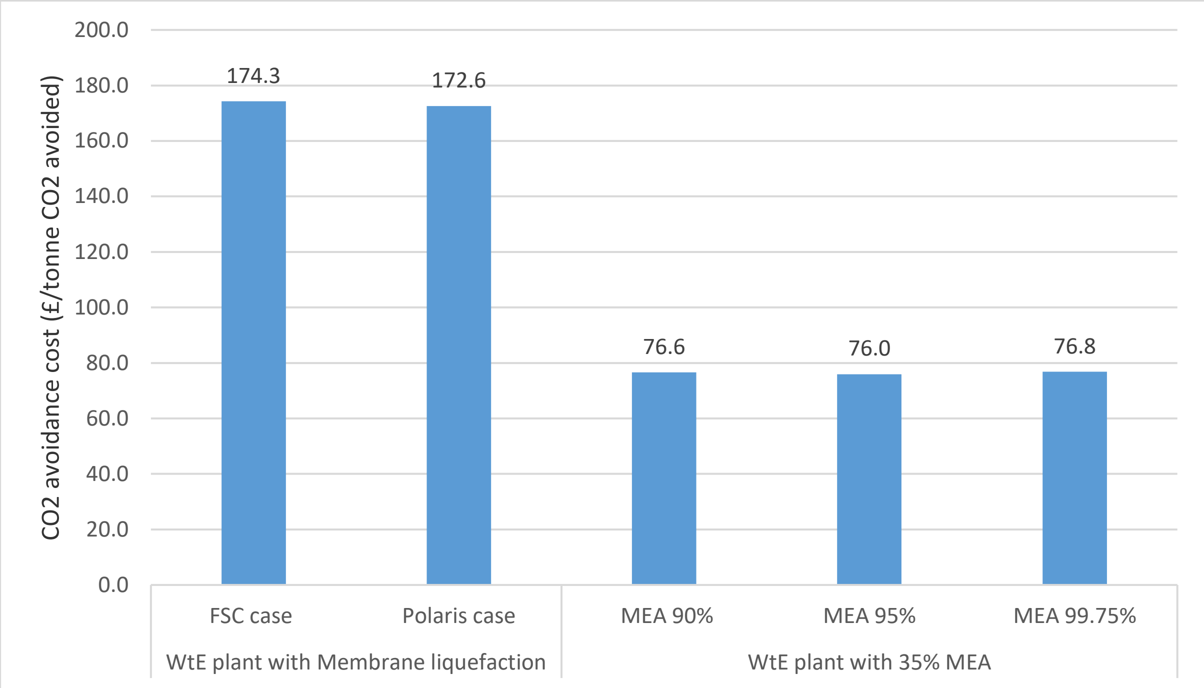

Figure 8 Comparison of CO2 avoidance cost for Membrane cases at 90% capture rate (FSC, Polaris) and 35% MEA cases at 90%, 95% and 99.72% capture rates.

As can be seen in *Figure 8*, the CO_2 avoidance cost of MEA-based CO_2 capture are considerably lower than that under Membrane cases. For Membrane cases, the Polaris case shows a slightly lower CO_2 avoidance cost of £172.6/tCO_2 compared to the FSC case, £174.3/tCO_2. Although FSC case presents a relative lower power consumption (7.2 MW) compared to Polaris case (8.7MW) for the same reference WtE plant, the benefit on energy savings does not offset its relative high Capex and Opex, which leads to higher CO_2 avoidance cost for the FSC case compared to the Polaris case. For MEA cases, the CO_2 avoidance cost is around 44% of that of Membrane cases and it does not increase with the increasing of capture rate. This is due to the fact that the CO_2 avoidance cost is determined by the combination effect of LCOE without and with CO_2 capture, and the change of carbon intensity without and without CO_2 capture. From 90% to 95% capture rate, the system benefits from a reduction of carbon intensity when the CO_2 capture rate increases which is higher than the increase in the LCOE, leading to a slightly reduction in the CO_2 avoidance cost. From 95% to 99.72% capture rate, however, the increase in the LCOE is slightly higher than the reduction in the CO_2 avoided, leading to a slightly increase in the CO_2 avoidance costs.

4.2.3 Carbon price and negative emission credit

Due to the biogenic share of MSW in the WtE plant, the integration of CCS to a WtE plant leads to an effective negative carbon dioxide emissions. However, a major barrier for deploying CCS at a WtE plant is the high investment and operation costs associated tor the carbon capture plant, combined with lacking reward for the negative carbon dioxide emissions. Two business models are presented for enabling and incentivizing CCS at WtE plants, as described herein after:

❖ **Business model_1**

- Fossil emissions are penalised at CO_2 price
- Negative emissions are valued at CO_2 price
- No change in gate fee is considered
- Assuming that heat and power associated with CCS is solely based on integration with the WtE plant i.e. result only in a heat/power output penalty to the plant

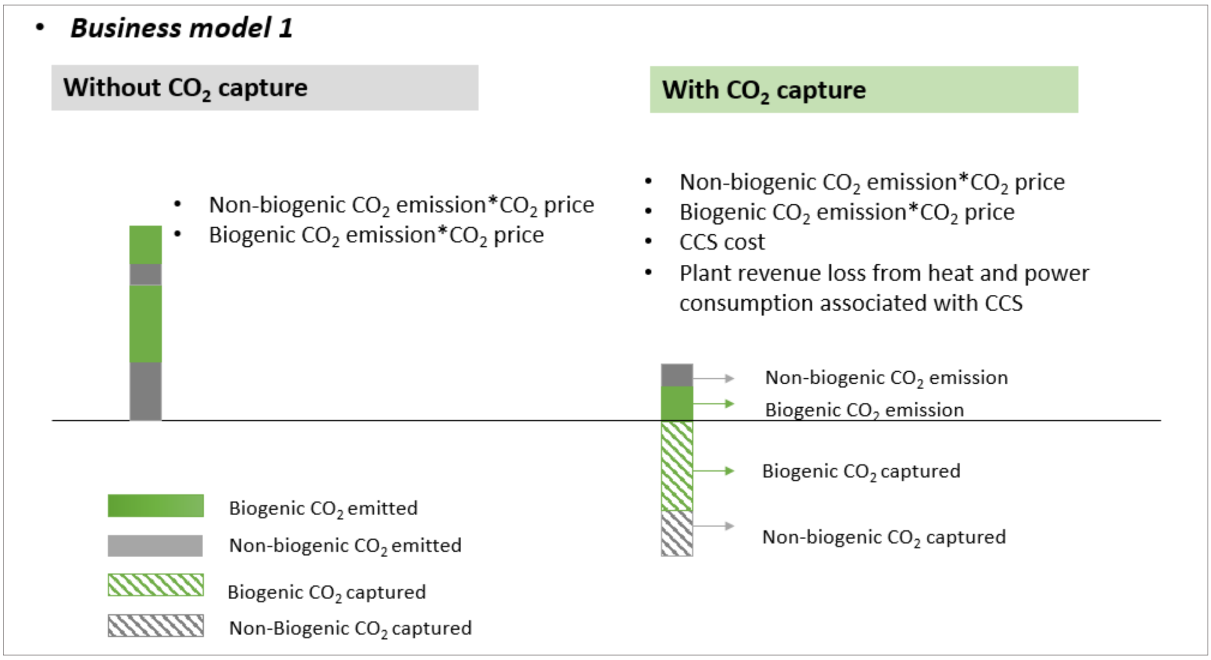

Figure 9 WtE with CCS business model_1

The Business model_1 allows to identify the break-even CO_2 price at which the cost of CCS (including the power output penalty due to CO_2 capture) is balanced off by the benefit of reducing carbon emission, thus reducing carbon cost. The break-even CO_2 price is calculated in Equation (5).

$$Break-even\ CO_2\ Price = \frac{CCS\ cost + Plant\ revenue\ loss\ from\ heat\&power\ consumption\ \text{associated with CCS}}{Non-biogenic\ CO_2\ captured + Biogenic\ CO_2\ captured} \tag{5}$$

The break-even CO_2 price for the investigated Membrane cases and MEA cases is shown in *Figure 10*. It can be seen that for Membrane cases, FSC and Polaris, the CO_2 price should be at 138£/tCO_2 and 129£/tCO_2 respectively, in order to make the cost of CCS be balanced off by the benefit it created due to reduced carbon cost. Similarly, the required break-even CO_2 price for MEA cases are around 65£/tCO_2.

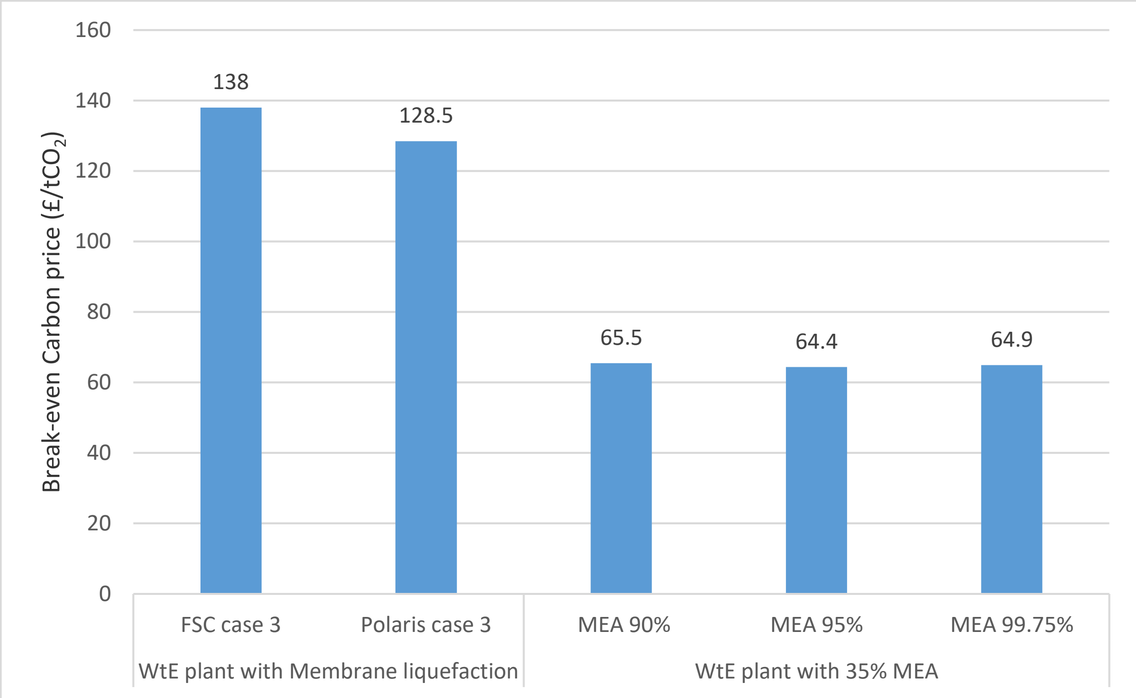

Figure 10 Break-even carbon cost under Business model_1 for WtE with Carbon capture

Business model_2

- Fossil emissions are penalised at CO_2 price (£40/t CO_2)
- Negative emissions are valued at Negative emissions credit (NEC)
- An increase in gate fee is considered
- Assuming that heat and power associated with CCS is solely based on integration with the WtE plant i.e. result only in a heat/power output penalty to the plant

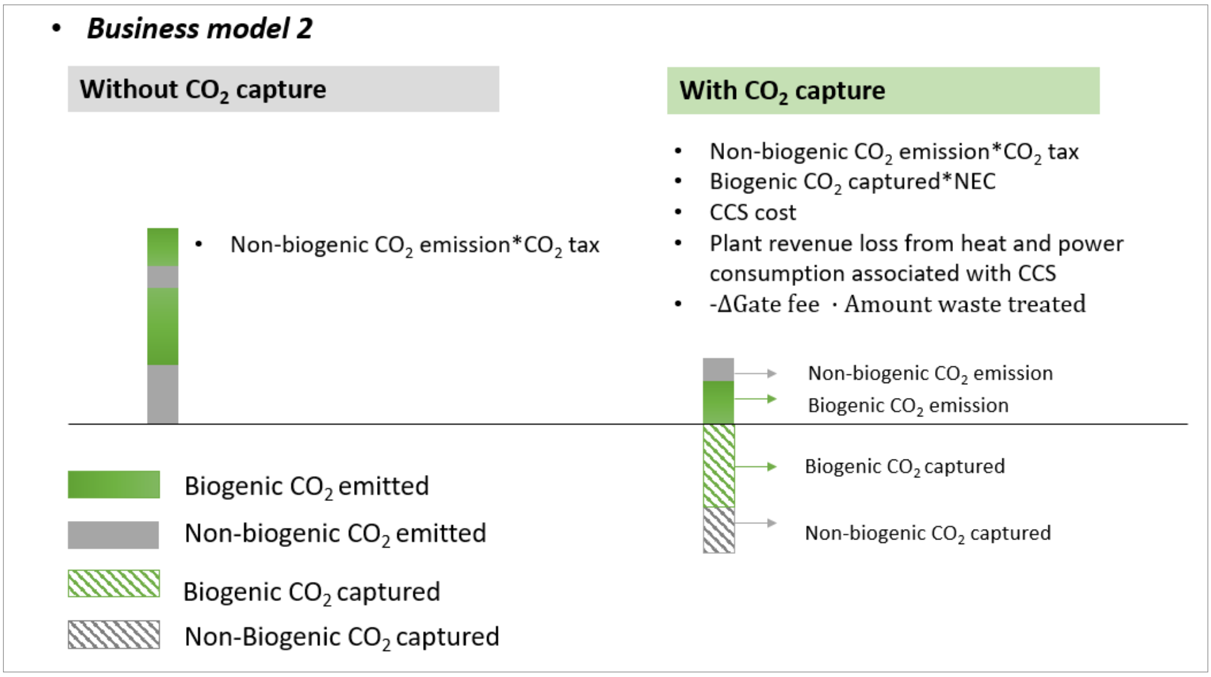

Figure 11 WtE with CCS business model_2

Business model_2 takes in to consideration two business incentives that might be feasible for the future application of CCS to WtE plants: Negative emission credit (NEC) and increased gate fee. The cost balance for Business model_2 is described in Equation (6).

$$\begin{aligned} CCS\ cost &+ \text{Plant revenue loss from heat and power consumption associated with CCS} \\ &= \text{Non-biogenic } CO_2 \text{ captured} \cdot CO_2\ tax\ + Biogenic\ CO_2\ captured \cdot NEC\ cred \\ &\quad + \Delta Gate\ fee\ \cdot Amount\ waste\ treated \end{aligned} \tag{6}$$

A sensitivity analysis is performed in terms of the required NEC value for the integrated WtE plant to achieve cost and benefit balanced off, under a range of gate fee increasing values from 0£/tMSW to 50£/tMSW.

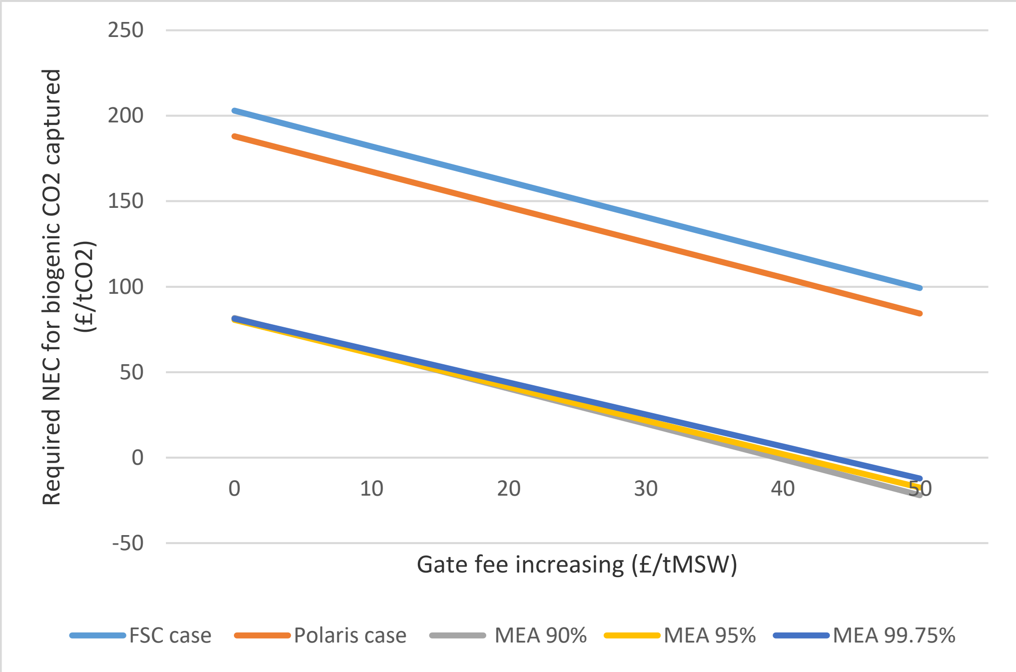

Figure 12 Sensitivity in terms of the required NEC under a range of Gate fee increasing scenarios

As can be seen in *Figure 12*, increasing the gate fees reduces the required NEC value to balance off costs and benefits associated to the carbon capture process. For Membrane cases, the required NEC is estimated to be £84 to £203 per tonne of Biogenic CO_2 captured for a range of gate fee increase within £0 to £50/t MSW. For 35% MEA cases, when the gate fee is increased by around £40/t MSW, the required NEC reaches zero, which means the WtE plant can achieve cost and benefit balancing off even without NEC incentives at this gate fee increasing value.

5 Level 3: Comparison with Oxy-fuel CO_2 capture

Two CO_2 capture technologies are compared in this section: direct combustion over a moving grate with 35%wt. MEA -based capture at 95% capture level, and an oxy-fuel carbon capture with circulating fluidized bed combustion (CFBC). The two WtE systems are processing different types of fuels in terms of fuel composition and quantity. The moving grate boiler is fed with the MSW composition considered as reference in this project and the CFB boiler is fueled with solid recovered fuel (SRF). A full description of the Oxy-fuel CO_2 capture system can be found in the Project deliverable NEWEST_D5.2.2 by USTUTT (Joseba Moreno, 2022). The performance parameters used for this comparison as obtained from process modelling of of a full-scale oxy-CFBC WtE plant developed in Aspen Plus® by project partner USTUTT. The model was subsequently validated to serve as a computer tool to predict the oxy-combustion process' behaviour under various operational conditions.

5.1 Quantitative KPIs-Performance parameters

5.1.1 Energy consumption

The main energy consumptions for Oxy-fuel CO_2 capture are the electrical energy required for the air separation unit (ASU) and the CO_2 compression and purification unit (CPU) and auxiliaries. Power consumption for Oxy-fuel based CO_2 capture is calculated on the basis of typical assumptions for power consumption in the main elements of the oxy-combustor block. Among them, oxygen production at the ASU is the main electricity consumer and current development of ASU technology, such as improved thermal integration makes possible an important reduction in the electricity consumption. CPU is another important electricity consumer and reduction of this value is reported to be more difficult than for ASU(Escudero et al., 2016). A value of 120KWh/tCO_2 is used in this study. Besides, 5% of the gross power output in the auxiliaries (Romeo et al., 2008) is assumed for this scenario (Escudero et al., 2016).

In literature, as from (Banaszkiewicz, Chorowski, & Gizicki, 2014), the minimum theoretical specific energy consumption for oxygen from the air is around 53 kWh/ton O_2. In literature, the energy penalty for producing pure O_2 by a standard ASU is around 200-220 kWh/ton O_2 (Energinet, 2021). With further optimizations, it is considered realistic to be reduced to 120 kWh/ton O_2 for 2020(Perrin et al., 2015). The overall electricity output penalty due to CO_2 capture under a range of ASU power consumption from 100 to 220 kWh/ton O_2 is conducted in this study, as shown in Figure 13. In general, Oxy-fuel cases consume more electricity per ton of CO_2 captured, ranging from 291 KWh/tCO_2 to 412KWh/tCO_2 for a range of electricity consumption at the ASU, compared with the specific energy consumption of 311 KWh/tCO_2 for the benchmark MEA solvent case. Great development on ASU specific energy consumption is required to (below 120 kWh/ton O_2) make the Oxy-fuel CO_2 capture be competitive with MEA based capture; this seems to be challenging at present standard but can be expected in the future, since the 120 kWh/ton O_2 is still significantly greater than the theoretical one (50 kWh/ ton O_2).

Besides power consumption, the addition of ASU for the retrofitting would increase water use, which further magnifies the pressure on water resources for WtE plants that in the water shortage districts. It is necessary to investigate the water use regarding oxy-combustion before large-scale utilization of this technology(Zhu et al., 2021). Improved integration between the ASU, Oxy-fuel Boiler and CO_2 Purification Unit may be useful to reduce both the power consumption and water usage (Darde, Prabhakar, Tranier, & Perrin, 2009; Nemitallah et al., 2017; Spero & Yamada, 2018); however this is awaiting further study.

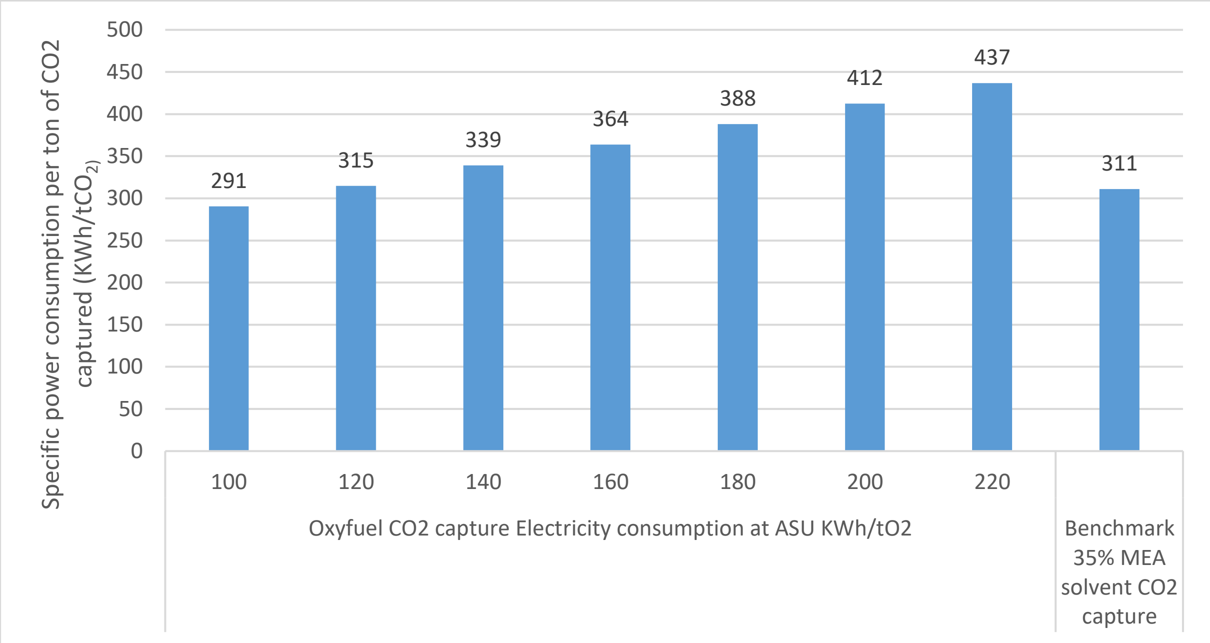

Figure 13 Specific energy consumption for Oxy-fuel CO2 capture and Benchmark 35% MEA solvent CO2 capture

5.1.2 Carbon capture rate

Compared with the benchmark MEA case, one of the advantages of Oxy-fuel CO_2 capture is the comparative ease with which CO_2 can be separated. Oxy-fuel CO_2 capture requires no solvent, which enables very high capture levels. Under ideal conditions, Oxy-fuel combustion systems with CO_2 compression and purification should be able to capture all the CO_2 present in the flue gas, i.e. the theoretical capture efficiency of this system is 100%. CO_2 emissions do occur, however, while operating this plant, especially during drying and purification of the concentrated CO_2 stream. A CO_2 material balance was conducted by the University of Stuttgart for the Oxy-fuel CO_2 capture case, and the results are illustrated in *Figure 14*.

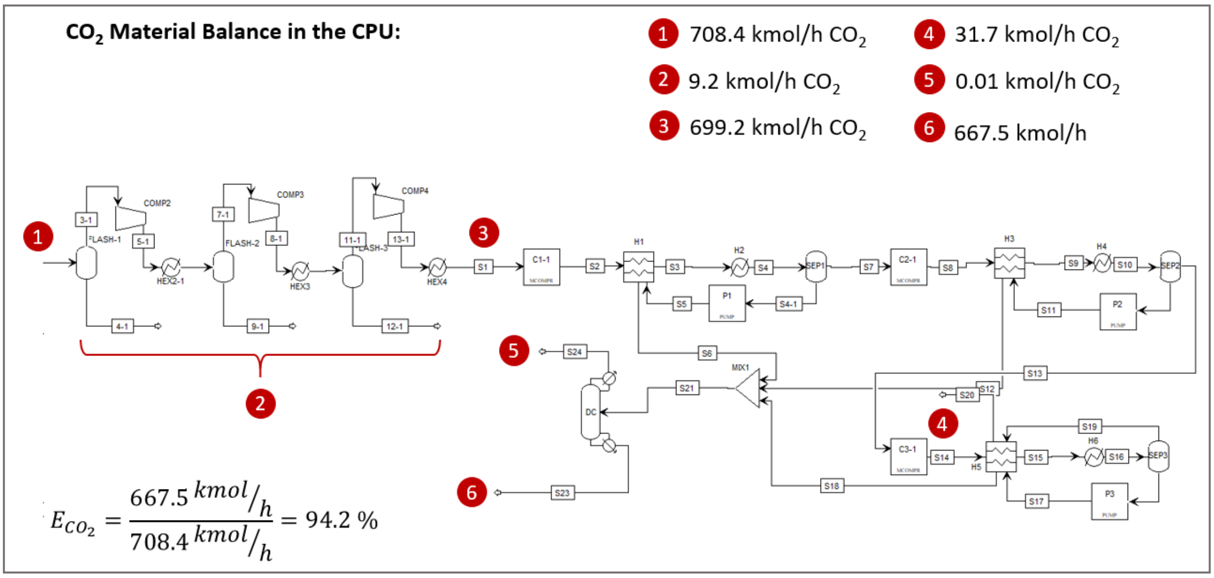

Figure 14 CO_2 Material Balance in the CPU of the Oxy-fuel CO_2 capture facility

The overall CO_2 capture level for the modelled Oxy-fuel case is around 94.2% with 98.6% purity at the outlet of product CO_2. This capture rate for Oxy-fuel is close to the benchmark case of 95%. Higher CO_2 capture rates could be achieved if the purity of the product is increased (even >99.99 mol%) through process modification. This indicates there is no technical barrier for Oxy-fuel capture to achieve high capture level.

Table 6 Performance parameters of Post-combustion and Oxy-fuel CO_2 capture technologies investigated in this study

KPI	Description / Units	CFB Oxy-Fuel combustion CO_2 capture	Grate boiler Post-combustion CO_2 capture
Fuel input	kg/h	**10080**	**19400**
LHV Fuel	MJ/kg	**16.82**	**9.3**
Thermal input	MWth	**53.5**	**55.6**
WtE plant with CO_2 capture performance			
Net power output	MWe	4.21	9.75
Gross power output	MWe	13.46	15.26
Auxiliaries	MWe	0.67	
ASU	MWe	4.29	
CPU	MWe	4.29	
Electrical efficiency after CO_2 capture	MWe/MWth (MSW)	7.9%	18%
<u>CO_2 capture process</u>			
Specific power consumption *	kWhe/t CO_2 captured	315	311 (including power loass from steam turbine and auxiliaries power consumption)
Specific heat consumption	Heat consumption per ton of CO_2 captured, [kWhth/tCO_2 captured]	Not applicable	3.59 MJ/kg CO_2

Overal CO_2 capture efficiency (%)	Defined as the amount of CO_2 captured for T&S relative to the amount of CO_2 generated in the combustion of waste [from point 1-6 in the CO_2 material balance]	94.20%	95%

Note: *For Membrane cases, the specific power consumption is estimated to be 120 kWhe/tO_2 in the ASU and CPU units, respectively. For Grate-boiler MEA based CO_2 capture, the specific power consumption is equal to the electricity output penalty of CO_2 capture and compression.

5.2 Quantitative KPIs-Cost analysis

The CO_2 avoidance cost for Oxy-fuel case is not calculated in this study. However, (Kheirinik et al., 2021) show that CO_2 avoidance cost for Oxy-fuel capture is about 1.66 times higher than Post-combustion capture, which results to the CO_2 avoidance cost of around 104 £/tCO_2, at similar value of the Membrane-Polaris CO_2 capture. Following this assumption, the MEA (solvent based) CO_2 capture cases represent the lowest CO_2 avoidance cost of all the investigated carbon capture technologies. Additional economic assessment could be done to perform detailed cost estimation of the Oxy-fuel based capture for more complete assessment.

6 Summary of Energy consumption for the investigated CO_2 capture technologies

The energy consumption (kWh/tCO_2) of including CO_2 capture to a grate-fired waste to energy plant is reported for the three technologies investigated in the project: Benchmark MEA CO_2 capture, Membrane based CO_2 capture, Oxy-fuel CO_2 capture, as shown in *Figure 15*.

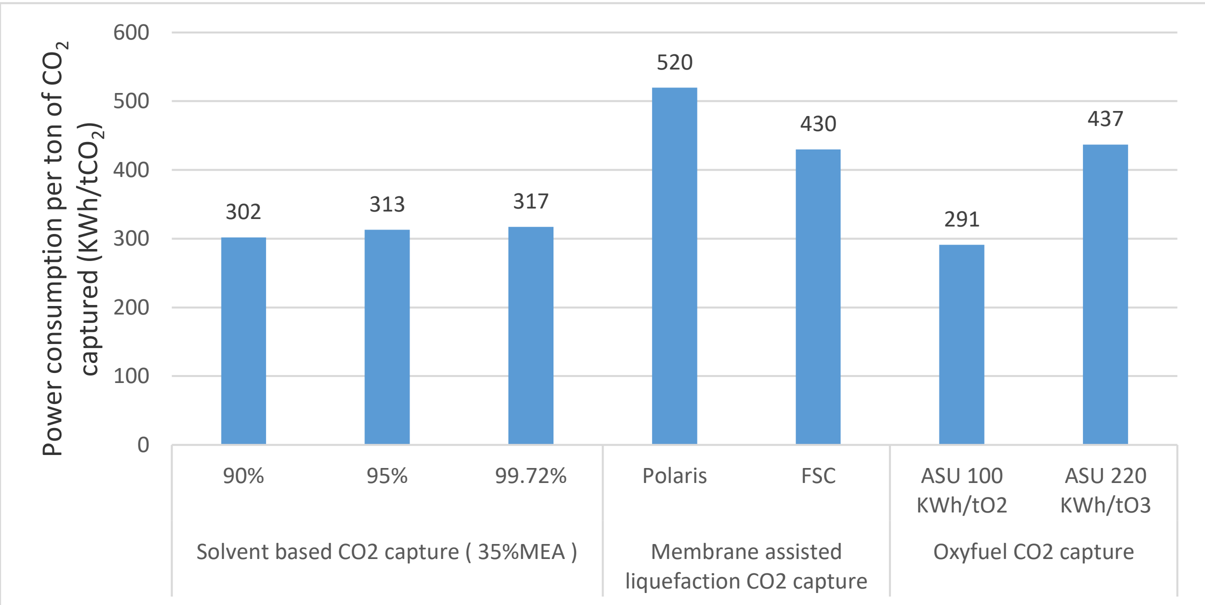

Figure 15 Summary of energy consumption per ton CO_2 captured for the three technologies investigated

The power consumption is lower for solvent-based CO_2 capture and remains competitive even at high CO_2 capture rate. For the Membrane cases, under the referenced WtE plant flue gas with 11.1% CO_2 concentration, the power requirement for Membrane cases are the highest, and are at 90% capture. The power consumption at higher capture rate may be more challenging for Membrane technologies. The investigated two membrane materials are not competitive comparing with the MEA cases under the current condition. However, as included in the qualitative assessment, there is quite a room for potential improvement in terms of power consumption. Report from (He, Fu, & Hägg, 2015) indicates that if the retentate stream can be preheated from membrane operating temperature to a higher temperature (depending on the available heat) before sending into expander, more work can be recovered and net power consumption can be significantly reduced. Compression heat from flue gas compressors is available for preheating retentate streams. With improved design, the specific energy consumption can be as low as 1.02 GJ_e/tonne CO_2. Another advantage is that the operation of membrane-assisted liquefaction does not need steam, which is a benefit for a WtE plant with limited steam available. For example, a WtE plant supplying heat for district heating by steam extraction from the power cycle. However, this improvement requires further experiment/pilot testing as supporting proof. For Oxy-fuel combustion CO_2 capture, the main uncertainty in terms of power consumption happens at the ASU. With bettered designed ASU system, the power consumption of CO_2 capture can close to that under MEA CO_2 capture. Overall, with improved system design, the investigated technologies can be expected to be comparable in terms of power consumption with the benchmark case.

7 Limitation of this comparison

There are several limitations to this comparative assessment.

The four CO_2 capture technologies investigated in this comparison only applies to power-only WtE plants. However, it is true that there is a considerable share of CHP WtE plants and heat-only WtE plants in Europe, and these two types of WtE plants are outside the scope of this comparison.

For the solvent-based CO_2 capture technologies (benchmark MEA cases and 2nd generation solvent cases), a significant fraction of the produced heat is used for solvent regeneration, opportunities for thermal integration with the capture & compression unit are not included. Flue gas or compressed CO_2 cooling represents an additional heat source, which is especially valuable for CHP/heat-only WtE plants. For CO_2 capture technologies that do not require steam extraction from the thermal cycle (Membrane cases and Oxy-fuel cases), the capture plant can run without affecting the core operation of existing plant. On the other hand, if the plant is not integrated with DH, there is no easily available heat sink for the capture plant; additional process cooling may be needed. Additional future work may be necessary to compare the potential of the each technologies on different WtE plants with different types of energy output.

Another worth noting limitation worth is the size of the reference WtE plant selected in this study. WtE plants are relatively heavy capital investment. A typical medium size (capacity) WtE plant is identified as the benchmark case in this study. There may be economies of scale for WtE plant with a larger capacity, which is not included in this comparison. This limitation is extended to the flue gas composition. There will be more fluctuation in terms of flue gas composition from the WtE plant due to the heterogeneous nature of the MSW (and SRF), which is different from the traditional fossil based CO_2 capture. An Assessment of this aspect is included in the Qualitative assessment in Appendix B, however a more comprehensive assessment may be beneficial to understand the potential of each technology.

A third limitation is the level of details when comparing different technologies. A relatively detailed comparison is provided for the comparison of benchmark MEA cases and Membrane cases, based on the existing resources available and valuable input from project partners. There is limited expertise in the project for the cost analysis, of Oxy-fuel combustion and it has proven difficult to access reliable data in the literature.

8 Conclusions

A techno-economic comparative assessment of three carbon capture technologies, including the 2nd generation solvent-based CO_2 capture, membrane-assisted CO_2 liquefaction and oxy-fuel combustion, for the WtE sector is included in this report, using as benchmark process chemical absorption with a 35 %wt MEA aqueous solution.

It is clearly seen that, for the benchmark MEA solvent based CO_2 capture in this report, the influence of higher CO_2 capture rates (from 90% or 95% to 99.72%) on plant performance in both energy consumption aspect and economic aspect is marginal. This may lead to the question of what is the reasonable targeting CO_2 capture rate for the future MEA based capture with WtE plants. Concepts like Zero emissions, high CO_2 capture rate, deep CCS (IEAGHG, 2019; Zhai & Rubin, 2022), (Du, Gao, Rochelle, & Bhown, 2021) etc. have been around for several years, and this of course not limited to the WtE sector itself but also to a broader industry applications. Robust policies, effective R&Ds, comprehensive pilot & commercial scale testing results will be highly valuable in fastening the progress towards essentially zero and negative industrial CO_2 emissions.

As a relatively well-developed technology, post-combustion CO_2 capture with 35 %wt MEA at 90%, 95% and 99.72% capture rate generally outperform membrane-assisted CO_2 liquefaction process with FSC and Polaris membranes. The specific power consumption for membrane capture is approximately 1.4 to 1.7 times higher than that for MEA-based capture. For the assumptions considered in this study, the LCOE of membrane-assisted CO_2 liquefaction is 6% to 26% higher than that of the 35 %wt MEA solvent capture. With the CO_2 capture rate concerned in this study, the CO_2 avoidance cost for Membrane based CO_2 capture is around 2.3 times higher than that of 35% MEA capture cases. Specific power consumption for Membrane assisted liquefaction is affected by the targeted carbon capture rate and the feed gas CO_2 concentration and a further optimisation should be conducted. The optimal CO_2 capture rate for membrane-assisted CO_2 liquefaction is however a trade-off between capital and operation costs.

The adaptation of oxy-fuel combustion CO_2 capture technologies for WtE facilities are investigated in this project, particularly for the oxy-combustion of solid recovered fuels (SRF) in circulating fluidised bed combustors (CFBC). Regarding the type of fuel, oxy-fuel combustion in CFBC requires a pre-treated solid waste with a higher calorific value and a more homogeneous particle size compared with a moving grate- technology and it therefore only suitable for new-build WtE plants. Post-combustion amine-based CO_2 capture can however be retrofitted to existing WtE plants. Although, oxy-fuel combustion capture could theoretically achieve a 100% CO_2 capture rate, a CO_2 material balance conducted in this project by USTUTT indicates that the CO_2 capture rate in their full-scale oxy-fuel CFBC model is approximately 94.2% due to remaining CO_2 emissions through the process. In terms of energy consumption, the specific electricity consumption for oxy-fuel CO_2 capture presents a specific electricity consumption strongly depends on the technology used in the ASU, which is the main electricity consumer in the processes. The specific electricity consumption varies from 291 kWh/t CO_2 to 437 kWh/t CO_2 for ASU electricity consumption from 100 to 220 kWh per tonne of CO_2 captured. Compared with amine-based CO_2 capture, an ASU energy consumption below 120 kWh/t CO_2 would be required in the oxy-fuel CFBC process to achieve an overall specific electricity consumption similar to the electricity output penalty of 311 kWh/t CO_2 evaluated for a 35 %wt MEA capture system at 95% capture rate. The pilot-scale test campaign has shown a promising performance for oxy-combustion of SRF in CFB boilers (key findings are available in *NEWEST_D5.2.2_USTUTT*), yet the TRL of this technology is relatively lower and it needs to be demonstrated at scale to reduce uncertainties.

The calculation of the KPIs relies on a series of assumptions related to important operation parameters, for example, gate fees of WtE plant and electricity prices, feed gas CO_2 concentration. A more detailed sensitivity analysis is required to assess the effect of these variables on the KPI for each investigated technologies.

Report of the WP5.3 helps to understand the potential of the key promising CO_2 technologies that can be applied in the WtE sector, along with improvement direction for future implementation to make the WtE sector a Negative emission provider. Advantages and challenges exist in each technology and the optimal solution will always be a three-way trade off in terms of minimizing energy consumption, maximizing profit and minimizing net CO_2 emission.

9 Acknowledgement

The authors gratefully acknowledge the cooperation and support by the NEWEST-CCUS project partners TNO, Sintef and University of Stuttgart, for providing lively discussion and input for this comparison. A special acknowledgement is also given to Simon Roussanaly (Sintef) for providing data and the methodology for the cost analysis

The NEWEST-CCUS project (Project No. 299683) is co-funded by the ERA-NET Accelerating CCS Technologies initiative, which supports the delivery of safe and cost-effective carbon capture, utilisation and storage. The governments of each participating country have contributed funding through the ACT2 initiative.

The authors thank FCC Environment, for providing operating data of the WtE plant, as well as thoughtful comments and suggestions.

10 Appendix A. CAPEX calculation methodology of CO_2 capture process for techno-economic assessment

10.1 Key financial assumptions

- The project is assumed to be located in North-West Europe.
- The reference year for the cost is 2019.
- Project evaluations are performed based on an economic lifetime of 25 years.
- The real discount rate and cost of capital are assumed to be both equal to 8%[1].
- The plant is assumed to operate 7650 h/y.
- Decommissioning and remediation of the land at the end of the project is excluded. It is assumed that the residual value of the plant and the selling of the land should cover any cost related to the decommissioning of the plant.
- Inflation assumptions are not included. No allowance for escalation of fuel, raw materials, labour and other cost relative to each other is taken into account.
- Depreciation is not included. The calculation of cost Key Performance Indicators are calculated based on an EBITDA basis (Earnings Before Interest, Taxes, Depreciation and Amortisation).

10.2 Investment

A bottom-up approach is considered in order to evaluate the Total Plant Cost (TCR). A schematic overview of the BUA is given in Figure 10-1.

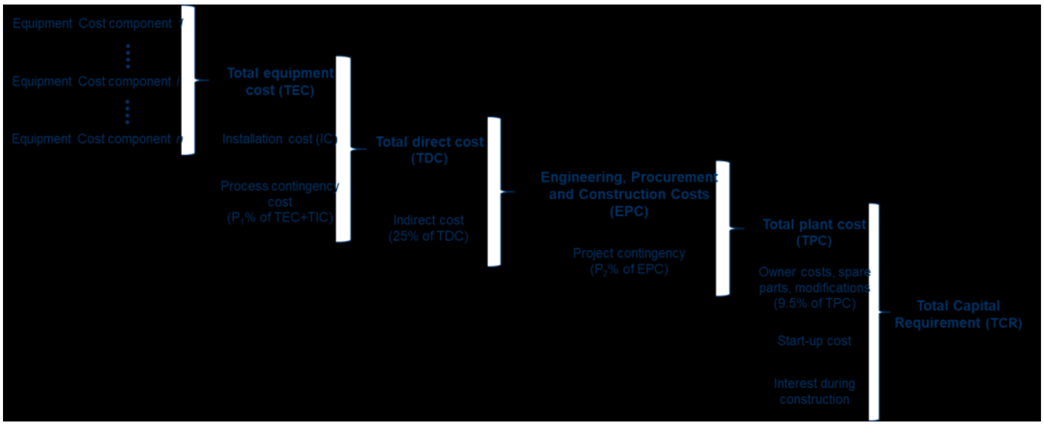

Figure 10-1: The Bottom-Up approach for estimation of total plant costs

The following cost elements are included:

- *Equipment Costs (EC)* – The Equipment Cost for each main basic equipment of the different processes can be estimated based on a step-count exponential costing method, using the dominant or a combination of parameters derived from mass and energy balance computations, combined with cost data obtained from equipment suppliers and/or other available data. The *Total Equipment Cost (TEC)* is the sum of all Equipment Costs in the plant.

---

1 This real discount rate of 8% corresponds to a nominal discount rate of around 10% if an inflation rate of 2% is considered

- *Installation Costs (IC)* – The Installation Costs are estimated as additional expenses to integrate the individual equipment into the plant, such as costs for piping/valves, civil works, instrumentations, electrical installations, insulations, paintings, steel structures, erections and OSBL (outside battery limits).

- *Total Direct Costs (TDC)* – The Direct Costs is the sum of the Equipment Costs and the Installation Costs and shall also include the appropriate process contingency factor in order to reflect the differences in technology maturity of the different processed considered as shown in Table 10-1. It is worth noting that, within one process, different units might have different maturity level and this process contingency factors.

Table 10-1: Guidelines for process contingency cost (S. Roussanaly et al., 2021)

Technology Status	**Process Contingency cost [% TDC without contingencies]**
New concept with limited data	40+
Concept with bench-scale data	30-70
Small pilot plant data	20-35
Full-sized modules have been operated	5-20
Process is used commercially	0-10

- *Engineering, Procurement and Construction Costs (EPC)* – The EPC cost is the sum of Total Direct Cost and Indirect Costs. The indirect costs are fixed to 25 % of the TDC and include the costs for the yard improvement, service facilities and engineering costs as well as the building and sundries.

- *Total Plant Cost (TPC)* – The TPC is the sum of EPC cost and project contingency estimated following the AACE 16R-90 guidelines shown in Table 10-2.

Table 10-2: Guidelines for project contingency costs (S. Roussanaly et al., 2021)

Estimate AACE Class*	**Design effort**	**Project contingency cost (%-EPC)**
Class 5/4	Simplified	30-50
Class 3	Preliminary	15-30
Class 3/2	Detailed	10-20
Class 1	Finalised	5-10

* Estimate class are defined in AACE (2011) as function of maturity level of definition

- *Total Capital Requirement (TCR)* – The TCR is the sum of total plant cost, the owner costs, spare parts, modifications, interest during construction and the start-up cost. The owner cost, spare parts, modifications are set as percentage of the TPC (7, 0.5 and 2% respectively) (IEAGHG, 2017). The interest during construction are calculated assuming that the construction costs are shared over a three-year construction period following a 40/30/30 allocation (R. Anantharaman et al., 2011). Finally, the start-up costs are evaluated based on the following considerations (IEAGHG, 2017):
    - 3 months of maintenance, operating and support labour
    - 1 month of materials, chemicals, consumables and disposal costs
    - 1.25 month of fuel costs bottom up approach.

References

AECOM. (2021). Next Generation Carbon Capture Technology, Technoeconomic Analysis, Work Package 6, Department for Business, Energy and Industrial Strategy.

Anantharaman, R. (2020). Presentation at the NEWESTCCUS Project Online meeting.

Anantharaman, R., Bolland, O., Booth, N., Dorst, E. V., Ekstrom, C., Franco, F., . . . Robinson, L. (2011). *D1.4.3 European best practice guidelines for assessment of CO_2 capture technologies (DECARBit Project)*.

Banaszkiewicz, T., Chorowski, M., & Gizicki, W. (2014). *Comparative analysis of cryogenic and PTSA technologies for systems of oxygen production*.

BEIS. (2020). Electricity-Generation-Cost-Report-2020. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/911817/electricity-generation-cost-report-2020.pdf

BEIS. (2022). Business Models for Engineered Greenhouse Gas Removals A consultation on accelerating investment in engineered carbon removals. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1087918/greenhouse-gas-removals-business-models-consultation.pdf

Bouma, R., Vercauteren, F., van Os, P., Goetheer, E., Berstad, D., & Anantharaman, R. (2017). Membrane-assisted CO2 Liquefaction: Performance Modelling of CO2 Capture from Flue Gas in Cement Production. *Energy Procedia, 114*, 72-80. doi:10.1016/j.egypro.2017.03.1149

Darde, A., Prabhakar, R., Tranier, J.-P., & Perrin, N. (2009). Air separation and flue gas compression and purification units for oxy-coal combustion systems. *Energy Procedia, 1*(1), 527-534. doi:10.1016/j.egypro.2009.01.070

Du, Y., Gao, T., Rochelle, G. T., & Bhown, A. S. (2021). Zero- and negative-emissions fossil-fired power plants using CO2 capture by conventional aqueous amines. *International Journal of Greenhouse Gas Control, 111*. doi:10.1016/j.ijggc.2021.103473

Energinet, D. E. A. a. (2021). Technology Data for Carbon Capture, Transport and Storage. Retrieved from https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_carbon_capture_transport_and_storage.pdf

Escudero, A. I., Espatolero, S., Romeo, L. M., Lara, Y., Paufique, C., Lesort, A.-L., & Liszka, M. (2016). Minimization of CO2 capture energy penalty in second generation oxy-fuel power plants. *Applied Thermal Engineering, 103*, 274-281. doi:10.1016/j.applthermaleng.2016.04.116

Gibbins, J., & Lucquiaud, M. (2021). BAT Review for New-Build and Retrofit Post-Combustion Carbon Dioxide Capture Using Amine-Based Technologies for Power and CHP Plants Fuelled by Gas and Biomass as an Emerging Technology under the IED for the UK, UKCCSRC Report, Ver.1.0, July 2021. (https://ukccsrc.ac.uk/best-available-technology-bat-information-for-ccs/).

He, X., Fu, C., & Hägg, M.-B. (2015). Membrane system design and process feasibility analysis for CO2 capture from flue gas with a fixed-site-carrier membrane. *Chemical Engineering Journal, 268*, 1-9. doi:10.1016/j.cej.2014.12.105

IEAGHG. (2017). *Evaluating the Costs of Retrofitting CO_2 Captured in an Integrated Oil Refinery. 2017/05. Cheltenham, United Kingdom.* Retrieved from

IEAGHG. (2019). Towards Zero Emissions CCS from Power Stations using Higher Capture Rates or Biomass.

IEAGHG. (August 2017). IEAGHG Technical Review 2017-TR8.

Joseba Moreno, M. S. (2022). NEWEST_D5.2.2_USTUTT, Results from oxy-fuel CFBC process simulations.

Josh Morgan, B. O., Debangsu Bhattacharyya, Anuja Deshpande. (2021). CCSI Steady State MEA Model (MEA ssm) User Manual, Version 3.2.0, February 2021. Retrieved from https://github.com/CCSI-Toolset/MEA_ssm

Kheirinik, M., Ahmed, S., & Rahmanian, N. (2021). Comparative Techno-Economic Analysis of Carbon Capture Processes: Pre-Combustion, Post-Combustion, and Oxy-Fuel Combustion Operations. *Sustainability, 13*(24). doi:10.3390/su132413567

Morgan, J. C., Soares Chinen, A., Omell, B., Bhattacharyya, D., Tong, C., Miller, D. C., . . . Lucquiaud, M. (2018). Development of a Rigorous Modeling Framework for Solvent-Based CO2 Capture. Part 2: Steady-State Validation and Uncertainty Quantification with Pilot Plant Data. *Industrial & Engineering Chemistry Research, 57*(31), 10464-10481. doi:10.1021/acs.iecr.8b01472

Nemitallah, M. A., Habib, M. A., Badr, H. M., Said, S. A., Jamal, A., Ben-Mansour, R., . . . Mezghani, K. (2017). Oxy-fuel combustion technology: current status, applications, and trends. *International Journal of Energy Research, 41*(12), 1670-1708. doi:10.1002/er.3722

Perrin, N., Dubettier, R., Lockwood, F., Tranier, J.-P., Bourhy-Weber, C., & Terrien, P. (2015). Oxycombustion for coal power plants: Advantages, solutions and projects. *Applied Thermal Engineering, 74*, 75-82. doi:10.1016/j.applthermaleng.2014.03.074

REMONDIS. (2014). Production and use of Solid Recovered Fuels – developments and prospects. Retrieved from https://bgs-ev.de/wp-content/uploads/2015/02/AFR_Remondis-Glorius_final_280814.pdf

Romeo, L. M., Abanades, J. C., Escosa, J. M., Paño, J., Giménez, A., Sánchez-Biezma, A., & Ballesteros, J. C. (2008). Oxyfuel carbonation/calcination cycle for low cost CO2 capture in existing power plants. *Energy Conversion and Management, 49*(10), 2809-2814. doi:10.1016/j.enconman.2008.03.022

Roussanaly, S. (2019). Calculating CO2 avoidance costs of Carbon Capture and Storage from industry. *Carbon Management, 10*(1), 105-112. doi:10.1080/17583004.2018.1553435

Roussanaly, S., Rubin, E., van der Spek, M., Booras, G., Berghout, N., Fout, T., . . . Ramirez, A. (2021). *Toward improved guidelines for cost evaluation of carbon capture and storage [White paper]. Edited by Roussanaly S., Rubin E.S., van der Spek M. Zenodo. http://doi.org/10.5281/zenodo.4940264.* Retrieved from

Soares Chinen, A., Morgan, J. C., Omell, B., Bhattacharyya, D., Tong, C., & Miller, D. C. (2018). Development of a Rigorous Modeling Framework for Solvent-Based CO2 Capture. 1. Hydraulic and Mass Transfer Models and Their Uncertainty Quantification. *Industrial & Engineering Chemistry Research, 57*(31), 10448-10463. doi:10.1021/acs.iecr.8b01471

Spero, C., & Yamada, T. (2018). Callide Oxyfuel Project, Final Results, Global CCS Institute. Retrieved from https://www.globalccsinstitute.com/resources/publications-reports-research/callide-oxyfuel-project-final-results/

Wheeler, A. F. (2015). Addendum to Energy from Waste Business Case, Aberdeen City Council. Retrieved from https://committees.aberdeencity.gov.uk/mgConvert2PDF.aspx?ID=61677

Zhai, H., & Rubin, E. S. (2022). It is Time to Invest in 99% CO2 Capture. *Environ Sci Technol, 56*(14), 9829-9831. doi:10.1021/acs.est.2c01615

Zhu, Y., Chen, M., Yang, Q., Alshwaikh, M. J. M., Zhou, H., Li, J., . . . Fantozzi, F. (2021). Life cycle water consumption for oxyfuel combustion power generation with carbon capture and storage. *Journal of Cleaner Production, 281*. doi:10.1016/j.jclepro.2020.124419