RETROFITTING WASTE-TO-ENERGY WITH CARBON CAPTURE AND STORAGE IN THE UK: A TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

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ABSTRACT: Waste incineration facilities are the prevailing technology for disposing of non-recyclable or unsorted fractions of municipal solid waste: waste is combusted and, in the case of Waste-to-Energy (WtE) plants, the resulting energy can be used to generate electricity and excess heat recovered. This work aims at understanding the technical, environmental, and economic values of retrofitting an existing WtE facility equipped with a carbon capture and storage (CCS) facility in the UK. The study is based on advanced process simulation using Aspen Plus and Life Cycle Assessment (LCA) to understand integration challenges and the impact of several variables (e.g. waste composition, carbon capture rate) on the techno-environmental performance of the plant. The results show that for the WtE-CCS system to operate self-sufficiently, substantial energy penalties are required with the reduction of the heat and electricity export to power the CCS. The significant additional economic penalty makes CCS unfavourable, considering the current lack of negative emissions market mechanisms and incentives in the UK. The LCA results show that CCS contributes to reducing the overall climate change impact of WtE from 68 to -816 kgCO_2 eq per tonne of MSW treated. The biogenic nature of the waste feedstock plays a key role in determining the environmental performance of WtE plants with and without carbon capture.
Keywords: Municipal Solid Waste (MSW), Waste to Energy, Carbon Capture and Storage (CCS), Life Cycle Assessment (LCA), Climate change.

1 INTRODUCTION

The growth of the global population, changes in people's lifestyles, and industrial development are all contributing factors to a significant increase in consumption levels and, consequently, the production of solid waste. This trend is expected to continue in the future. This increase is primarily driven by low-income countries, with waste management relying mostly on landfills, and only a small portion is incinerated using environmentally friendly technologies [1].

While recycling is the preferred environmental solution for waste management, incineration, especially through modern efficient Waste-to-Energy (WtE) plants, is expected to maintain an important role, and potentially increase over time. This trend would result in the increase of carbon emissions from the WtE sector from 2020 to 2050 [2], which conflicts with net-zero targets if carbon emissions are not abated, such as by deploying carbon capture and storage (CCS) or utilization technologies [3].

Capturing and permanently storing CO_2 from WtE plants can have substantial climate benefits, which are mainly associated with the biogenic nature of the municipal solid waste (MSW) because it leads to a net reduction in CO_2 content in the atmosphere. Consequently, WtE equipped with CCS has the potential to contribute with negative emissions as part of the bioenergy with carbon capture and storage (BECCS) technologies. These technologies, together with direct air capture (DAC), are expected to play a crucial role in addressing climate change in the future [4,5].

Extensive research in the literature has thoroughly examined the techno-economic and environmental impact of various waste management technologies, including incinerators with and without energy recovery [6–10]. Nevertheless, there have been limited research efforts focusing on the implementation of CCS in WtE plants, especially when it comes to retrofitting existing facilities [11–13]. Studies using Life Cycle Assessment (LCA) have shown that advanced WtE plants that prioritize the generation of electricity and/or heat offer significant environmental advantages. These plants replace the electricity and heat generated by traditional fossil carbon-intensive sources.

In this study, a holistic approach has been adopted to address and study the techno-economic and environmental implications of integrating CCS capabilities into a WtE plant, to identify challenges and opportunities for decarbonizing the energy sector in the UK scenario. To achieve this, a comprehensive process simulation of the WtE facility was developed using Aspen Plus considering both scenarios with and without carbon capture. A cradle-to-gate LCA was then performed to quantify and compare the environmental performance of the system. These two tools together can also be used to assess the economic and social costs and benefits of large-scale implementation. Different scenarios of carbon capture rates and feedstock were considered to investigate the effect of these key parameters on the technical and environmental sustainability of the WtE-CCS plant.

2 METHODS

2.1 Process description

Conventional WtE plants rely on burning the combustible fraction of waste feedstocks like MSW or wood waste (WW). This process generates a high-temperature flue gas that is used to produce electricity through a steam cycle and heat. Prior to being released into the atmosphere, the flue gas is treated to eliminate contaminants and harmful species. Figure 1 shows a schematic block flow diagram of the WtE plant coupled with CCS capability.

The incineration process also produces a solid residue in the form of bottom ashes, which is mainly associated with the incombustible fraction of waste. Typically, these residues undergo a processing stage to recover both ferrous and non-ferrous metals, whilst the remaining portion can be repurposed, such as being utilized as a substitute for gravel in pavement construction [14].

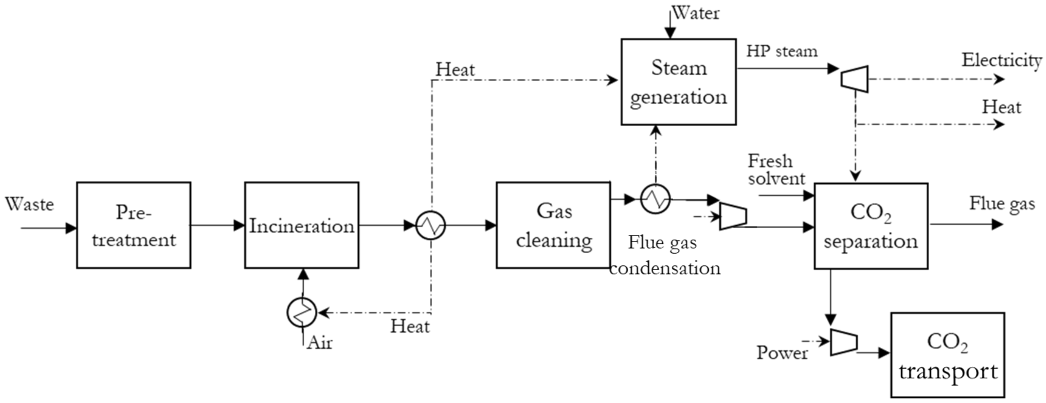

Figure 1: Schematic of the steps modelled to simulate the operation of Waste-to-Energy retrofitted with CCS.

After cleaning, the flue gas contains 11% CO_2 and is typically released into the atmosphere, thereby contributing to climate change. One possible solution to mitigate the impact is to separate and capture CO_2 from the flue gas prior to being vented.

Amine-based technologies are the most commonly adopted for post-combustion capture applications [15–17]; in this work, monoethanolamine (MEA) in an aqueous solution of 30% wt was used as an absorption solvent in the carbon capture unit.

When retrofitting a WtE with CCS, a flue gas condensation unit is usually required to better integrate the two plants. This unit takes the high-temperature flue gas from WtE and reduces its moisture content (from ~14% to about 4%) via condensation with heat recovery.

In this work, a commercial scale WtE plant was modelled to treat approximately 28 ton/h of MSW, corresponding to 75MW_{HHV} based on the waste calorific value. The energy throughput has been kept constant when investigating a different scenario in which the feedstock is wood waste. In the latter case, the WtE process would treat approximately 25 ton/h of WW, equal to 75 MW_{HHV}. The differences in amount of waste fed into the incinerator are attributed to the higher heating value of the wood waste, as shown in Table I, having a lower content of inert material compared to MSW.

The capture unit yields a CO_2 removal of 85% and 95% and a high-purity CO_2 stream (>99%), which is then compressed and refrigerated for transportation purposes [18]. CO_2 is first compressed at a pressure of 60 bar and transported via truck to a UK carbon cluster hub, where it is then injected into the geological storage site via pipeline, in supercritical conditions, at a pressure of 120 bar.

2.2 Waste characterization

The heterogeneous nature of MSW, both in terms of composition and origin, determines the heating value of the waste and, consequently, can impact the operation and the energy throughput of the WtE plant. Amaya-Santos and Chari et al. [19] reported a typical composition of MSW in the UK, which is also illustrated in Figure 2.

Proximate and ultimate analyses were assigned to each component present in the waste (paper, cardboard, dense plastic, etc.) based on literature data [20–22]. Then, the proximate and ultimate analyses for the waste feedstock were calculated as a weighted average of each fraction and used in the process simulations.

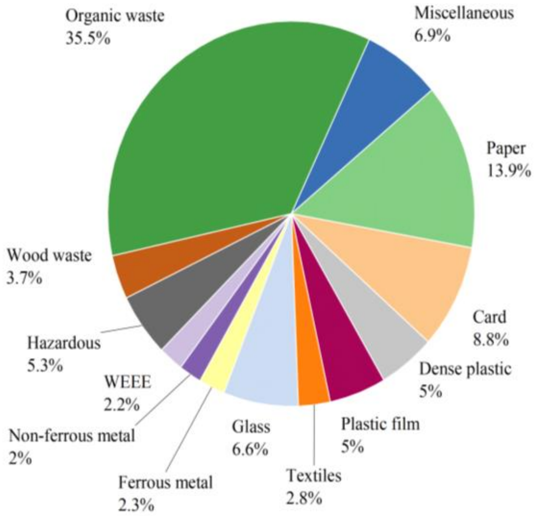

Figure 2: Average MSW feedstock composition, adapted from [19].

The proximate and ultimate analyses obtained and used in the models are reported in Table I, together with other useful parameters, such as the biogenic content and heating value.

Table I: Waste Characterization [19,23].

	MSW	WW
Proximate analysis [% wt dry]		
Volatile matter	68.5	85.2
Fixed carbon	8.5	14.3
Ash	23	0.5
Ultimate analysis [%wt dry]		
C	40.78	50.65
H	5.64	5.73
O	28.91	42.78
N	1.14	0.28
Cl	0.23	0.01
S	0.25	0.01
Ash	23	0.54
Other		
Moisture [%wt]	17	26
Calorific value [MJ/kg]	9.5	10.4
Biogenic carbon [%]	64	98

2.3 Life Cycle Assessment

The LCA Methodology was used to assess the carbon and environmental performance of the WtE plant with and without CCS capabilities. This approach allows identifying the environmental advantages and disadvantages of CO_2 capture by comparing the performance of CCS with the baseline case without carbon capture, while the main contributors of the impact are identified through detailed hot-spot analyses.

The functional unit of this analysis is 1 tonne of waste treated. The system boundaries encompass the entire life cycle, from the origin of waste to its final disposal, including waste treatment in a WtE plant, as well as the capture, transportation, and storage of CO_2. The LCA study relies on mass and energy balances obtained from the Aspen models, complemented with data from the ecoinvent database, cut-off system model, version 3.8 [24].

The circular footprint formula [25] was adopted to allocate the environmental impacts to the function of waste management. This formula follows a "crediting" approach to account for the environmental benefits of substituting electricity from the grid mix and heat from natural gas. For the recovered products (i.e. metals and ashes) the formula allocates the benefits between the "producer" and the "user". The extent of the benefit distribution is determined by the ratio between the demand and supply of recyclable materials in the market.

Fig. 3 shows a schematic representation of the system boundaries, divided into Background and Foreground systems

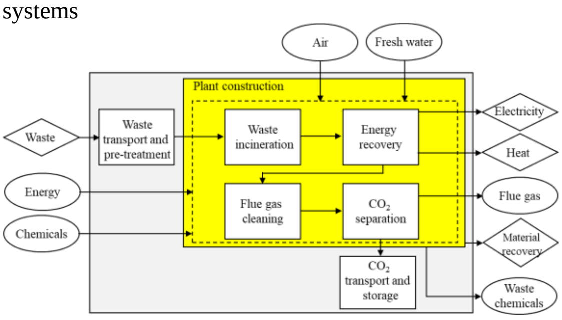

Figure 3: Schematic representation of the LCA system boundaries.

3 RESULTS AND DISCUSSION

3.1 Techno-economic assessment

3.1.1 Process simulation

The results of the process simulation are reported in Table II in the form of mass and energy balance together with key performance indicators.

The base case of the WtE plant without carbon capture exports approximately 14.4MW of electricity and 14.75MW of thermal energy when treating about 231 kilotonnes of MSW per year. The ratio between heat and electricity is in line with literature data [26–28]. Retrofitting the WtE with CCS results in additional electric and thermal energy requirements which reduce the overall efficiency of the plant. The heat demand is mainly due to the regeneration of the MEA solution and supplied to the reboiler. Electricity is instead needed for the initial compression of the flue gas to be sent into the adsorption unit, for solvent circulation, and for the final CO_2 compression and storage.

Notably, about 5MW of additional heat can be recovered from the flue gas condensation unit that interconnects the WtE and CCS, and used for district heating [27,29].

The results indicate that, depending on the carbon capture rate (CCR), the carbon capture (CC) unit requires almost 4 MJ of heat for solvent regeneration and around 0.6 MJ of electricity per ton of CO_2 captured. The overall energy intensity of the CC increases with increasing the amount of carbon captured and the amount of flue gas to be treated.

Table II: Summary Mass and Energy balance for the WtE treating MSW and the WtE-CCS for the different capture rates examined.

	MSW		
Capture rate	**No CCS**	**85%**	**95%**
Feedstock	28.4 ton/h 75MW	28.4 ton/h 75MW	28.4 ton/h 75MW
Air	160 ton/h	160 ton/h	160 ton/h
CO_2 captured	n.a	27.3 ton/h	30.5 ton/h
Flue gas	181 ton/h	142 ton/h	139 ton/h
Make up solvent	n.a.	0.1 ton/h	0.1 ton/h
Net Electricity exported	13.8 MW	6.3 MW	5 MW
Net Heat exported	14.2 MW	4.7 MW	4.7 MW
CC reboiler duty	n.a.	3.82 MJ/kgCO_2	3.96 MJ/kgCO_2
CHP efficiency	37.3%	14.6%	12.9%

The thermal energy required by CCS (29MW and 34MW depending on the capture rate) cannot be satisfied with the excess heat available in the WtE plant. Therefore, in order for the WtE-CCS system to operate self-sufficiently, ~10 MW of steam is diverted from the turbine to provide for the thermal energy required by the CCS. This corresponds to an electricity sacrifice of about 3.4MW and 4.4MW for 85% and 95% CCR respectively, hindering the overall performance of the plant.

A similar trend is found in the case reported in Table III when WW is the feedstock for WtE, requiring a higher energy sacrifice due to the higher amount of flue gas and CO_2 being generated.

This is a direct of two effects: on one side the lower fraction of inerts results in more flue gas being generated, on the other side the higher fraction of carbon in the waste (see Table I) ends up in more CO_2 in the flue gas. The higher heat required by the CC unit (~37MW) is partly counterbalanced by the overall higher amount of electricity produced by the WtE plant when operating with WW, resulting in an electricity sacrifice of about 5MW.

Flue gas stack emissions for the scenarios investigated are reported in Table IV. The flue gas has a high content of CO_2 and Steam, around 12% and 14% respectively, as the product of complete combustion, and O_2 due to the excess air required for complete combustion. The product stream is highly diluted by the inert N_2 present in the air used as the oxidizing agent.

Table III: Summary Mass and Energy balance for the WtE treating WW as feedstock and the WtE-CCS with 95% capture rate.

	WW	
Capture rate	**No CCS**	**95% CCR**
Feedstock	25.98 ton/h 75MW	25.98 ton/h 75MW
Air	160 ton/h	160 ton/h
CO_2 captured	n.a.	34 ton/h
Flue gas	185.7 ton/h	139 ton/h
Make up solvent	n.a.	0.1 ton/h
Net Electricity exported	14.4 MW	4.7 MW
Net Heat exported	14.75 MW	4.8 MW
CC reboiler duty	n.a.	3.96 MJ/kgCO_2
CHP efficiency	38.9%	12.6%

Table IV: Flue gas stack emissions for the different cases investigated.

	MSW			WW	
Capture rate	**No CCS**	**85%**	**95%**	**No CCS**	**95%**
Flowrate (ton/h)	181	142	139	186	139
Composition					
H_2O [%]	13.9	4.3	4.3	14.3	4.3
CO_2 [%]	11.5	2.2	0.7	12.6	0.8
N_2 [%]	69.6	87.2	88.6	68.1	88.4
O_2 [%]	5	6.3	6.4	5	6.5
CO [ppm]	7.4	9.3	9.5	10.4	13.5
NOx [ppm]	148	185	188	158	205

3.1.2 Economic considerations

The economic impact of adding CCS to an existing 230ktpa WtE plant has been investigated by means of the Aspen Plus economic analysis tool. The main results are summarized in Table V together with the economic assumptions that have been used in this indicative techno-economic assessment.

Table V: Key economic assumptions and costs for the WtE-CCS facility.

Assumptions	
Plant availability	8109 h/year
CO_2 generation	1.13 tonCO_2/tonMSW
Waste throughput	28.4 ton/h
CC heat requirement	3.96 MJ/kgCO_2
CCR	95%, 85%
Biogenic content	64%
Cost results	
Gate fees	80 £/tonMSW
Power price (2030)	60 £/MW
Heat price (2030)	11 £/MW
Carbon price (2023)	76.9 £/tonCO_2
Total WtE	44 £/tonMSW
Total CCS	85 £/tonCO_2

The assumed power price and carbon price relationship have been derived using a Plexos model of the UK power market [30,31].

Figure 3 refers to a projected case in which carbon credits and carbon taxation regulation would exist, assuming the present carbon price (average of the first half of 2023 in UK) of £76.9/ton of CO_2 emitted or removed [32]. Using the assumptions from T V, with the hypothesis that all non-biogenic CO_2 emitted attracts a carbon tax, and stored biogenic carbon attracts a credit, a simple picture of revenue streams for a typical WtE-CCS plant can be built as reported in Figure 4.

The largest costs are those associated with the operation of the CCS and WtE facilities. Gate fees, followed by power exported and carbon credits, which are all related to plant throughput and CCR, are key for the economic sustainability of the WtE and WtE with CCS plant. However, currently, WtE plants do not pay a carbon tax and no credit is available to WtE plants with CCS for storing or using biogenic CO_2. Nonetheless, with a carbon price of £76.9/tonCO_2, retrofitting a WtE plant with CCS of the scale investigated in the work represents an unfavourable and financially unreasonable option.

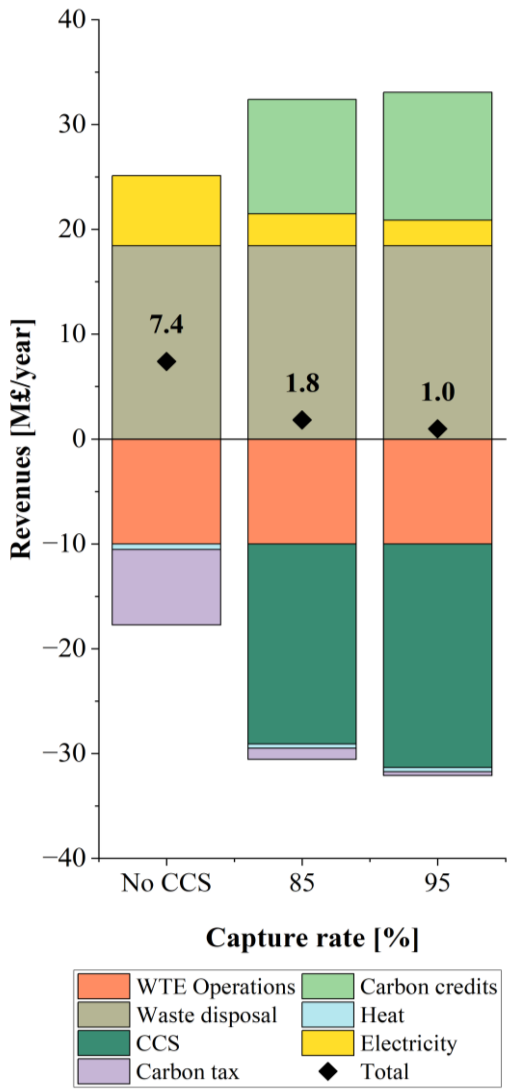

Figure 4: Revenue streams of the WtE plant with and without CCS at different CCRs.

A reduced penalty would be generated by reducing the cost associated with solvent regeneration in the CCS plant and transport infrastructure, or by increasing the share of biogenic carbon in the waste if a carbon incentive mechanism is established.

3.2 Life Cycle Assessment

3.2.1 Carbon capture rate

The climate performance of the WtE plant with and without CCS is reported in Figure 5. The results show that the WtE plant alone contributes to climate change with net carbon emissions equal to 86 kg CO_2-eq. per tonne of MSW combusted, including credits for metal and bottom ashes recovery. Conversely, capturing CO_2 from the flue gas mitigates the climate change impact of the WtE-CCS plant contributing with net negative climate impacts. The climate change impact is in the range of -720 kg CO_2-eq./tonMSW up to -816 kg CO_2-eq./tonMSW for CCRs of 85% and 95%. As expected, the 95% capture rate would be the most favourable from a climate standpoint, despite the reduced credits for energy export.

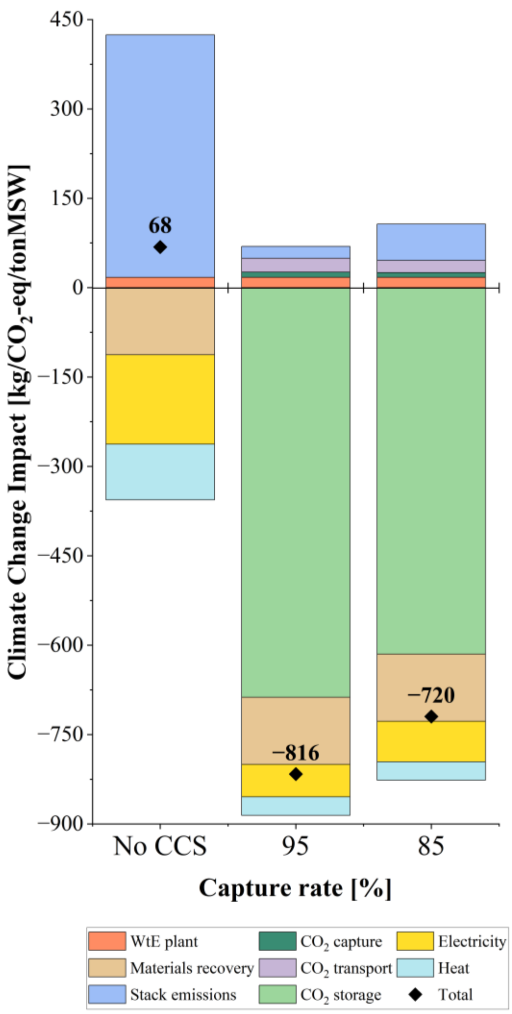

Figure 5: Climate change impacts for the WtE with different carbon capture scenarios.

Without CCS, the main contributor to climate change impacts is the direct emissions of fossil CO_2 with the flue gas. Credits for electricity and heat export, and materials recovery, only provide partial compensation for stack emissions.

The process of capturing CO_2 offers two primary advantages: firstly, it reduces emissions of fossil carbon in the flue gas and vented, and secondly, it sequesters biogenic CO_2, thereby contributing to climate change mitigation by removing CO_2 from the natural carbon cycle and lowering its concentration in the atmosphere. Increasing the capture rate improves climate performance. Despite potentially resulting in lower exports of heat and electricity, capturing CO_2 remains environmentally beneficial. The results are in line with literature data [33,34].

3.2.2 Waste composition

The impact of the waste composition on the climate performance of a WtE plant with and without carbon capture is shown in Figure 6. In particular, the baseline scenario of the WtE treating MSW as feedstock is compared with the scenario of WW being the primary feedstock of the process.

The analysis shows that increasing the biogenic fraction results in a notable decrease in climate change impacts, regardless of whether CO2 is captured or not. When WW is used, the WtE plant would become a “carbon negative” technology, with an overall climate change impact of -237 kg CO_2-eq/tonWW. This is due to the biogenic nature of the carbon emitted that does not contribute to a net overall increase in CO_2 concentration in the atmosphere. This is justified by the counterbalancing effect played by the amount of CO_2 captured in a reasonable timeframe by the wood whilst growing.

In general, the effect of waste composition on climate performance is predominantly influenced by three key parameters: the biogenic fraction and calorific value of the waste, as well as the quantity of recoverable material after incineration.. In the WW scenario, the waste has both a higher biogenic fraction and higher calorific value, however, no credits for metals and bottom ashes have been considered for wood.

The advantages of a higher proportion of biogenic carbon outweigh the missing credits for material recovery and the decrease in electricity and heat export due to the higher energy requirements for CCS, compared to the MSW case. Furthermore, despite the amount of WW treated being lower than in the MSW case, it generates a higher amount of flue gas and more CO_2 is captured: 276 ktpa compared to 248 ktpa in the case of MSW. This results in higher credits for the WW scenario, despite the impact of the difference in biogenic content.

This analysis suggests that using WW would be a preferable option to bolster the environmental performance of the process. However, this might not hold true when considering the economic implication of using biomass instead of waste, with the loss of revenues associated with the gate fees. However, a similar outcome of the WW scenario could be achieved by changing the MSW composition.

An increase in the biogenic fraction of carbon in MSW can be obtained by upgrading the MSW supply chain upstream, reducing the plastics content or increasing that of bioplastics. This suggests that the climate performance of WtE plants will improve over the long term as waste collection and separation methods become more efficient and the global consumption of single-use plastic decreases.

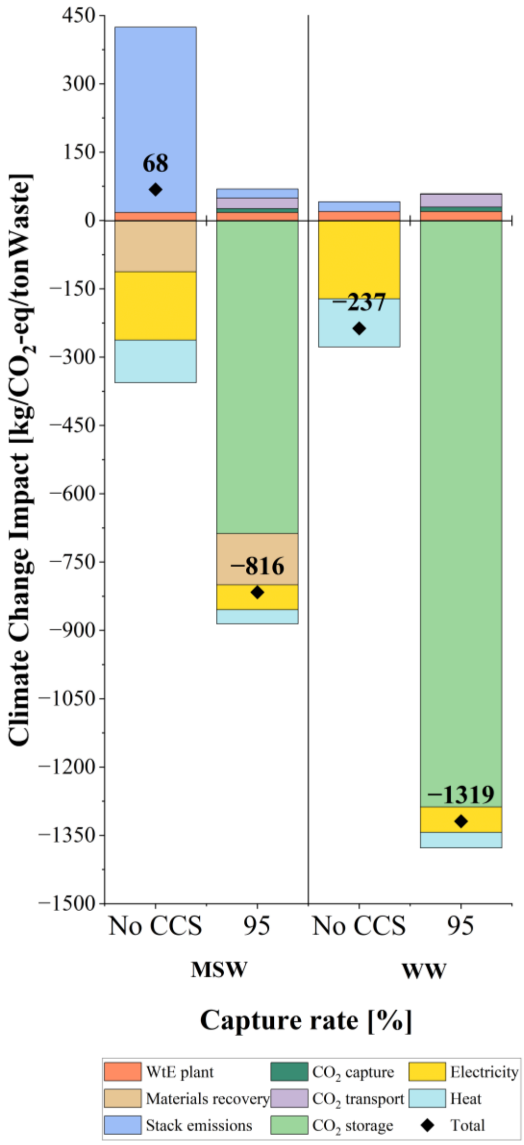

Figure 6: Climate change impact for waste composition scenarios for a WtE plant with and without CC.

4 CONCLUSIONS

In this study, the techno-economic and environmental implications of decarbonising Waste to Energy (WtE) plants were investigated by means of detailed process simulations on Aspen Plus, used to then inform a comprehensive LCA study, which also relies on inventory data.

The integration of CCS with the WtE plant shows that energy sacrifice is deemed necessary to operate the plant self-sufficiently. The CC unit requires about 3.9 MJ of heat and 0.6 MJ of electricity per ton of CO_2 captured, depending on the capture rate. These resulting energy penalties affect the overall plant CHP efficiency, reducing from 37% to 13% due to the lower energy export.

Capturing carbon significantly reduces climate change impacts compared to the case when CO_2 is not captured, from 68 kg CO_2-eq. to -720/-816 kg CO_2-eq. per tonne of MSW.

The scenario analysis indicates that the composition of the waste feedstock can affect largely the environmental performance of WtE, both with and without carbon capture. The main key parameters associated with the waste composition are the biogenic fraction, which determines the extent of carbon credits, and the calorific value, which affects the size and the functional unit of the study. Despite wood waste showing the best environmental performance, its use as feedstock might either not be an economically viable option or involve major issues with the sourcing and supply chain. Benefits similar to the use of WW can be achieved by reducing the plastic component in MSW via enhanced separation upstream or in the pre-treatment stage.

Overall, economics is the biggest limitation to deploying carbon capture in any sector due to additional operational costs; but it is particularly challenging in the WtE sector due to additional costs linked to transport. Therefore, carbon taxation, and in particular tax credits for biogenic carbon removals, are key to the economic feasibility of capturing carbon. The economic estimation shows that at current market conditions, a WtE plant with carbon capture may at best break even or provide limited revenues.

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