Reliably Accounting for Negative Emissions of Waste-to-Energy with Carbon Capture and Storage

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Abstract:
When equipped with Carbon Capture and Storage (CCS), the Waste to Energy (WtE) sector can play a significant role in creating an overall system that removes excess greenhouse gases from the atmosphere while sustainably managing waste. Ultra-high CO2 capture rates can be achieved to eliminate all CO2 emissions from the combustion of the waste feedstock. As the biogenic carbon in most waste feedstocks originates in the atmosphere, the implementation of CCS on WtE plants can create a 'negative emissions' system; i.e., the removal and permanent storage of atmospheric carbon dioxide. Existing studies exploring the negative emissions potential of this technology are of limited scope, however, and do not account for the system-wide change in impacts or identify relevant cause-effect pathways. By not accounting for the impact of removing recyclable materials from the supply chain, for example, the comparative benefit of sending biogenic materials for recycling or to WtE with CCS is poorly understood. It is important to understand these benefits in the context of the whole economy. This paper reviews existing analyses of the carbon reduction of WtE with CCS and discusses the challenges of understanding its role in the transition to Net Zero in the context of the circular economy.

Keywords: Waste to energy; carbon capture and storage; negative emissions; biogenic carbon

1. Introduction

Waste-to-energy (WtE) is rapidly becoming one of the primary methods of treating residual waste in Europe, due to legislation diverting waste from landfills, and mandating the implementation of energy recovery on waste incineration plants (European Union, 2018, Brown et al., 2023). This process, however, still has significant carbon emissions, estimated to be 700 to 1200 kg CO_2eq/t_{MSW} (IPCC, 2003). The addition of post-combustion carbon capture and storage (CCS) can completely eliminate all CO_2 emissions from the waste incineration process, significantly reducing the climate change impacts, and potentially creating a negative emissions pathway due to the biogenic carbon in the waste feedstock (Su et al., 2023).

A significant proportion (50-70%) of the carbon in residual waste (waste that remains after separation for re-use and recycling) is of biogenic origin (Herraiz et al., 2023). Traditional waste treatment processes, including landfill and WtE, release this biogenic carbon back into the atmosphere in the form of methane or carbon dioxide. WtE-CCS, like other types of bioenergy with carbon capture and storage (BECCS), will capture and permanently store it. Existing studies suggest that significant carbon dioxide removal can be achieved, with an estimated potential removal of 30 to 100 Mt CO_2eq/yr in the European waste sector (Muslemani et al., 2023).

Waste-to-energy is, however, considered only one step above landfill as a waste treatment option (Figure 1), with circular economy principles aiming to minimise the amount of material reaching this stage. If the addition of CCS to WtE plants results in a greater reduction in atmospheric CO_2 concentrations than material reuse and recycling, should this still be the case?

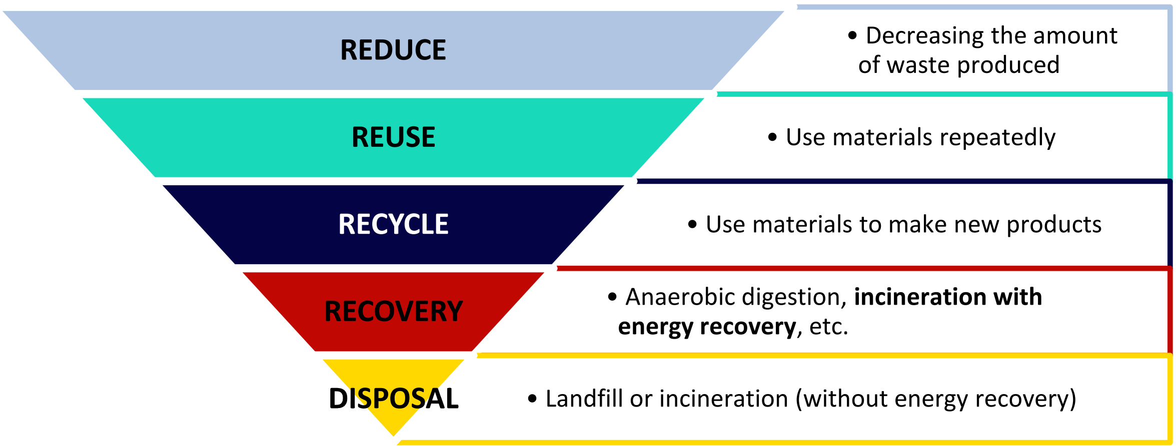

Figure 1 - Waste hierarchy

While the principles of the circular economy are intended to minimise material consumption and waste production, a key driver for this is environmental sustainability. Initial results from analyses considering a range of different waste compositions suggest that the diversion of dry biogenic waste away from WtE-CCS plants to recycling may actually have a higher carbon impact (Herraiz et al., 2023). If these results are correct, there is a potential conflict between circular economy policies, which aim to minimize waste and promote recycling, and climate policies, which seek to maximize negative emissions to achieve Net Zero.

A comprehensive analysis comparing the relative environmental merits of WtE-CCS and recycling for dry biogenic waste has not yet been carried out to test this conclusion. Furthermore, the existing analyses are limited in scope, considering only the direct emissions and assumed avoided impacts of the waste treatment process within the boundaries of attributional life cycle assessment (Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018, Struthers et al., 2022, Herraiz et al., 2023). The conventional methodologies applied in these studies are unable to account for the system-wide change in impacts caused by waste management interventions, and related cause-effect pathways, such as the displacement of existing uses through diversion of constrained resources.

Furthermore, there is an ongoing debate whether WtE-CCS is a true carbon removal technology or not; it may not qualify as a NET (Negative Emission Technology) due to an assumption that the removals would have occurred anyway, as the production of the biogenic material is independent of the waste treatment process. This debate over the language used to describe atmospheric emissions reductions could divert attention away from the potential benefits of this technology, and merits clarification. The conversion of waste to energy with geological CO_2 storage is the only known waste treatment method that can prevent the majority of biogenic carbon from returning to the atmosphere over geological timescales. It typically includes conversion of waste to electricity and/or heat in Waste to Energy plants, but could be extended to the production of zero-carbon fuels from waste.

There is an urgent need to identify the most cost-effective and rapid routes to reducing carbon emissions and atmospheric carbon concentrations. In order to improve confidence in negative emissions processes like WtE-CCS, the uncertainty about the analytical methods and the clarity of the language applied to describe them must be addressed. More comprehensive and integrated approaches are required to understand the implication of WtE-CCS for carbon emissions and removals, and to allow analysts, investors and policy makers to have confidence in the conclusions about the position of this technology in the pathways to Net Zero.

The overall aim of this paper is, therefore, to review how well the carbon benefits of waste-to-energy with carbon capture and storage are understood in the context of the whole circular economy, and discuss what methodological developments are needed to reliably evaluate any trade-offs between Net Zero and Circular Economy targets.

2. Defining negative emissions

Negative emissions technologies (NET) are defined as those that remove and permanently store greenhouse gases (GHGs) from the atmosphere, through intentional human efforts (Minx et al., 2018, Terlouw et al., 2021). In order to mitigate the impacts of climate change through atmospheric carbon removals, "an overarching necessity is to ensure that the total effect of all components within the complex system of a NET is the permanent removal of atmospheric greenhouse gases, and thereby a net decrease in the greenhouse gas concentration in the atmosphere" (Tanzer and Ramírez, 2019).

A number of studies have examined the GHG emissions of WtE-CCS technologies and have found them to be net-negative, resulting in the assertion that WtE-CCS is a NET (Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018, Struthers et al., 2022). When calculating the net GHG emissions of a technology through LCA, however, both the 'avoided emissions' from substituting alternative processes (such as displacing energy production through combustion of fossil fuels) and the true 'negative emissions' are often aggregated, which can easily cause misinterpretation (Allen et al., 2020, Forster et al., 2021). Although calculations for avoided emissions result in negative numbers, they are distinct from the measurable physical removal of greenhouse gases from the atmosphere (Tanzer and Ramírez, 2019).

In order to evaluate the negative emissions attributable to WtE-CCS, it is therefore important to understand the positive, negative, and neutral flows of GHGs within the WtE-CCS system. These can be classed as follows:

- **Net direct emissions from MSW incineration** (positive flow): This includes all GHGs released in the flue gases after air pollution control and the carbon capture process, characterised according to radiative forcing in units of kg CO_2eq. Note that biogenic CO_2 emitted to the atmosphere is typically given a characterisation factor of 0 kg CO_2eq/kg, so is a neutral flow (ReCiPe, 2016). The direct emissions-reduction due to capture and long-life/permanent storage in geological formations of CO_2 of fossil origin is directly accounted for within this metric, in reducing the GHG content of the flue gases.
- **Net direct emissions from CCS** (positive flow): This includes all GHGs released in the CCS process (typically amine and degradation products like ammonia), and leakage of CO_2 during transportation and storage.
- **Net indirect emissions from WtE-CCS** (positive flow): All GHG emissions associated with the life cycle of the WtE and CCS infrastructure, and the materials consumed during operation.

- **Avoided emissions from co-products/processes** (negative flow): This is the estimated reduction in emissions due to the displacement or substitution of other processes by conventional means, such as energy generation, primary metal production or waste treatment. This is highly subjective and difficult to test; for example, it is unclear which type of electricity generation reduces its output as a result of electricity exported from a WtE plant, and thus the corresponding emissions intensity of this displaced generation. It is not typically calculated as part of an attributional LCA, but is often considered in the analysis of the results in evaluating the significance of the findings. This has been included in several published LCA studies of WtE-CCS (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018).
- **Negative emissions from biogenic CCS** (negative flow): The capture and permanent storage of CO_2 from incineration of biogenic materials in the MSW feedstock.

The assertion that this final activity is a true negative emission is an open question for debate, particularly with regards to WtE-CCS. This is because the biogenic feedstock is a waste material; the removal of carbon from the atmosphere happens as the plants are grown to make bio-based products (food, paper, card etc.), which are then disposed of as waste. This happens independently of the existence of the WtE-CCS plant, and therefore the removals can be considered outside the system boundary and would happen anyway. This assumption is in line with the existing guidance for evaluating BECCS as a NET, where the production of the biogenic feedstock *is* included in the system boundary, so it includes a removal from the atmosphere (Tanzer and Ramírez, 2019).

The IPCC defines a “removal” as the transfer of GHGs from the atmosphere to non-atmospheric reservoirs, which is separate from “storage” (IPCC, 2006). In WtE-CCS, the removal of the GHG from the atmosphere into the biospheric reservoir occurs outside of the system boundary (note that the growth of the crop also doesn’t meet the definition of a NET, as it is not permanent). It may be appropriate to expand the system boundary to include this upstream removal, but this is contentious as the upstream impacts of product manufacture are not included. If the carbon removals of making a cardboard box are attributed to the waste treatment process, then there is a case for attributing all of the manufacturing impacts to the waste treatment, rather than to the product. The problem arises because this analysis is only considering a partial life cycle of the cardboard box (disposal, from gate to grave).

The intervention of the carbon capture process in the biogenic carbon cycle with subsequent long-term storage, however, does occur within the system boundary, and should be accounted for. This process prevents the transfer of the biogenic CO_2 back into the atmosphere by transferring it into long-term storage in the geosphere. The impact on climate change of impermanent removals into the biosphere is different from the impact of permanent removals into the geosphere. The current taxonomy does not have appropriate terminology for this; the best approximation is that this is an “avoided emission”. These avoided emissions are, however, distinct from the “avoided emissions” due to displacement of processes like landfilling and energy generation, so the term “negative emissions” is retained in this paper.

The attribution of biogenic CO_2 capture and storage as a negative emission aligns with the current convention in attributional LCA of giving biogenic CO_2 a characterisation factor of 0 kg CO_2eq/kg at the point of absorption from/emission to the atmosphere. This is either due to the assumption that it is in balance as part of the natural carbon cycle, or that the biomass is continually replaced by an equivalent amount of new planting, thus balancing out the CO_2 absorption and emissions (Tanzer and Ramírez, 2019). (Note that emissions of other GHGs of biogenic origin, such as methane, are given the same characterisation factors as those of fossil origin.) Although the assumption of the carbon neutrality of biogenic CO_2 is contested (Liu et al., 2017) in all the analyses discussed in this article, the permanent removal of biogenic CO_2 to geological storage is, therefore, given a characterisation factor of -1 kg CO_2eq/kg at the point of human intervention in the carbon cycle, as this is the point where the balance has been disrupted.

3. Negative emissions of WtE with CCS

Although the application of carbon capture to waste-to-energy is currently only operational at pilot scale in a handful of locations (Aker Solutions, 2019, Fortum Oslo Varme AS, 2020), or at commercial scale to sell CO_2 as a commodity (i.e. without geological storage) (Wright, 2021, Ros et al., 2022) a number of studies have been published that assess the potential environmental impacts and burdens of this technology (Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018, Struthers et al., 2022). In accordance with legislation on environmental sustainability evaluation of waste treatment (European Union, 2009), these assessments are based on the internationally-standardised LCA methodology (ISO, 2006a, ISO, 2006b). The results from these studies have been used to draw conclusions on the relative benefits of WtE with CCS over other waste treatment and energy generation options.

3.1. Carbon impacts per tonne of waste treated

Figure 2 summarises the current estimates of the carbon impacts and benefits of WtE with CCS (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018). These are all process-based attributional LCA studies examining a single WtE plant, with the results reported per unit of waste treated, ranging from -532 to -773 kg CO_2eq/t_{MSW}. This includes direct emissions from the combustion of waste and supplementary fuels and the environmental burdens from the production of required ancillary materials and energy. Defining the system boundary at the level of the WtE-CCS plant implicitly excludes the consequential impacts on the wider economy; however, these studies have all reported the captured and stored CO_2 of biogenic origin as a negative emission at the point of removal from the flue gases.

All of these studies also account for the avoided emissions due to energy export and metal recovery. Assumptions of the carbon intensity of the avoided processes may significantly over- or under-estimate the emissions reductions – particularly with the rapid decarbonisation of the energy sector – so these estimates should be treated with caution. This is illustrated well by the high emissions reduction attributed to electricity export in Pour et al. (Pour et al., 2018), which is due to the case study plant being in Australia where there is a higher-carbon energy generation mix than for the European countries considered by Struthers et al. (2022) and Bisinella et al. (2021, 2022). Without the avoided emissions impacts, the net emissions are -350 to -533 kg CO_2eq/t_{MSW}.

Avoided waste treatment is not considered in any of these studies, because the results are reported per unit of waste treated to enable comparison with other waste treatment options, so inclusion of the emissions reduction of avoided waste treatment could lead to double-counting.

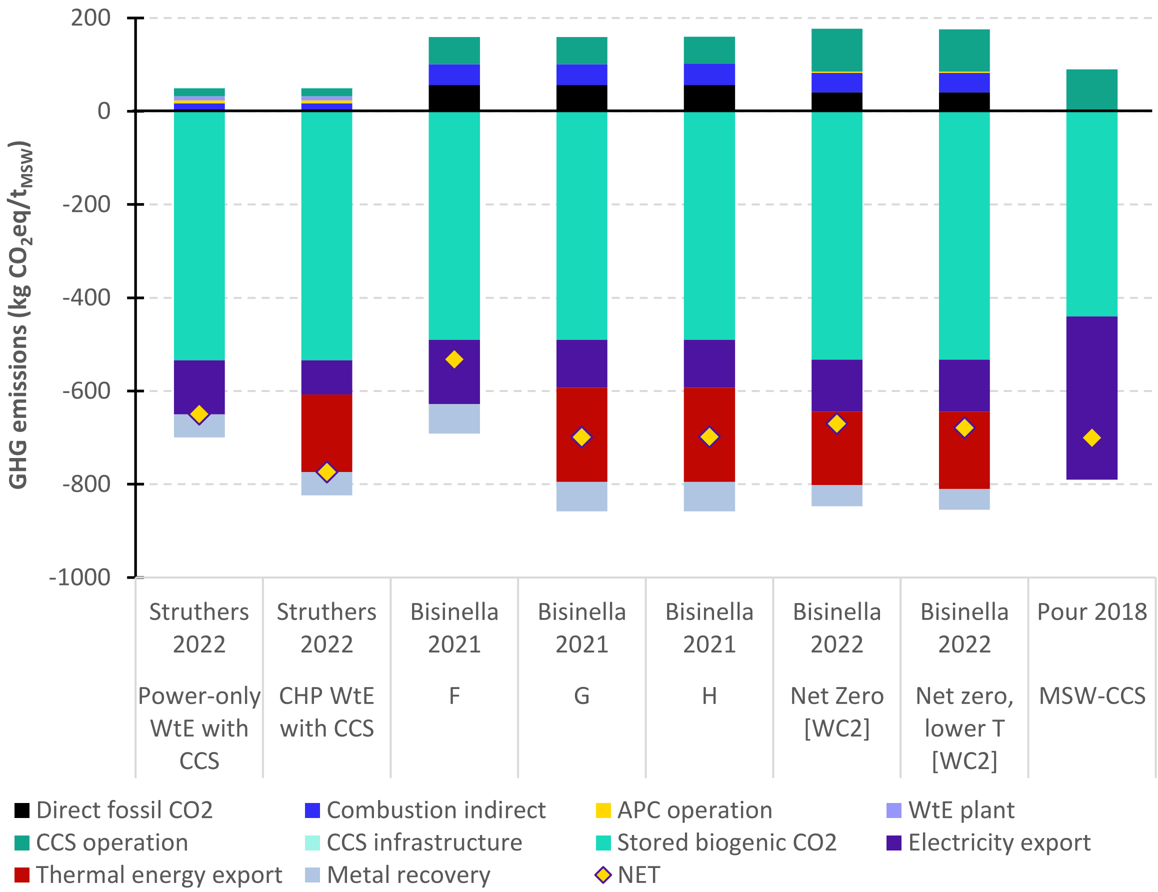

Figure 2 – Published estimates of the climate impacts of WtE with CCS, with detailed breakdown of impacts (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, Pour et al., 2018)

If the avoided or negative emissions are excluded from the analysis, the GHG emissions of the WtE-CCS process are found to range from 50 to 177 kg CO_2eq/t_{MSW}, significantly lower than waste-to-energy without CCS (388 to 448 kg CO_2eq/t_{MSW} from the same studies) or landfill (estimated to be 744 kg CO_2eq/t_{MSW} calculated by applying characterisation factors from the ReCiPe method to data on treatment of municipal solid waste in sanitary landfill) (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022, ReCiPe, 2016, ecoinvent, 2021). The lowest of these estimates is from Struthers et al. (2022), which has very low direct CO_2 emissions due to the ultra-high capture rate that has been shown to be possible with current technology (Su et al., 2023). While the impacts of plant infrastructure and operation are also very low in Struthers et al. (2022), Pour et al. (2018) does not account for these at all. This is due to the cut-off criteria applied, where all processes contributing less than 5% to the total impacts were excluded (Pour et al., 2018). It is worth noting that if the captured and stored biogenic CO_2 were not given a negative emissions value in this analysis, this cut-off criteria would no longer exclude the plant infrastructure and operations.

3.2. Carbon impacts per unit of energy output

While these studies have all reported the carbon impacts of WtE-CCS per unit of waste treated, under the Carbon Reporting Framework applied to UK national and regional greenhouse gas inventories all emissions from waste-to-energy are reported in the energy category (Brown et al., 2023). This has the effect of burden-shifting waste incineration emissions from waste treatment to energy production, which could be misleading if applied inappropriately in decision-making.

The impacts of WtE-CCS per unit of energy produced are shown in Figure 3, with the avoided impacts of energy production replaced by the avoided impacts of landfill (estimated to be 744 kg CO_2eq/t_{MSW} as described in Section 3.1). It can be seen that the power only configurations (which include case F in Bisinella et al. (2021)) have the higher greenhouse gas emissions and reductions per unit energy than the CHP configurations, due to the higher total energy production of the CHP plant. Note that this is an artefact of the denominator being larger due to the greater total energy production in the CHP configuration.

It is also interesting to note that when the avoided or negative emissions are excluded from the calculation, the GHG emissions of the WtE-CCS process are found to range from 42 to 330 g CO_2eq/kWh, the upper range of which is very high for a renewable energy technology, even with ultra-high CO_2 capture rates to minimise direct fossil emissions at the plant. This is because all of the environmental burden has been allocated to the energy production processes, without accounting for the co-product of waste treatment.

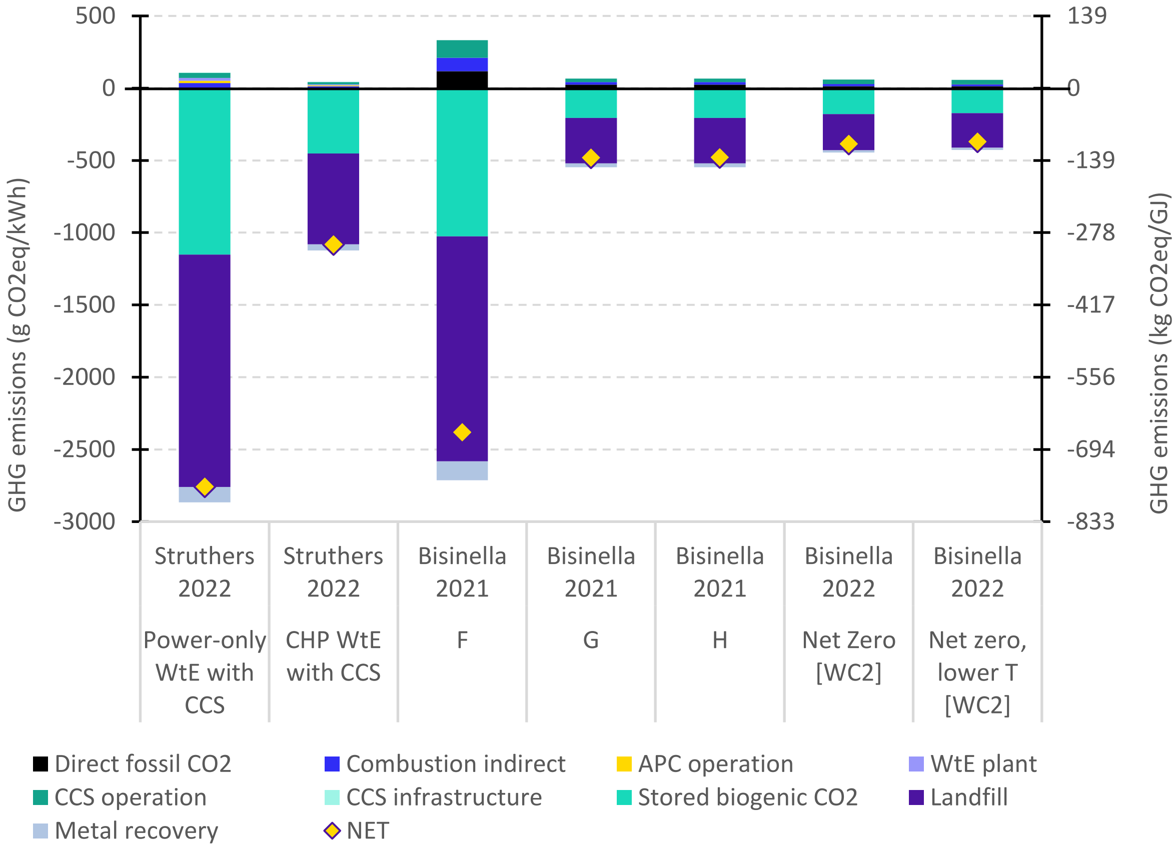

Figure 3 – Published estimates of the climate impacts of WtE with CCS per unit of energy (thermal and electrical energy output combined) (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022). The avoided impacts of landfill are also included.

3.3. Economic allocation of carbon impacts between co-products

It may be more appropriate to allocate the carbon impacts and benefits of WtE-CCS between the multiple co-products. Allocation is commonly applied in LCA, and could be of value for informing decision-making about WtE-CCS. Correct allocation will ensure that the total emissions impact will remain constant, but in national reporting allocation could allow for a more realistic division of carbon impacts between the waste and energy sectors.

A number of allocation methods exist and are discussed in detail in the LCA literature (Baumann and Tillman, 2004). For the purposes of this preliminary analysis, a simple economic allocation has been applied to allocate the impacts between the three co-products of waste treatment, thermal energy and electrical energy. Note that carbon reduction could be considered a fourth product (by means of selling carbon credits), but this has not been considered here.

Table 1 – Revenue estimates for use in the economic allocation

Gate fee at EfW plants	£110/tMSW	(Wrap, 2022)
Average selling value electricity	£0.23/kWh	(Statista Research Department, 2023)
Estimated selling value heat	£64/GJ	(Statista Research Department, 2023, ecoinvent, 2021)

The estimated revenue for each of the three co-products is based on 2021 data and shown in Table 1. The resulting allocated impacts for each of the co-products are given in Table 2. This shows that CHP WtE-CCS compares favourably with established renewable generation technologies (e.g. wind has a carbon footprint of ~11 g CO_2eq/kWh (Dolan and Heath, 2012)) , even when negative emissions from biogenic CO_2 capture are not considered. In order to avoid double-counting, the avoided impacts from displacing alternative waste treatment and energy production are not considered, but the avoided impacts of metal recycling have been included. In future work it would be more accurate to include waste metal as a fourth co-product rather than an avoided impact, but this requires reliable estimates of the value of the output material.

Table 2 – Carbon impacts for each co-product after applying economic allocation. Energy production values are as reported in the original analyses (Struthers et al., 2022, Bisinella et al., 2021, Bisinella et al., 2022).

	Struthers 2022	Struthers 2022	Bisinella 2021	Bisinella 2021	Bisinella 2021	Bisinella 2022	Bisinella 2022
	Power-only WtE with CCS	CHP WtE with CCS	F	G	H	Net Zero [WC2]	Net zero, lower T [WC2]
Excluding avoided emissions from metal recycling and capture of biogenic CO2							
Waste treatment (kg CO_2eq/t_{MSW})	25	14	79	27	27	24	24
Electricity produced (g CO_2eq/kWh_e)	54	8	167	7	8	5	5
Heat produced (kg CO_2eq/GJ_{th})	0	6	0	13	13	13	12
Including avoided emissions from metal recycling and capture of biogenic CO2							
Waste treatment (kg CO_2eq/t_{MSW})	-269	-153	-196	-66	-66	-55	-54
Electricity produced (g CO_2eq/kWh_e)	-570	-81	-415	-18	-19	-12	-12
Heat produced (kg CO_2eq/GJ_{th})	0	-67	0	-33	-33	-29	-28

4. Negative Emissions v the Circular Economy

As mentioned in Section 1, the principles of the circular economy promote the recycling and reuse of materials before incineration with energy recovery (Figure 1). This, however, is based on an implicit assumption that the former is more environmentally sustainable, which may no longer be the case in the context of WtE-CCS being a net negative emissions technology.

Herraiz et al. (2023) investigated the sensitivity of the negative emissions found in Struthers et al. (2022) to MSW composition. This found that a 60% decrease in the amount of plastic or wet biogenic (kitchen and garden) waste in the MSW mix would result in slightly higher negative emissions of CHP WtE-CCS (Herraiz et al., 2023). This suggests that it might be preferable to divert these waste streams to reuse or recycling, if possible..

The results for the sensitivity analysis of dry biogenic waste (paper & card), however, are particularly interesting. It was found that diverting 109 kg of paper and card out of the fuel-waste stream (the “enhanced paper and card recycling” case) reduces biogenic CO_2 removal of the CHP WtE-CCS plant by 112 kg CO_2/t_{MSW} (Herraiz et al., 2023). This implies that, from an emissions reduction perspective, it might be preferable to send dry biogenic waste to a WtE-CCS plant than to recycle it, in direct conflict with the waste hierarchy.

In order to test this, it is necessary to compare these findings with the avoided emissions of paper and card recycling. There is ongoing debate, however, about the true benefits of paper and card recycling with regards to climate change and it is challenging to identify consensus on the avoided emissions associated with these processes (van Ewijk et al., 2021). For the purposes of this article, the values collated by the Swiss Centre for Life Cycle Inventories are used: the application of the ReCiPe 2016 midpoint, hierarchist method (v1.07) to the ecoinvent v3.8 data on recycling of paper estimates the avoided emissions due to recycling to be due to avoiding softwood pulp production (ReCiPe, 2016, ecoinvent, 2021). Recycling 109 kg of paper and card results in carbon emissions of only -15 kg CO_2eq/t_{MSW}, which is significantly less beneficial for mitigating climate change than the 112 kg CO_2/t_{MSW} that would have been captured and stored if the same paper and card had passed to the WtE-CCS plant.

This is, however, only a very preliminary assessment, that is limited in its inclusion of the system-wide effects of the relevant cause-effect pathways. These could include aspects such as an induced demand for waste, diversion of constrained resources displacing other existing uses, reliable assessment of the substitution effects from the supply of co-products, and other market-mediated effects. Furthermore, other non-CO_2 environmental benefits, such as biodiversity and land use change, are not accounted for.

Alongside a clarification of the definition of negative emissions technologies, there is clearly also a need to clarify the carbon accounting and LCA methodologies to properly account for the impacts and benefits of carbon capture and storage in the waste treatment sector. This could include an expansion of system boundaries to include the removals that occur at the beginning of the product system, the product waste streams, consequential system-wide analysis and more sophisticated analysis of the time-series of emissions and removals.

5. Conclusions

The application of carbon capture and storage to waste-to-energy plants creates a form of BECCS that is a promising technology for reducing concentrations of atmospheric carbon dioxide, with significant negative emissions. There is, however, some debate as to whether it fits the strict definition of a Negative Emissions Technology, as the removal of greenhouse gases from the atmosphere occurs outside the system boundary. Instead, the CCS process moves the biogenic carbon dioxide in the waste stream from short-term storage in the biosphere to long-term storage in the geosphere. While this has a clear benefit for climate change, there is a need to clarify the language around such processes to ensure that their benefits are properly realised.

A review of existing life cycle analyses of WtE-CCS plants has found that they are expected to achieve net emissions of -350 to -773 kg CO_2eq/t_{MSW} due to avoided emissions from energy and metal recovery and negative emissions from the captured biogenic CO_2. This makes assumptions about the displaced impacts of energy production, and applies all of the GHG emissions to the waste treatment process. Economic allocation was used to divide the impacts between the three co-products of CHP WtE-CCS plants and found these to average -79 kg CO_2eq/t_{MSW}, -28 g CO_2eq/kWh_e and -38 kg CO_2eq/MJ_{th} for the waste treatment, electricity and heat respectively.

It has also been identified that the negative emissions of WtE-CCS are highly sensitive to the content of dry biogenic waste (paper and card) in the fuel-waste stream. The findings of the existing attributional LCA studies suggest that diverting such waste towards recycling instead of WtE-CCS would actually increase atmospheric GHG concentrations. There is a need to develop more nuanced approaches to properly account for carbon emissions and removals in scenarios involving waste-to-energy processes and carbon capture, assess the true system-wide carbon impacts.

Acknowledgements
The authors gratefully acknowledge the support of the NEWEST-CCUS project (Project No. 299683) funded through the ACT programme (Accelerating CCS Technologies) with financial contributions from: The Research Council of Norway (RCN), Norway; The Federal Ministry for Economic Affairs and Energy (BMWi), Germany; Netherlands Enterprise Agency (RVO), Netherlands; and the UK Department for Business, Energy & Industrial Strategy (BEIS).

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