Materials or gases? How to capture carbon

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Executive summary

Municipalities seeking to minimise their contribution to climate change typically scrutinise various activities over which they bear direct responsibility. One such area is usually waste management. Municipalities may seek to reduce waste generation, and strive to increase recycling rates, recognising that these deliver the most significant benefits as regards greenhouse gas reduction. Materials that evade recycling are – typically – either landfilled or incinerated. When landfilling happens without pre-treatment, the principle concern centres around methane emissions and their impact on climate change in the short-term. In the case of incineration, the concerns relate to the greenhouse gases emitted during the combustion process.[1]

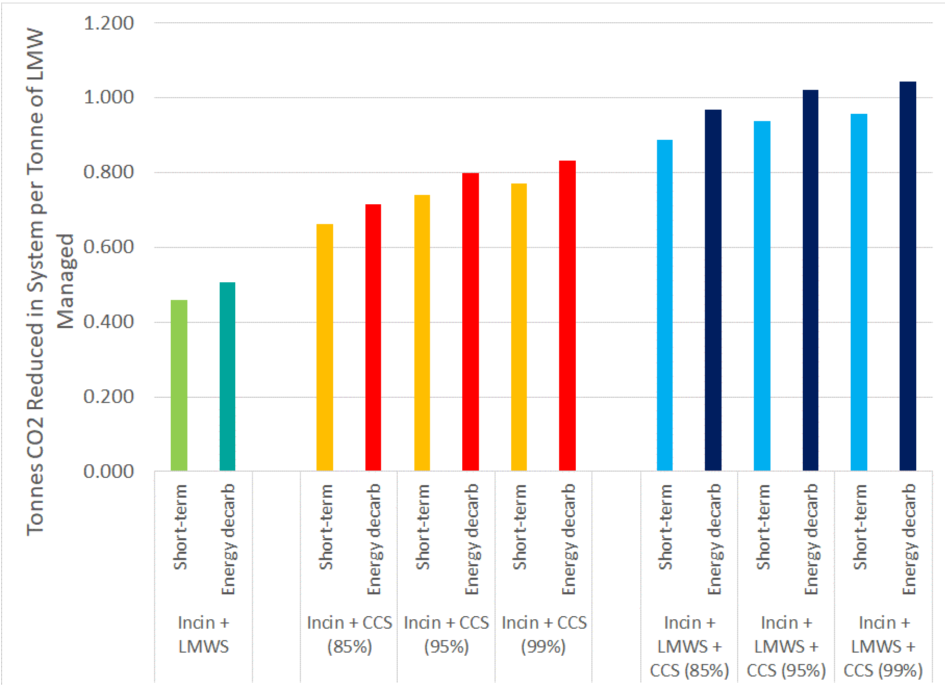
The European Union is increasingly likely to include incineration within the EU Emissions Trading Scheme in the near future. Consequently, questions arise as to how the operators of incineration facilities may respond. Although the potential exists for a range of different technologies and processes, this study compares two: the sorting of mixed waste leftover after separate collection (leftover mixed waste sorting, or LMWS); and the capture of carbon dioxide from incinerator flue gas for underground storage (carbon capture and storage, CCS). Key findings in this study focus onfacilities generating electricity only, with a main emphasis on a 200,000-tonne waste throughput facility. This scale aligns with the average size of EU facilities primarily dedicated to waste incineration. Cost models have also been developed for smaller (100kt) and larger (300kt) facilities.

The study assesses each of the two technologies in isolation (Incin + LMWS, and Incin + CCS), and also, in combination (Incin + LMWS + CCS), and compares them against the baseline where neither is deployed. The costs of the LMWS process are derived from previous work undertaken for ZWE. Estimated costs for CCS are based on literature review, incorporating both 'real-world' experience and modelling. One notable feature of the review of CCS costs is that the implied cost of capital (sometimes referred to as 'a discount rate') is often relatively low. While low costs of capital may be suitable for facilities heavily sponsored by the public sector in the short-term, as the technology becomes commercialised it might be reasonable to expect an increase in the weighted average cost of capital (WACC).

[1] In previous reports, we considered mechanical recycling and biological treatment (MRBT), which combines sorting of leftover mixed waste (in order to recover further recyclables from waste remaining after source separation) and biological stabilisation (for the biodegradable materials that were not captured by separate collection), with the remaining stabilised material landfilled at sites with suitable oxidation layers, to be a positive approach to management of leftover mixed waste. This was due to its environmental characteristics, and because it is more likely to retain flexibility in the waste management system to allow for continuous improvement in recycling (see Zero Waste Europe (2020) Building a bridge strategy for residual waste. Material Recovery and Biological Treatment to manage residual waste within a circular economy, Policy briefing, https://zerowasteeurope.eu/library/building-a-bridge-strategy-for-residual-waste/). The current report considers the relevance of mixed waste sorting in the context of incineration. It considers this in the context of ongoing discussions among policy makers, and within the waste management industry, regarding the potential application of carbon capture and storage (CCS) to incineration facilities. Because of the report's focus on the greenhouse gas impacts of different incineration configurations, it largely abstracts from matters such as the extent to which the application of the technologies concerned might increase, or diminish, the extent to which a waste management system is 'locked-in' to specific solutions.

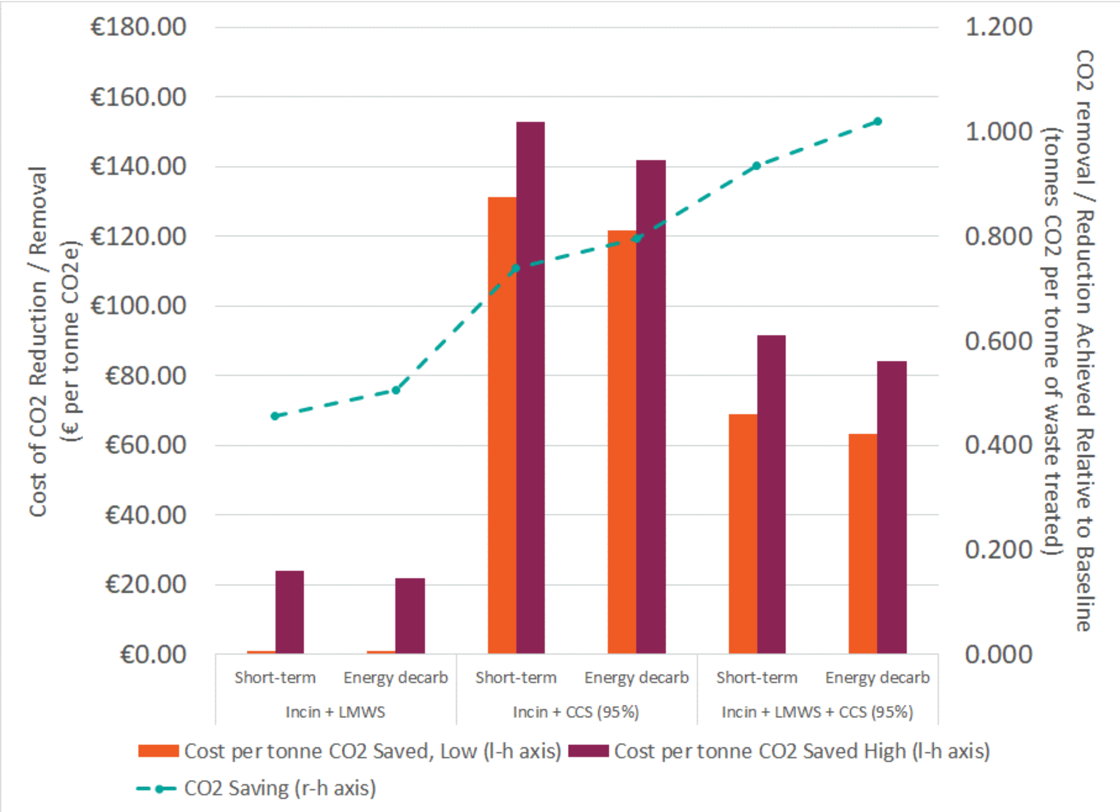
These technologies offer different levels of GHG reduction when compared to the baseline of LMW incineration directly. The LMWS process modelled here extracts materials (215kg per tonne of waste input), with the remaining residual waste incinerated. Less energy is exported than in the baseline situation, but that reflects a reduced amount of waste with a reduced carbon content and a lower calorific value. The remaining carbon in the residual waste is released as CO_2, with a reduced fossil component compared to the baseline situation. In the CCS case, reduction depends on capture rates of CO_2. Energy used in the CCS process is assumed to be derived from the incinerator itself (in line with our literature review), resulting in less energy being exported. In both the LMWS and CCS cases, transitioning to a completely decarbonised power sector results in a reduction of CO_2 emissions compared to the baseline. This is because the lower energy output from the incinerator becomes less relevant in the assessment.

Figure E - 1: Level of CO_2 Reduction Achieved Using Different Technologies (tonnes CO_2 per tonne of LMW Handled), Incinerator Generating Electricity Only (relative to baseline of incinerating all leftover mixed waste (LMW))



The two technologies have very different costs. We have assumed a 10% weighted average cost of capital. The LMWS net costs are more likely to fluctuate depending on the material revenues, while CCS costs may vary based on the energy price used. We have, however, used a central value from previous work for LMWS and assumed some variability for CCS costs. When we pull both costs and CO_2 reduction / removal together, the situation is as shown in Figure E - 2.

Figure E - 2: System Cost of GHG Reduction (€ per tonne CO_2 reduction achieved), Electricity Only Incinerator, 200kt Capacity



Although less CO_2 is abated, Incin + LMWS nevertheless proves superior on affordability. Costs are €1 – €24 per tonne CO_2 reduced in the current case, falling to €1 - €22 per tonne CO_2 reduced as energy is decarbonised. At the lower end, the costs are close to zero. This is dependent on revenues from material sales being as assumed in the central case. In earlier work, we flexed these values by +/- €9 per tonne of waste treated.

Using only CCS (Incin + CCS) reduces CO_2 at a higher rate, but it is relatively expensive at €132 – €153 per tonne CO_2 initially, dropping to €122-€143 per tonne CO_2 as energy is decarbonised. This cost is higher than recent EU allowance under the ETS which mostly range between €80-€90 per tonne CO_2 over the last 2 years, and only briefly exceeded €100.

The Incin + LMWS+CCS system achieves the highest level of CO_2 reduction of any of the scenarios, but more affordable per tonne of CO_2 reduced compared to the Incin + CCS system (being between 52%-60% of the equivalent costs). Costs are €69 – €92 per tonne CO_2 in the current case, falling to €63-€84 per tonne CO_2 as energy is decarbonised. Indeed, the costs per tonne of CO_2 reduced by the LMWS + CCS system are at levels at or below prices at which EU allowances have recently been trading. It should be noted that even if revenues from the sale of materials from the LMWS process were valued at zero, the costs would still be somewhat below those where CCS is deployed alone.

Key observations

The suggestion from the above is that:

- Incin + LMWS offers a potentially quick way to make a significant reduction / removal of greenhouse gases from incineration and at low cost;
- Higher levels of reduction / removal are achieved by Incin + CCS, but the costs are much higher (they will vary significantly, not least with the weighted average cost of capital used to purchase capture equipment, but also with local conditions); and
- The lower cost of CO_2 reduction from LMWS helps partially mitigate the much higher costs of CCS. Combining the two technologies (Incin + LMWS + CCS) offers a way to achieve the highest levels of removal / reduction at a lower *average* cost per unit of CO_2 reduction than where CCS is deployed alone (even though the marginal costs of CO_2 reduction from CCS remain high). Importantly, application of CCS would be compatible with LMWS, and complements its effect.

LMWS can be implemented in places where it might be difficult to apply CCS (it can, within reason, be separated spatially from the incineration facility). It can also be implementable relatively swiftly and with lower capital requirement.

This suggests a sequential logic, in which LMWS is applied as widely and as early as possible (subject to relevance of the waste streams) with CCS being deployed in its wake at facilities deemed most likely to be needed in future. The future of incineration facilities may indeed be shaped by which factors are likely to make CCS deployment more favourable, though equally, it should be considered that the case for deploying CCS may be greater at co-incineration facilities (such as cement kilns), which have purposes beyond treating waste, and for which CCS may be a necessary component of a broader decarbonisation pathway.

An important point is that the deployment of LMWS is likely to be a 'lower regret' solution with much reduced potential for lock-in. The fact that it seems eminently *compatible with* CCS suggests, as per our previous paper, a need for a rational scaling-back of incineration capacity in those Member States with too much capacity in place.[2] LMWS can also help support in the phasing down of capacity.

In subsequent work, we plan to explore these issues in further detail.

[2] Equanimator (2023) Enough is Enough: The Case for a Moratorium on Incineration, Report for Zero Waste Europe, September 2023.

Introduction

Equanimator is pleased to have been asked by Zero Waste Europe (ZWE) to compare the cost effectiveness of two options for reducing greenhouse gas emissions from incineration.

It looks increasingly likely that waste incineration facilities will be included within the scope of the EU (and UK) Emissions Trading Scheme(s) in the near future. Inclusion of incineration under the EU-ETS might trigger a range of actions, assuming that these are not rendered less likely as a result of prevailing contractual arrangements. In the first instance, and all other things being equal, the short-term static effect would be to increase the price that incinerators would have to charge existing users of their service. Their ability to pass through the price increase in full would, though, be affected by the elasticity of demand for the service (and the existence of contracts – and what they permit when legislation changes - can influence responsiveness to price changes).

One would expect there to be both 'own-price' and 'cross-price' effects. An example of the former would be that some users seek to reduce the quantity of waste they generate in the first place (e.g., making greater use of reusable products), or reducing the amount of waste sent to incineration as a result of waste prevention. An example of the latter would be where customers find that alternative ways of dealing with waste become – relatively – more attractive, so they switch the management of waste – either partially or completely – to the alternative ways of management. Examples of the latter would be where users make attempts to ensure more of their waste is recycled (because cost savings from doing so may increase).[3]

'Recycling more' might take place through a number of different routes. One way in which this could happen is through the implementation of sorting systems designed to extract plastics for recycling from the leftover mixed waste (LMW) following the deployment of separate collection (we refer to this as leftover mixed waste sorting, or LMWS). Several recent reports have shown that, this type of approach can have a beneficial impact

[3] UK Government has, for example, linked its proposal to include incineration in the UK ETS to support for their target to reduce residual waste arisings per capita, stating that: "*In the Call for Evidence, we proposed exploring expansion of the UK ETS to waste incineration and EfW by the mid-to-late 2020s. This was on the basis that this would align with wider reforms to resources and waste policies later this decade and would help to achieve the UK Government's target to halve residual waste arisings (excluding major mineral wastes) on a kilogramme per capita basis by 2042 from 2019 levels*" (see Developing the UK Emissions Trading Scheme: Main Response, A joint response of the UK Government, the Scottish Government, the Welsh Government and the Department of Agriculture, Environment and Rural Affairs for Northern Ireland https://assets.publishing.service.gov.uk/media/649eb7aa06179b000c3f7608/uk-emissions-trading-scheme-consultation-government-response.pdf ; see also).

not only on greenhouse gas emissions, but also in terms of contributing to increasing recycling rates.[4] The beneficial effect of the use of the technology is not, however, experienced purely in terms of reduced emissions from the incineration facility itself: the application of LMWS realises GHG reduction benefits partly by reducing the quantity and carbon content of what is incinerated, but also, through avoiding the use of primary materials (by increasing recycling). The latter contribution is not 'felt' by the operator of the incinerator, and the extent to which it leads to the realisation of a monetised benefit is affected by a number of considerations.

Another technology which it has been assumed would be applied to incineration is carbon capture and (utilisation and) storage (CC(U)S). Some EU Member States which have excess capacity for incineration are known to be considering the potential for deployment of CC(U)S as a relevant consideration that might influence which incineration facilities have their authorisations extended when they expire at some future date. CC(U)S effectively seeks to capture (either fully or partially) the CO_2 that would otherwise be emitted from the facility. In the case of CCS, the full benefit of deployment, in terms of CO_2 reduction, is more likely to be felt by the operator as the emissions reduction relates entirely to the facility itself (so that fewer allowances would need to be paid for to cover the remaining emissions).

This report seeks to compare these options through understand the costs, and the effect, of deploying both technologies on waste that might be sent to an incinerator. While we consider a reduction in residual waste (the waste remaining following efforts to avoid / reduce waste, recycle through separate collection, and recycle through sorting of LMW), and associated reduction in capacities for incineration to be the key routes towards decarbonising management of waste, the aim of this report is to assess the cost-effectiveness of technologies for incinerators that are still operational and focus on their ability to reduce system-wide CO_2 emissions while they remain in operation. We also review the performance of a situation where both systems are combined.

Note that previous reports considered that mechanical recycling and biological treatment (MRBT)[5] to be the best approach to management of leftover mixed waste, not only because of its environmental characteristics, but importantly, because it is more likely to retain flexibility in the waste management system to allow for continuous improvement in recycling.[6] This report considers the relevance of mixed waste sorting in the context not of MRBT, but of incineration. It considers this in the context of ongoing discussions among policy makers, and within the waste management industry, regarding the potential application of carbon capture and storage (CCS) to incineration facilities. Because of its focus on the greenhouse gas impacts of different

[4] Eunomia (2023) Mixed waste sorting to meet the EU's Circular Economy Objectives, Report for Reloop and Zero Waste Europe, February 2023; Dominic Hogg (2022) The Case for Sorting Recyclables Prior to Landfill and Incineration, Special Report prepared for Reloop, June 2022.

[5] MRBT combines sorting of leftover mixed waste (in order to recover further recyclables from waste remaining after source separation) and biological stabilisation (for the biodegradable materials that were not captured by separate collection). The remaining stabilised wastes are typically either used in restricted applications on specified uses of land or landfilled at sites with suitable oxidation layers, thereby largely eliminating methane generation from the system.

[6] Zero Waste Europe (2020) Building a bridge strategy for residual waste. Material Recovery and Biological Treatment to manage residual waste within a circular economy, Policy briefing, https://zerowasteeurope.eu/library/building-a-bridge-strategy-for-residual-waste/; see also

incineration configurations, it largely abstracts from matters such as the extent to which the application of the technologies concerned might increase, or diminish, the extent to which a waste management system is 'locked-in' to specific solutions.

Methodology

The methodology is as follows:

1. Cost data for the LMWS process are derived from a previous study: these are presented in summarised form below;[7]
2. Costs for deployment of CCS are estimated based on existing literature, but assuming the same cost of capital as for the LMWS process;
3. Costs are estimated for facilities of different sizes but for ease of presentation, we have presented the main results only 200 thousand tonne (kt) facility, as this represents an average capacity in the EU;
4. Similarly, although we have considered the implications for both 'electricity only' and combined heat and power (CHP) incinerators, and have considered assumptions for modelling each, for ease of presentation our results are limited to the 'electricity only' facilities;
5. Based on a notional composition of residual waste, we estimate the GHG savings that would be realised by the two different technologies. The model has been set up to accommodate any starting composition of 'leftover mixed waste', but to simplify presentation, we assume a single composition. Note that we do not consider in this report the extent to which specific policies affect one or other source of emissions reduction: the reduction in emissions are effectively those achieved for the system as a whole;
6. Based on 1 to 5 above, for each of the technologies, as well as deploying both technologies in combination, we calculate an average 'cost per tonne of CO_2 saved' as a measure of cost-effectiveness;
7. We then consider what may be some key 'takeaways' from the analysis.

Key assumptions

In this Section, we present the underlying assumptions which drive the cost and GHG reduction calculations.

[7] For further details, the reader is referred to the full report – see Dominic Hogg and Dinkar Suri (2023) *Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change*, Report for Zero Waste Europe, April 2023.

Scale of facility

For this exercise, the central case modelled assumes an overall system capacity of 200kt per annum. Generally, the greater capacity, the lower the costs per tonne of waste processed, assuming the facility operates at capacity. According to the data reported by CEWEP, the average capacity of dedicated incinerators in the EU 27, was just over 200kt in the EU-27.[8]

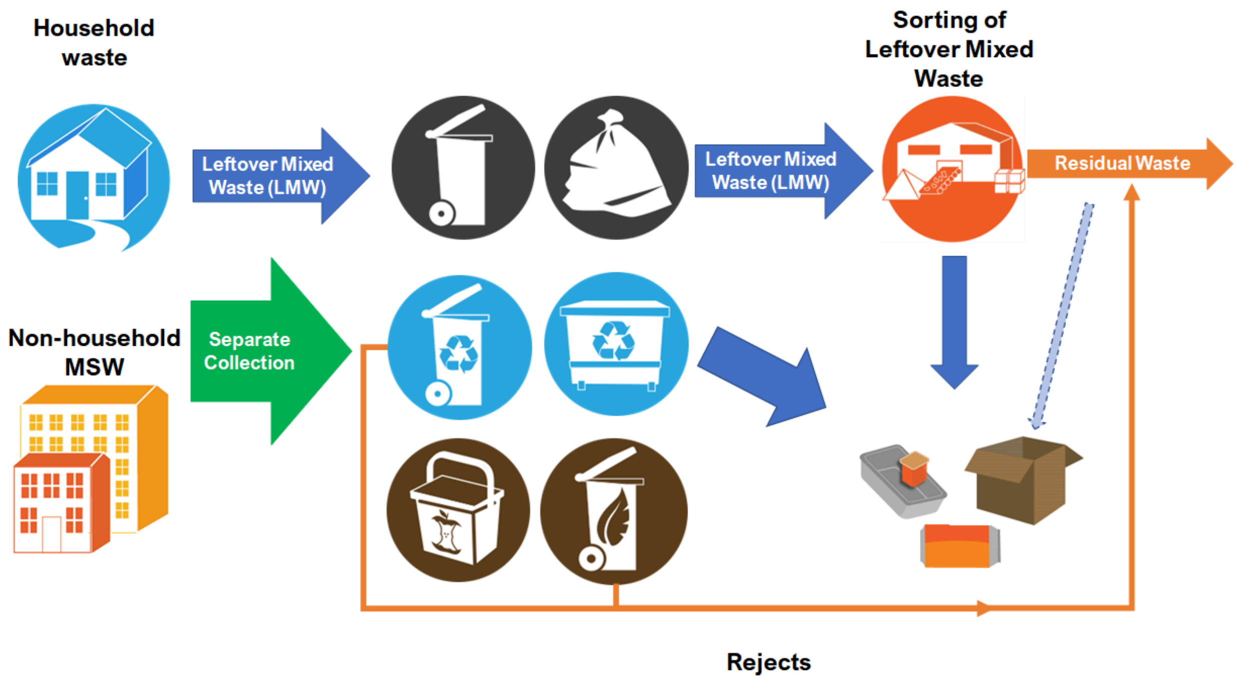
Waste composition

Waste composition varies with a host of factors. Our interest is in the composition of what we refer to as 'leftover mixed waste' (LMW). In referring to 'leftover mixed waste' (LMW), we are speaking about the mixed waste which remains following source separation of recyclable and compostable fractions by citizens (see Figure 1). The term 'residual waste' is henceforth used to refer to the waste which remains after LMW has been subject to further sorting by a suitable designed Leftover Mixed Waste Sorting (LMWS) facility.

The composition of LMW reflects not only those factors that affect the composition of the totality of waste as generated by households / businesses, but also, the degree to which systems of separate collection are successful in targeting materials for recycling.

[8] The figure for 2020 was 201,194 tonnes (80.88 million tonnes treated at 402 facilities) – see Table 4 in Dominic Hogg (2023) Enough is Enough: The Case for a Moratorium on Incineration, Report for Zero Waste Europe, September 2023.

Figure 1: Schematic showing role of facility and convention for naming waste at different stages of sorting



Source: Dominic Hogg and Dinkar Suri (2023) Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change, Report for Zero Waste Europe, April 2023.

The composition of LMW affects a range of key parameters in this report:

a) The LMW composition will have associated with it a specific (fossil and non-fossil) carbon content. That will largely determine the CO_2 released on combustion of the waste.
b) This, in turn, affects the amount of CO_2 available to be captured, and the extent to which any CO_2 captured is of fossil or non-fossil origin;
c) Similarly, the LMW composition will have associated with it a specific net calorific value, which will be a key factor influencing the energy generated by an incinerator;
d) The LMW composition influences the extent to which materials can be extracted from the LMW stream by deploying a suitable Leftover Mixed Waste Sorting (LMWS) system. This, in turn, influences the potential for revenue generation from material sales;
e) The composition of the resulting residual waste will be affected by the LMW itself, the efficiency with which the LMWS captures materials, and the extent to which these are actually recycled (as opposed to being extracted for recycling). The composition of that residual waste will affect an incinerator combusting residual waste in much the same way as the composition of LMW affects one incinerating LMW: hence, matters a), b) and c) above are also relevant when incinerating residual waste.

Compositions are ever-changing and difficult to predict, and no single composition can be ascribed as representative of all situations. Nevertheless, a singular composition of waste has been modelled in this analysis to be broadly representative of compositions one might find in the EU after separate collection has occurred (see Table 1). The composition of residual waste deriving from the LMWS process (derived from the composition in Table 1 and the assumed sorting efficiencies – see below) is shown in Table 2. These are the same as was used in a previous report, and further details behind the assumptions can be found therein.[9]

Table 1: Waste composition assumed for LMW (may not sum to 100% due to rounding)

Material	Percentage
Food	22%
Garden	7.5%
Plastics	14%
Paper	7%
Cardboard	9%
Glass	6%
Ferrous Metals	3.5%
Non-ferrous Metals	1%
Textiles	7%

[9] Dominic Hogg and Dinkar Suri (2023) *Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change*, Report for Zero Waste Europe, April 2023.

Sanitary	7%
Inert Material	8%
Wood	4%
Other	4%

Source: Dominic Hogg and Dinkar Suri (2023) Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change, Report for Zero Waste Europe, April 2023.

Table 2: Residual waste output from LMWS (may not sum to 100% due to rounding)

Material	Percentage
Food	26%
Garden	9%
Plastics	7%
Paper	6%
Cardboard	7%
Glass	7%
Ferrous Metals	0%
Non-ferrous Metals	1%

Textiles	8%
Sanitary	8%
Inert Material	10%
Wood	5%
Other	5%

Source: Dominic Hogg and Dinkar Suri (2023) Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change, Report for Zero Waste Europe, April 2023.

The two different waste compositions give rise to waste with the physical characteristics as per Table 3.

Table 3: Physical characteristics of LMW and residual waste

LMW as Received			
Total (MJ as received)	9,938	Fossil C (tonnes C)	0.138
Fossil energy (MJ)	6,261	Organic C (tonnes C)	0.091
Non fossil (MJ)	3,676	Moisture content (%)	34.9%
			0.229
Output Residual Waste (after LMWS, expressed per tonne residual waste)			
Total (MJ as received)	8,575	Fossil C (tonnes C)	0.100
Fossil energy (MJ)	4,785	Organic C (tonnes C)	0.094
Non fossil (MJ)	3,790	Moisture content (%)	39.4%
		Total C content (tonnes C)	0.194
Output Residual Waste (after LMWS, expressed per tonne input LMW)			
Total (MJ as received)	6,686	Fossil C (tonnes C)	0.078
Fossil energy (MJ)	3,717	Organic C (tonnes C)	0.074
Non fossil (MJ)	2,970	Moisture content (%)	39.4%
MJ/kg	8.532	Total C content (tonnes C)	0.152

Materials sorting efficiencies

The LMWS facilities modelled in this study aim to sort a high percentage of the targeted recyclables. Generally, attempting to achieve higher sorting efficiencies results in greater complexity in the sorting process, thereby increasing the sorting cost per tonne of waste processed. The sorting efficiencies used in the model are displayed in Table 4.

Table 4: Assumptions regarding efficiency of extraction of key materials

Plastics	Percentage	Material Assumed to be Displaced (primary)
PET Bottles Clear	92%	PET / Polyester
PET Bottles Blue	92%	PET / Polyester
PET Bottles Coloured	90%	PET / Polyester
PET Trays Clear	52%	PET / Polyester
PET Trays Black	0%	n/a
HDPE Bottles Clear	92%	HDPE
HDPE Bottles Coloured	92%	HDPE
LDPE Film	70%	LDPE
PP Rigids	85%	PP
PP Film	75%	PP
PS	70%	PS
Metals	Percentage	Material Assumed to be Displaced

		(primary)
Ferrous Cans	90%	Steel
Ferrous Other	88%	Steel
Non-ferrous Cans	88%	Aluminium
Non-ferrous Other	75%	Aluminium
Fibres	Percentage	Material Assumed to be Displaced (primary)
Cardboard Corrugated	45%	Low-grade paper
Other Cardboard Packaging	45%	Low-grade paper
Beverage Cartons	85%	Low-grade paper
Other Cardboard	20%	Low-grade paper
Paper (De-inking)	80%	Low-grade paper
Other Recyclable Paper	20%	Low-grade paper
Other Paper	20%	Low-grade paper
Textiles	Percentage	

Poly/cotton	70%	0[10]

Source: Dominic Hogg and Dinkar Suri (2023) Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change, Report for Zero Waste Europe, April 2023.

The reduction in greenhouse gas emissions associated with the materials extracted for recycling is dependent on what the extracted materials are used for, and in particular, the materials whose use they are assumed to displace.[11] This is a matter which has the potential to evolve over time not only as a result of changes in waste composition, but also, as the potential substitution possibilities change as a result of a combination of improved design for recyclability (of the packaging and products), stronger demand for secondary materials (potentially driven by policy and/or the wider effects of the EU-ETS), improvements in technology for recycling, and (potentially) changes in the way in which regulations affect the use of recycled plastics in food contact packages (the effect of which has the potential to be both positive and negative). The figures used are shown in Table 5.

Table 5: Assumed losses and GHG savings associated with materials extracted by LMWS

Material	% Loss (of weight extracted)	Assumed GHG reduction from recycling (tonnes CO_2e per tonne of material recycled)
PET Bottles Clear	15%	2.20
PET Bottles Blue	15%	2.20
PET Bottles Coloured	15%	2.20
PET Trays Clear	30%	2.28
PET Trays Black	n/a	n/a
HDPE Bottles Clear	25%	1.67

[10] No benefit has been assigned to sorted textiles – this partly relates lack of clear evidence as to an appropriate figure.

[11] Eunomia (2023) Mixed waste sorting to meet the EU's Circular Economy Objectives, Report for Reloop and Zero Waste Europe, February 2023; Dominic Hogg (2022) *The Case for Sorting Recyclables Prior to Landfill and Incineration*, Special Report prepared for Reloop, June 2022.

HDPE Bottles Coloured	25%	1.67
LDPE Film	30%	1.76
PP Rigids	30%	1.48
PP Film	30%	1.47
PS	30%	2.28
Ferrous Cans	7%	1.83
Ferrous Other	7%	1.83
Non-ferrous Cans	7%	8.60
Non-ferrous Other	50%	8.60
Cardboard Corrugated	25%	0.10
Other Cardboard Packaging	25%	0.10
Beverage Cartons	25%	0.10
Other Cardboard	25%	0.10
Paper (De-inking)	25%	0.10
Other Recyclable Paper	25%	0.10

Other Paper	25%	0.10
Poly/cotton	70%	n/a

Sources: Association of Plastic Recyclers and Franklin Associates (2018) Life Cycle Impacts for Postconsumer Recycled Resins: PET, HDPE, and PP, 2018, https://plasticsrecycling.org/images/library/2018-APR-LCI-report.pdf. Chen, Y., Cui, Z., Cui, X., Liu, W., Wang, X., Li, X., and Li, S. (2019) Life cycle assessment of end-of-life treatments of waste plastics in China, Resources, Conservation and Recycling, Vol.146, pp.348-357; Turner, D.A., Williams, I.D., and Kemp, S. (2015) Greenhouse gas emission factors for recycling of source-segregated waste materials, Resources, Conservation and Recycling, Vol.105, pp.186-197; Ecoinvent. Note that figures for paper and card were attributed as non-zero, though at lower levels than is typically afforded to recycling of these materials.

Material revenues

Assumptions regarding material revenues are taken from a recent analysis.[12] The central figure shown in Table 6 was used in the analysis for this work.

Table 6: Assumed material revenues under different scenarios, €/tonne of LMW Input

Scenario (commodity values)	Revenue from Materials Recovered (€ per tonne of input LMW)
Low	€28.25
Central	€37.29
High	€46.33

Source: Dominic Hogg and Dinkar Suri (2023) Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change, Report for Zero Waste Europe, April 2023

Cost of capital and estimated lifetimes

The cost of capital reflects the opportunity cost of the use of capital and is measured as either the cost of capital charged by a financing organisation, or as the opportunity cost of not reinvesting capital in an alternative project. There is no readily available figure for cost of capital in the waste sector, rather, it is influenced by the risk associated with the investment being made, which affects the mix of different sources of capital that may be used to finance the investment: different sources of capital make their capital available

[12] Dominic Hogg and Dinkar Suri (2023) Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change, Report for Zero Waste Europe, April 2023.

on different terms. As municipal contract structures seek to ensure risk is borne, where appropriate, by the technology providers, cost of capital may be lower as the overall risk associated with an investment fall. Cost of capital will also vary due to the structure of the funding arrangement. For example if a project is financed with a combination of bank debt and equity, equity investors usually require a higher return on capital, increasing the cost of capital relative to a situation where a project is financed with ban borrowing alone. [13]

In our previous analysis, we assumed a weighted average cost of capital (WACC) of 12%.[14] However, a review of literature (see below) suggests the costs associated with carbon capture technology are often based on capital costs being annualised at relatively low rates (described, often, as 'discount rates', partly because the cost data being derived as are often 'levelised costs'). The WACC that might be applicable for carbon capture is uncertain, given that existing pilot projects as regards waste incineration rely heavily on public funding. It is important to note that this situation is not anticipated to persist beyond the short-term demonstration phase. Commercially implemented and operated facilities will likely have a WACC above the discount rates assumed in costings below. Indeed, it might be considered counter-productive if public policy makers chose, on the one hand, to incentivise adoption of CCS at incineration via inclusion within the EU-ETS, only then to offer access to capital on preferred terms to support the adoption of CCS.

In this work, we have chosen to apply a WACC of 10% for both LMWS and CCS capital. The two projects carry with them different risk profiles: currently, the technology risk associated with CCS would be considered greater, but the revenue streams associated with LMWS are highly variable. Note that a higher WACC tends to favour LMWS over CCS as the capital component is smaller. Note also that although we use an assumption of a 12-year lifetime for LMWS, we assume that capital costs for CCS are annualised over a 20-year lifetime. There is no solid evidence available to understand what the longevity of a CCS facility might be when treating flue gases from an incinerator, so this assumption may be generous (and assumes that the facility lasts as long as a typical incinerator contract with a municipality). Generally, the longer the useful lifetime of an investment, the lower the annual cost associated with the capital investment, yielding a lower cost per unit of activity in a given year. Conversely, the higher the WACC, the higher the per year cost for that investment, yielding a higher cost per tonne of waste processed.

Incinerator performance (GHGs)

Where incineration is concerned, the main process emissions are deemed to result from the combustion process itself, with release of CO_2 and some N_2O. The CO_2 emissions are deemed to be related to combustion of the carbon in the material, which is assumed to be fully released from materials known to be combustible. N_2O emissions are assumed to be 40g per tonne of waste incinerated.

[13] For a discussion, see Eunomia (2010) *Landfill Bans: Feasibility Research, Appendices to Final Report*, Report EVA130 for WRAP.

[14] The concept of the weighted average cost of capital is used to represent the cost of capital where, for example, different sources, such as debt and equity, are used to fund a project, each with its different cost to those undertaking the project. Cost are weighted in line with relative contribution to the capital costs of the different sources. Note this picture can shift over time if there are options for re-financing of a given project once it has demonstrated that it does what was planned (risks have been, demonstrably, overcome).

Incinerator performance (energy generation)

We modelled two configurations for the incinerator, one where the facility generates electricity only, the other, where the facility generates both electricity and heat. The performance of the facilities was based on results obtained from a previous review of facilities in the EU-27.[15] The figures used are set out in Table 7.

Table 7: Assumed performance of incineration facilities

Scenario (commodity values)	Electricity Delivered (net) (as % LHV of waste)	Electricity Delivered (net) (as % LHV of waste)
Electricity Only	22%	n/a
CHP (co-generation)	12%	35%

Emissions avoided (as a result of energy generation)

The energy exported by an incinerator for use by others has generally been associated with an 'emissions credit' (if the exported energy had not been generated, it is argued it would need to be generated elsewhere in the economy). As we have argued in previous studies, this 'credit' for the emissions reduction is likely to be in decline as energy systems decarbonise, though exactly what assumption should be made regarding the credit at any given point in time might be influenced by considerations of whether the facility is already operational, or is to be so in future, and what is happening in the energy system of the country in which the incinerator is located.[16] To simplify matters, we assume for the time being that the credit for electricity generation is linked to the EU average carbon intensity of 251g CO_2/kWh.[17] We also investigate a 'full decarbonisation' scenario in

[15] D. Hogg (2023) Debunking Efficient Recovery: The Performance of EU Incineration Facilities, Report for Zero Waste Europe, January 2023.

[16] See Equanimator (2021) *Rethinking the EU Landfill Target*, Report for Zero Waste Europe, October 2021, https://zerowasteeurope.eu/library/rethinking-the-eu-landfill-target/ ; D. Hogg (2023) Debunking Efficient Recovery: The Performance of EU Incineration Facilities, Report for Zero Waste Europe, January 2023.

[17] This was, in 2022, according to the EEA, 251 g CO_2 / kWh (see https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1).

which (reflecting the downward trajectory in carbon intensity over time) a much lower carbon intensity of 10g CO_2/kWh is achieved (note that in order to achieve this, CCS capacity would be required to abate emissions from remaining fossil-fuel power stations). For heat, the picture is more complex: as we have previously explored, the most plausible counterfactual is heavily context dependent.[18] Given the emergence of heat pumps as viable alternatives for households / development in a range of circumstances (not least, new developments), and given also the potential for reducing heat demand through improved insulation, a straightforward assumption that heat supplied through heat networks displaces alternative sources on a one-for-one basis is questionable.[19] For the purposes of the study, we assume a credit in the current situation of 175g CO_2 / kWh (i.e. a 'small discount' relative to an efficient gas-fired boiler, which generates heat at a carbon intensity slightly greater than 200g CO_2/kWh).[20] In a decarbonised scenario, this is assumed to have fallen to 5g CO_2/kWh.[21] The precise nature of the scenarios is, arguably, less important than the exploration of the sensitivity of results to the flexing of these parameters.

As will become clear, although assuming a 'high' CO_2 credit for energy generation might help improve the apparent performance of an incinerator without any CCS or LMWS, it tends to have the effect of penalising the benefits claimed for CCS and LMWS to the extent that **the deployment of the former reduces energy exported from the facility, whilst the deployment of the latter reduces the generation and export of power (and heat) from a given quantity of waste as a result of the reduced calorific content of waste sent to the facility.**

Efficiency of carbon capture technology

We look at three cases for the 'capture efficiency' – where the proportion of CO_2 emitted which is captured is 85% (the maximum assumed by De Leeuw and Koelemeijer[22]), 95% and 99% (these being captures explored – in modelling – by Su et al[23]).

[18] D. Hogg (2022) Incineration: What's the Effect on Gas Consumption? Report for Zero Waste Europe, October 2022; and D. Hogg (2023) Debunking Efficient Recovery: The Performance of EU Incineration Facilities, Report for Zero Waste Europe, January 2023.
[19] Stockholm Environment Institute (2017) Swedish heat energy system – new tensions and lock-ins after a successful transition: Policy Brief, https://mediamanager.sei.org/documents/Publications/SEI-2017-PB-Dzebo-Nykvist-SweHeatEnergySystem-eng.pdf
[20] Note that if EU-27 average carbon intensity of electricity is 251 CO_2/kWh, then in principle (without delving into the details of the timing of supply / demand), an air-source heat pump with a seasonal coefficient of performance of 3 would generate heat at an intensity of around 84g CO_2/kWh. In some situations, but not all, this is now the most appropriate counterfactual and hence the 'discount' applied to the commonly assumed counterfactual of gas-fired boilers.
[21] Emissions associated with an efficient gas fired boiler would be of the order 210g CO2 / kWh. We have assumed that it is not always justified to claim gas as the displaced source.
[22] De Leeuw, M. and Koelemeijer, R. (2022), Decarbonisation options for the Dutch waste incineration industry, The Hague: PBL Netherlands Environmental Assessment Agency and TNO Energy Transition.
[23] Dan Su, Laura Herraiz, Mathieu Lucquiaud, Camilla Thomson, Hannah Chalmers, Thermal integration of waste to energy plants with Post-combustion CO_2 capture, Fuel, Volume 332, Part 1, 15 January 2023. Note this work was based on modelling as opposed to empirically observed outcomes.

Costs of the technologies

In this Section, we present the cost data for the different technologies. We start by presenting the key underlying assumptions.

Leftover mixed waste sorting (LMWS)

The leftover mixed waste sorting (LMWS) facility achieves high levels of separation of targeted materials for recycling, including sorting of plastics into specific fractions. Key materials targeted are metals, plastics, some paper and card fractions, and polyester / cotton textiles. Although sorting facilities now have the potential to extract glass for recycling from LMW, this process is relatively expensive and quite challenging, technically, to achieve. In this model, no glass is sorted at the mechanical sorting facility. The costs are presented in Table 8 (please refer to the source for further details).

Table 8: Summary figures using central values for revenue (€/tonne input LMW)

Component costs / revenues	"Lower Cost" Member States (€/tonne)	"Higher Cost" Member States (€/tonne)
100kt LMWS		
LMWS (excl Revenue)	55	71
Revenue (central value)	-37	-37
TOTAL	**18**	**34**
200kt LMWS		
LMWS (excl Revenue)	39	50
Revenue (central value)	-37	-37

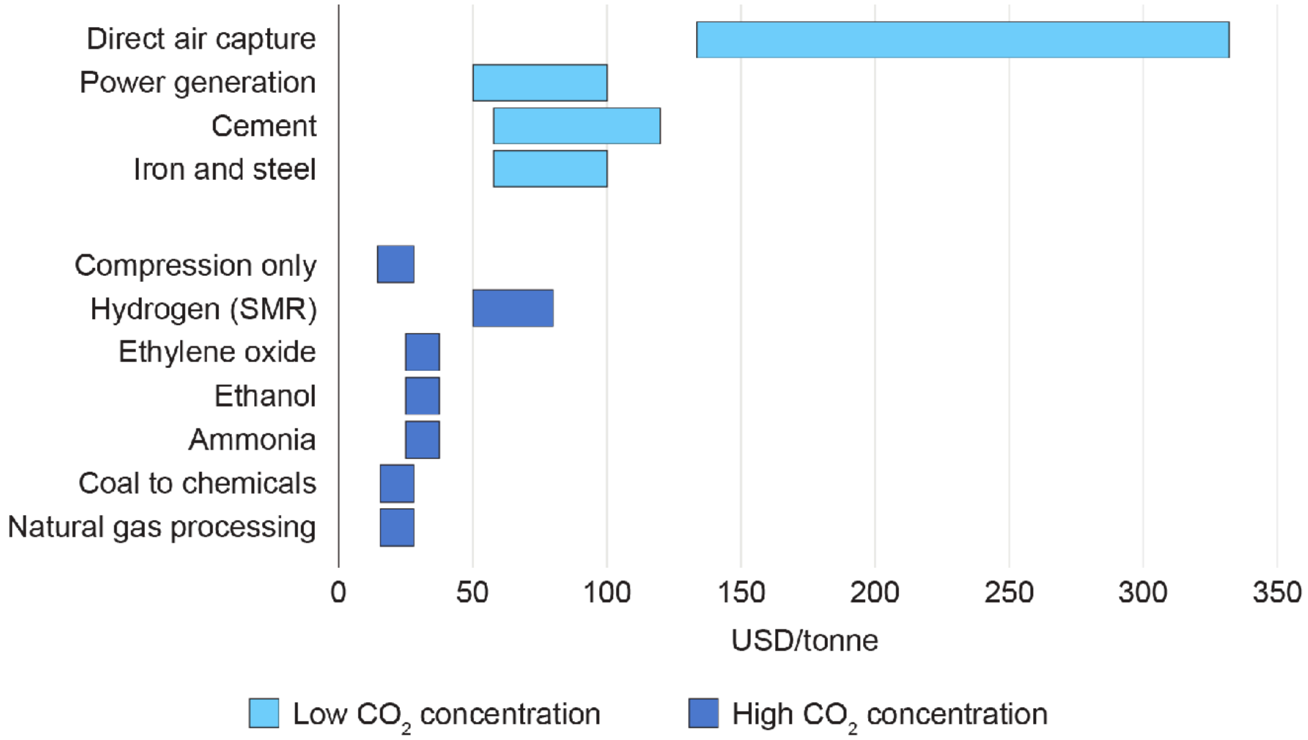
TOTAL	**2**	**13**

Source: Dominic Hogg and Dinkar Suri (2023) Nothing left behind: Modelling MRBT to maximise recovery of resources and minimise contributions to climate change, Report for Zero Waste Europe, April 2023.

Carbon capture and storage

Work by the International Energy Agency (IEA) in 2020 shed some light on the costs of CC(U)S.[24] The costs of CCS are related to the partial pressures of CO_2 in the stream of gas from which the CO_2 is being removed. The partial pressure represents the proportion, by volume, of CO_2 in the gas. For incinerators, this is typically of the order 11%, which is relatively low, but by no means 'the lowest' which prevails in any stream of gas from which CO_2 is likely to be targeted for capture in future.[25] The figures for carbon capture from the IEA study are shown graphically in Figure 2 below.

Figure 2: Costs for carbon capture from different sources



Notes: CO_2 capture costs for hydrogen refers to production via SMR of natural gas; the broad cost range reflects varying levels of CO2 concentration: the lower end of the cost range applies to CO2 capture from the concentrated "process" stream, while the higher end applies to CO_2 capture from the more diluted stream coming out of the SMR furnace. Cost estimates are based on the United States.

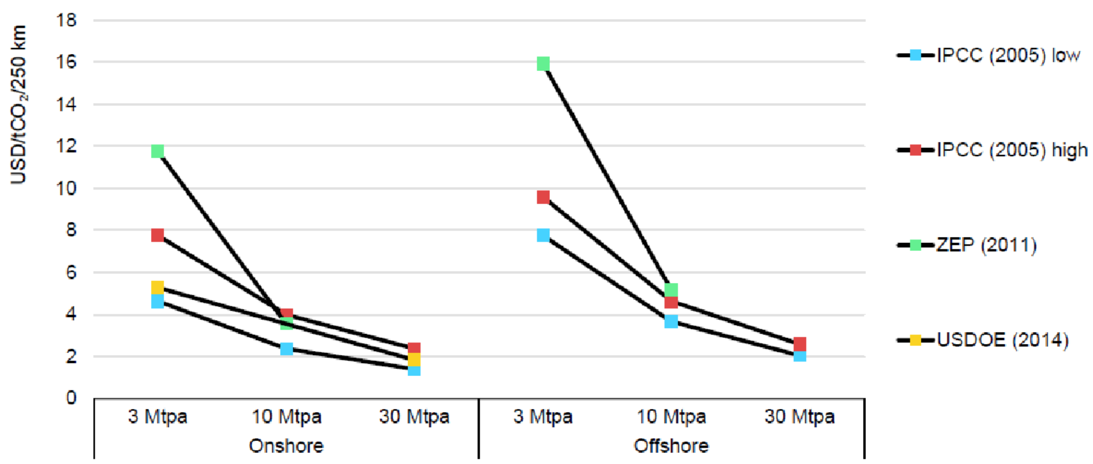
[24] IEA (2020) Energy Technology Perspectives 2020 Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions September 2020.

[25] The partial pressure of CO_2 is around 3.8-4.6kPa in flue gas from a power station fuelled by natural gas, whilst the partial pressure in coal fired power stations is 12.2-14.2 kPa (figures from Global CCS Institute (2021) Technology Readiness and Costs of CCS, March 2021).

All capture costs include cost of compression.
Source: IEA (2020) Energy Technology Perspectives 2020 Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions, September 2020, quoting the following sources: GCCSI (2017), Global costs of carbon capture and storage, 2017 update, IEAGHG (2014), CO_2 capture at coal based power and hydrogen plants, Keith et al. (2018), A Process for Capturing CO_2 from the Atmosphere, NETL (2014), Cost of capturing CO2 from Industrial sources, Rubin, E. S., Davison, J. E. and Herzog, H. J (2015), The cost of CO_2 capture and storage.

The same study also offered cost estimates for pipeline transport. This showed estimates from different sources at different volumes of CO_2 transport, depending on whether transport was on- or offshore. It highlighted that pipeline costs are highly sensitive to scale and location (see Figure 3). Furthermore, it reviewed the variation in unit costs with distance and suggested that shipping of CO_2 might be competitive with offshore pipeline transport for long-distance transport of small volumes of CO_2 (see Figure 4).

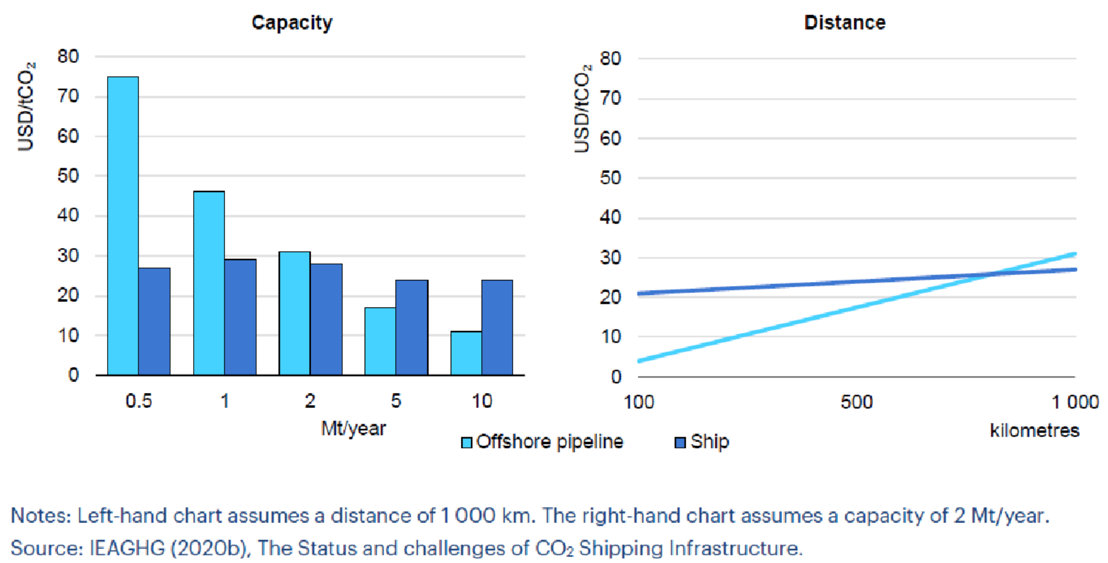
Figure 3: Costs of pipeline transport of captured CO2, onshore and offshore



Note: ZEP = Zero Emissions Platform; USDOE = United States Department of Energy.
Source: Based on Rubin, E. S., Davison, J. E. and Herzog, H. J (2015), The cost of CO_2 capture and storage.

Source: IEA (2020) Energy Technology Perspectives 2020 Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions September 2020,

Figure 4: Shipping and offshore pipeline transportation costs



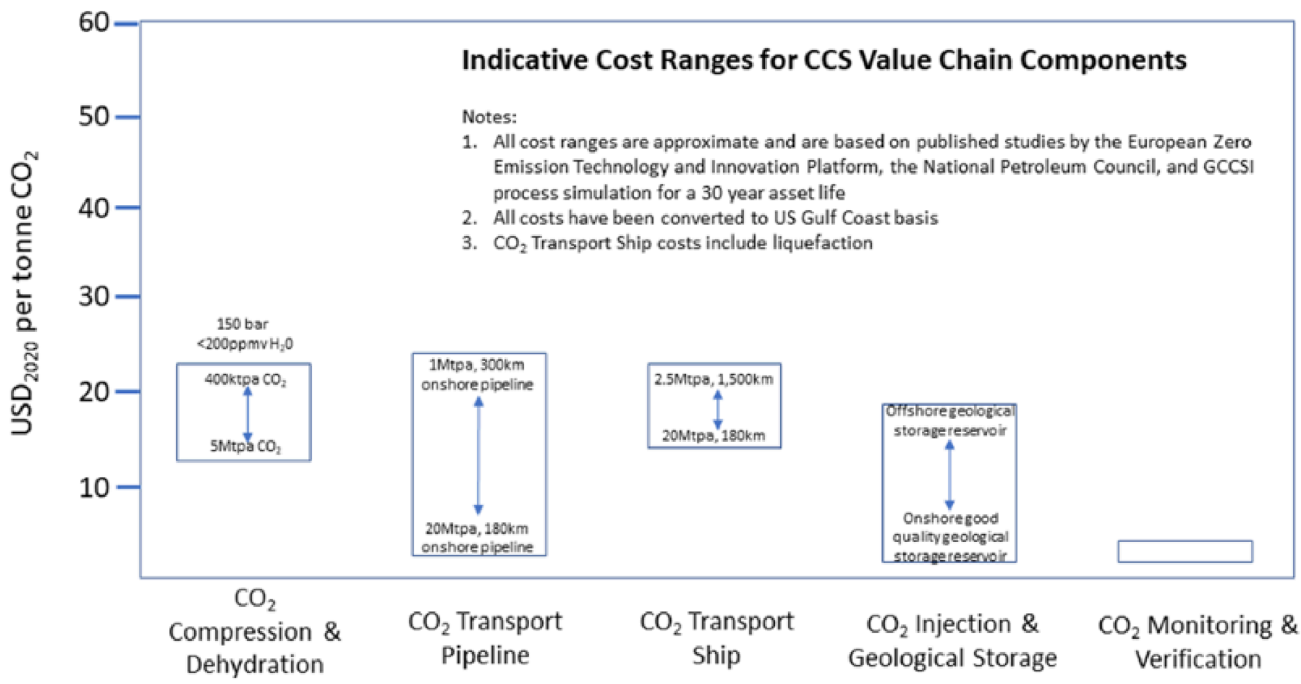
Source: IEA (2020) Energy Technology Perspectives 2020 Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions September 2020,

A study by the Global CCS Institute suggested that costs, for capture alone, would likely be of the order \$50-\$70 (2020 \$US) per tonne CO_2 at the partial pressures appropriate to biomass / waste combustion, and at the scale considered in this report (equivalent to €48-€67 per tonne CO_2 at Q1 2023 prices).[26 27] When considered by industry type, the same study indicated a figure of the order \$60-\$80 (2020 \$US) (€57-€77 in €Q1 2023 terms) per tonne CO_2.[28] These costs are for capture only. They are within the range quoted by IEA (of \$50-100 for power generation – see Figure 2 above).

The same report considers costs for onward activities, including transport, for which there are different options (the main ones considered being shipping and transport by pipeline), and geological storage. These are shown in Figure 5. Note that only one of the 'Transport' options would apply. These would, however, be additive, so that the mid-points of each would give additional costs of the order \$45 (€43 in €Q1 2023) per tonne CO_2. The total cost of capture, compression, transport and storage would be of the order €100-€120 per tonne CO_2, expressed in €2023 values.

Figure 5: Indicative cost ranges for CCS value chain components (excluding capture) – US Gulf Coast

[26] Global CCS Institute (2021) Technology Readiness and Costs of CCS, March 2021.
[27] Converted to euros at the 2020 exchange rate (assumed to be \$1 = €0.87) and inflated at a further 10% based on GDP deflators from ECB and the World Bank.
[28] Converted to euros at the 2020 exchange rate (assumed to be \$1 = €0.87) and inflated at a further 10% based on GDP deflators from ECB and the World Bank.



Source: Based on GCCSI process simulation and analysis of: ZEP 2019, The cost of subsurface storage of CO2, ZEP Memorandum, December 2019. IEAGHG ZEP 2011, The Costs of CO2 Storage, Post-demonstration CCS in the EU. National Petroleum Council 2019, Meeting the Dual Challenge, A Roadmap to at-scale deployment of carbon capture use and storage. National Petroleum Council 2019, Topic paper #1, Supply and Demand Analysis for Capture and Storage of Anthropogenic Carbon Dioxide in the Central US.
In Global CCS Institute (2021) Technology Readiness and Costs of CCS, March 2021.

The same study, noting that results will tend to be project specific, indicated that:[29]

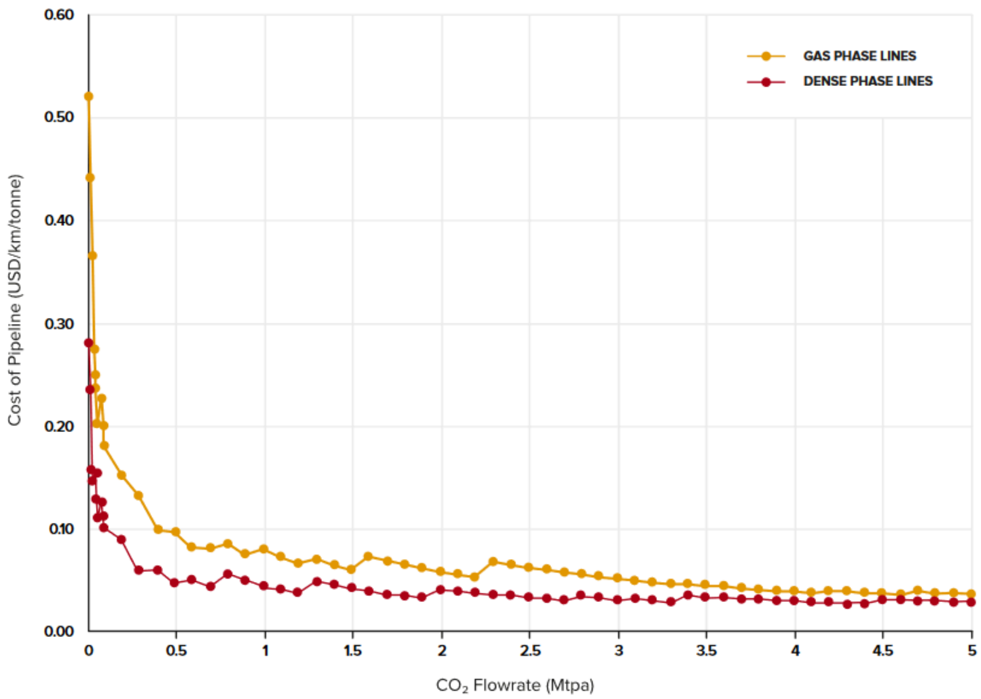
> *For example, the Northern Lights project, which plans to transport CO_2 by ship from various ports to a storage site under the seabed of the North Sea, is targeting storage costs of €35-50/tCO_2 which is considerably higher than the shipping costs shown in Figure 5* (our Figure 2).

Evidently, there are a number of variables which could drive costs higher or lower. Without understanding the details underlying the primary data, and the assumptions behind their derivation, it is also difficult to know whether they may be conservative or otherwise.

The study noted differences in transport costs for gas pipeline transport where the transport was in the gas phase, or in the dense phase. The former tends to have higher costs especially at lower annual flow rates, so that whether compression occurs pre- or post-transport might need to be considered in the context of the flowrate associated with which particular sections of pipeline.

Figure 6: Indicative costs of CO2 pipelines - dense phase (> 74 bar) and gas phase

[29] Converted to euros at the 2020 exchange rate (assumed to be $1 = €0.87) and inflated at a further 10% based on GDP deflators from ECB and the World Bank.



Source: Global CCS Institute (2021) Technology Readiness and Costs of CCS, March 2021.

The above report is not explicit regarding the breakdown of capital and operating costs. This is somewhat problematic since whilst capital costs could be relatively consistent across countries (though perhaps, not over time), the way in which these are converted to costs per tonne of CO_2 being treated / actually captured (for the capture stage, we assume it is what is captured, though this is not always clear) will depend on a host of assumptions, not least of which is the assumed cost of capital, and also, the lifetime over which the costs are distributed, which usually reflects the useful lifetime of the investment made. The latter might, in some cases, be considered subject to some uncertainty at present (as might the costs of maintenance[30]) given that the technology has generally been deployed on incineration facilities only for a few years and at a pilot scale.

Regarding capital costs, a study by Dowen et al[31] cited a study by Gammer and Elks. That study indicates an additional capital cost for a 350,000 tonne incinerator of £97 million. The primary data source for this estimate was a feasibility study carried out by Foster Wheeler for Stockton Borough Council in the UK in 2017. The 350kt facility was assumed to be equipped with a capture process deemed able to achieve 90% capture from an incinerator which was modelled to be generating 1 tonne CO_2 per tonne waste treated. Global CCS Institute, making reference to process plants more generally, suggest:

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[30] For example, "The CCUS solvent is susceptible to degradation from many types of contaminant. It is not yet known if EfW flue gas when operated at full scale over long periods produces problems of this type. This technology risk is likely to have a negative impact on investment appetite, until operational experience is gained" (Gammer, D. & Elks, S. (2020) Energy from Waste Plants with Carbon Capture: A Preliminary Assessment of Their Potential Value to the Decarbonisation of the UK, Report for Energy Systems Catapult, https://es.catapult.org.uk/reports/energy-from-waste-plants-with-carbon-capture).
[31] ZWE (2021) CCS for incinerators? An expensive distraction to a circular economy, Report for ZWE by Shlomo Dowen, with Dr John Webb, Lorraine Dowen and Josh Dowen, October 2021.

"Capital costs of process plants (including CO_2 capture plants) tend to rise non-linearly with scale – typically with the capital cost being proportional to scale to the power of n (where n ranges from 0.6 (single train) to 0.8 (multiple trains in parallel)). The exponents can vary from plant to plant – these are simply typical values (Tribe & Alpine 1986)."

If one considers the £97 million, and that a scaling index of 0.7 applies (the midpoint of the two figures above), then the capital cost for CCS at a 200kt incineration facility would be, expressed in 2023 euros, €91 million.[32] This would imply an annualised cost for the capital for capture and compression of €53.43 per tonne of CO2 input to the facility at a cost of capital of 10% (€60.90 per tonne of at a cost of capital of 12%, and €46.33 per tonne at a cost of capital of 8%). The facility was modelled to capture 303kt CO_2 of the 350kt CO_2 emitted. The previous figures relate to the 350kt input CO_2 from 350kt waste. Expressed in terms of CO_2 captured, the figures are €61.72 per tonne CO_2 at a cost of capital of 10% (or €70.35 at 12% and €53.52 at 8%, respectively) The assumptions in the report suggest that this quote includes capture and compression, but not transport and storage. The operational costs of the capture plant were given as £4 million per annum, or €12.28 per tonne CO_2 treated, which is equivalent to €14.19 per tonne CO_2 captured.

A separate figure was given for transport and storage of £17 per tonne CO_2, this being referenced to a 2016 study.[33] These figures were calculated for major storage projects that may or may not materialise. An updated figure in 2023 euros would be of the order €19 per tonne CO_2. Judging by the above figures from the Global CCS Institute, these might represent costs only under particularly favourable set of circumstances (and the UK might indeed be able to provide this set of circumstances in some situations).

The implied total cost of carbon capture, compression, transport and storage would be of the order €94 per tonne CO_2 captured. This is below the lower end suggested by the Global CCS Institute figures above.

The study itself – which includes a number of other assumptions – assumes a given level of revenue from gate fees, and takes into account an energy penalty at the facility (see below). It considers the levelized cost of energy (LCOE) generated by facilities with and without CCS, and suggests:

A simple spreadsheet-based analysis, discounting (at 7.5%) showed that without a CfD [Contract for Difference – a form of price support in the UK energy market] *for the CCUS plant, a new EfW and a new EfW with CCUS plant would have similar LCOEs when the carbon price is around £90/te.*

To put this another way, there would be no difference in the net costs of a facility (assuming gate fees as 'given', and at an assumed price of energy generation) once value for captured CO_2 reached £90 per tonne CO_2. Factors that would tend to increase this 'break even' CO_2 price would be higher energy prices (the energy penalty would be more significant), and higher cost of finance for the carbon capture element. Movements in the opposite direction would lower the breakeven CO_2 price.

[32] The original figures were converted to euros at the average exchange rate for 2017 and then inflated using GDP deflators as above.
[33] Energy Technologies Institute (2016) Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource, April 2016, https://ukerc.rl.ac.uk/ETI/PUBLICATIONS/CCS_CC1026_14.pdf

Eunomia also estimated the costs of implementing CCS on incineration plants in the UK.[34] They estimated costs for sites in two phases: those close to CCS clusters being developed in the UK; and those not close to CCS clusters, but situated close to ports. In each phase, they considered the costs for bespoke capture installations at larger facilities, assumed to be specified for the facility concerned, and modular installations, assumed to be appropriate for smaller sites.

The basis for the costs in the report is the Tables in the report's Appendix. These are reproduced below as Table 9 and Table 10, though presented with rows in different order: the figures are in 2021 £ sterling terms. Although capex and opex are split, there is no clear basis for understanding how capital costs have been annualised. Similarly, it would be useful to have greater transparency as to what the opex includes: although the report states that, for the capture stage: '*OPEX includes costs such as labour, solvent, energy loss (parasitic load), and digital operation centre*', not all sources quoted include the lost revenue from the use of energy within opex figures (and if the figure includes energy loss, then the operating costs appear quite low). The reference to Opex as 5% of capex for both transport and storage appears to have been calculated as 5% of the figure for the annualised capex per tonne CO_2 captured, but that does not equate to Opex costs being 5% of the initial capital expenditure (a much higher figure would be expected). If the figures are as intended, then the opex figures would be 5% of the annualised capital costs (which, depending on how these costs are annualised, might imply Opex of less than 1% of the initial capital expenditure). Finally, the change in capture costs – in moving from the cluster phase to the ports phase – is pronounced for the 'bespoke' (both large and small sites). This is not explained, though reference is made to the second phase '*benefiting from knowledge and efficiencies gleaned from the Cluster Phase*.' The main change, though, is in the annualised capex per tonne, which is more or less halved, whilst the capture opex remains much the same: it is implied, therefore, that the learning translates into changes in capital outlay as opposed to operational costs.

Table 9:Cost Assumptions overview from Eunomia report

(£/tCO_2, unless otherwise specified)		Cluster Phase		Ports Phase	
		Bespoke	Modular	Bespoke	Modular
Capture CAPEX	Large Sites	18	14	10	13
	Small Sites	22		13	
Capture OPEX		24	30	22	27
Transport CAPEX	Onshore Pipeline	£3m/km		See Table 10 below	
	Offshore Transport	12			
Transport OPEX		5% of CAPEX			
Storage CAPEX		8			
Storage OPEX		5% of CAPEX			

[34] Eunomia (2021) CCUS Development Pathway for the EfW Sector. Report for Viridor, October 2021 https://www.eunomia.co.uk/reports-tools/ccus-development-pathway-for-the-efw-sector/

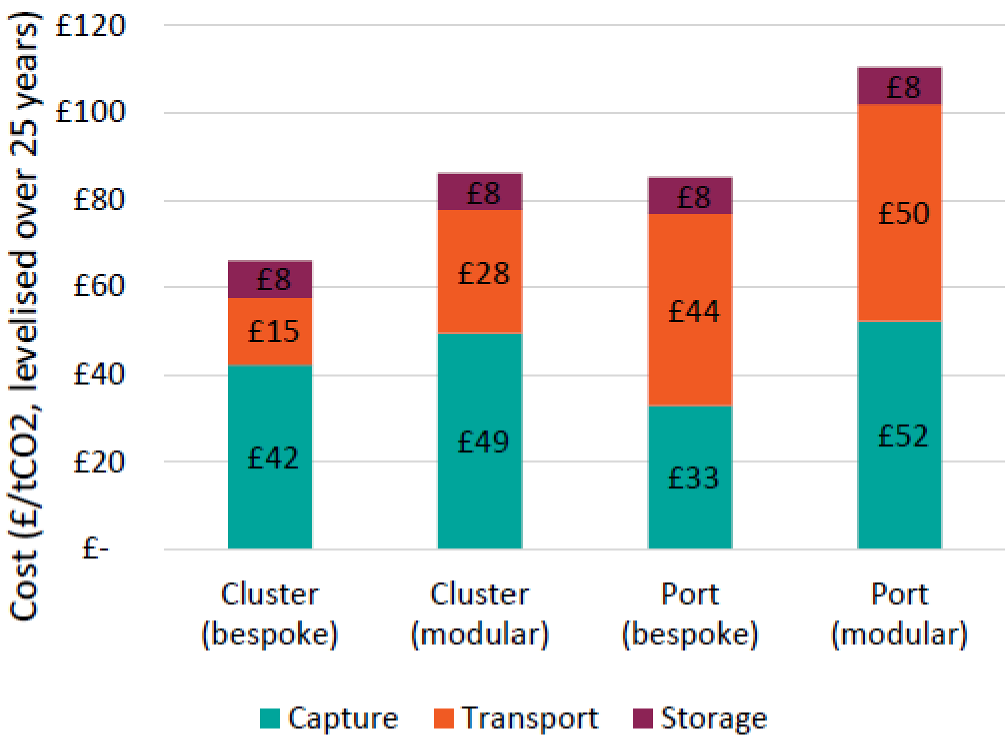
Source: Various sources including BEIS (2020) CCS deployment at dispersed industrial sites, A report by Element Energy for the Department for Business, Energy & Industrial Strategy, *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/929282/BEIS_-_CCUS_at_dispersed_sites_-_Report__1_.pdf; Energy Systems Catapult (2020) Energy from Waste Plants UK with Carbon Capture, Energy Systems Catapult, https://es.catapult.org.uk/reports/energy-from-waste-plants-with-carbon-capture/ Arup (2020) CCUS review - Technical note, A report by Arup for NLHPP Environmental Stakeholder Management Task Order,* *https://www.nlwa.gov.uk/sites/default/files/inlinefiles/CCUS%20review%20TN_Final_Ver2%20redacted%20for%20issue_0.pdf ; Element Energy (2020) Deep Decarbonisation Pathways for UK Industry, A report for the Climate Change Committee by Element Energy,* *http://www.element-energy.co.uk/wordpress/wpcontent/uploads/2020/12/Element-Energy-Deep-Decarbonisation-Pathways-for-UK-Industry.pdf* , and stakeholder feedback from Aker Carbon Capture and Viridor

Table 10: Transport CAPEX for ports phase, by size and location (£/CO2) from Eunomia report

Distance To Port (km) / Size	0-10	10-20	20-30
Large Sites	36	39	42
Small Sites	46	48	50

These Tables were combined by Eunomia to give results as shown in Figure 7 below. The lowest overall cost for capture, transport and storage is £66 per tonne CO_2 (£86 per tonne CO_2 is the lowest cost for modular facilities). The highest cost is £110 per tonne CO_2 (£85 per tonne CO_2 for bespoke capture facilities).

Figure 7: Comparison of Phases and Scenarios, by CCUS Stages



Source: Eunomia (2021) CCUS Development Pathway for the EfW Sector, Report for Viridor, 1st October 2021.

Referencing a report for a UK Government Department, Eunomia suggested:[35]

> *Offshore storage costs are derived from the CCC's assessment of decarbonisation pathways.[53] Across a 25-year timeframe, the levelised cost is assumed to be approximately £8/tCO_2 across all phases and scenarios*

This figure is relatively low, and could not be traced to the referenced source. Indeed, the referenced source includes the following under a section entitled 'Other Industrial Sectors':[36]

> *Costs of abatement are mostly focused in the £100-180/t CO_2 region, with the largest single portion from CCS on waste incinerators (~£170/tCO_2e)*

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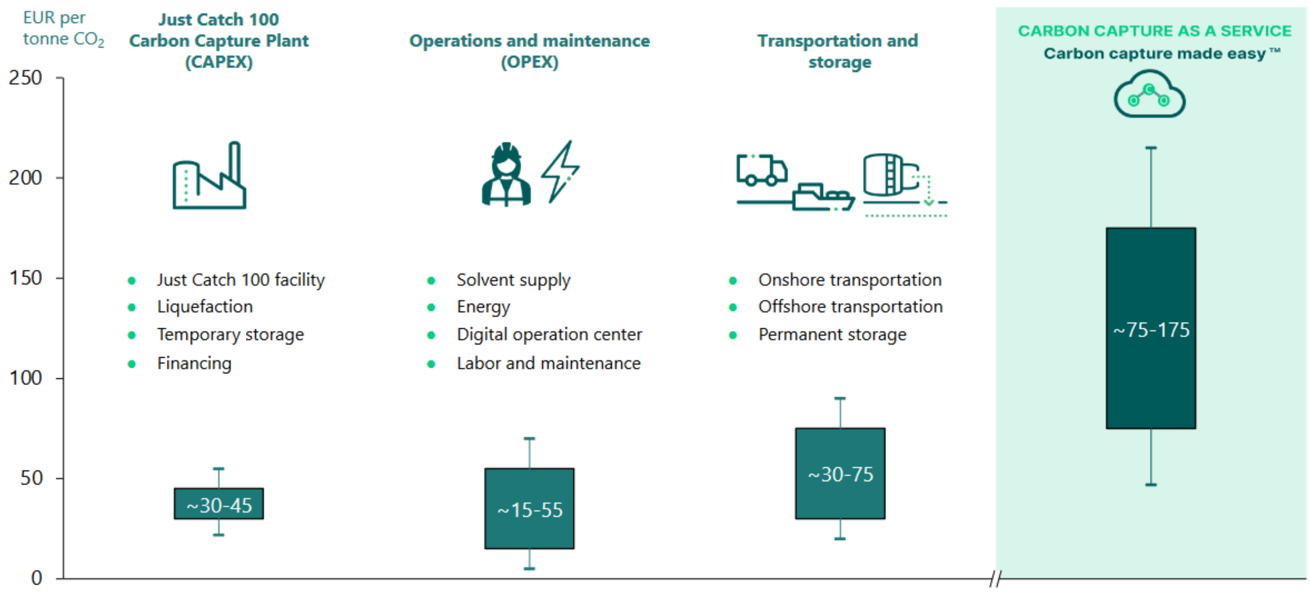
[35] Element Energy (2020) Deep Decarbonisation Pathways for UK Industry, A report for the Climate Change Committee by Element Energy, http://www.element-energy.co.uk/wordpress/wpcontent/uploads/2020/12/Element-Energy-Deep-Decarbonisation-Pathways-for-UK-Industry.pdf

[36] Element Energy (2020) Deep Decarbonisation Pathways for UK Industry, A report for the Climate Change Committee by Element Energy, http://www.element-energy.co.uk/wordpress/wpcontent/uploads/2020/12/Element-Energy-Deep-Decarbonisation-Pathways-for-UK-Industry.pdf

This does, however, appear to include an 'optimism bias' setting, where, in all but one scenario, capital costs were assumed to be 66% higher than early estimates have suggested '*taking into account some of the costs which might have been excluded from the scopes of cost estimates or underestimated*. On the other hand, the incineration facilities were deemed likely to be fitted with CCS some years in the future, and technology costs were modelled to fall over time.

The modular facilities modelled by Eunomia were based on technologies such as that provided by Aker Carbon Capture. The company itself provided some estimated costs, assuming: "*Cost discounted over project period divided by the amount of CO_2 captured discounted over project period; Discount rate: 7.5%.*" The graphic as presented by Aker Carbon Capture is shown in Figure 8. The suggestion is that overall costs would lie in the range €75-175 per tonne CO_2, but with a 'discount rate' (equivalent, for the purposes of calculation, to our WACC) of 7.5% as opposed to 10% used in this report. If a 20-year lifetime was assumed, then the capex costs would be increased by 20%, so that costs would lie between €81-€184 per tonne CO_2. It should be noted that the Opex costs are listed as including energy: the energy penalty alone (see below) might be expected to be valued at more than €20 per tonne or so at prevailing wholesale electricity prices, suggesting the operating costs might be too low given current energy prices.

Figure 8: Estimated costs of carbon capture and storage, Aker Carbon Capture figures



Source: Aker Carbon Capture (2023) Q1 2023 presentation,
[*https://akercarboncapture.com/wp-content/uploads/2023/04/ACC-Q1-2023.pdf*](https://akercarboncapture.com/wp-content/uploads/2023/04/ACC-Q1-2023.pdf)

Work by De Leeuw and Koelemeijer considers options for decarbonising Dutch waste incinerators. Two Dutch incinerators use post-combustion carbon capture based on use of amine solvents. The study takes an interesting view as regards the potential capture rate:[37]

[37] De Leeuw, M. and Koelemeijer, R. (2022), Decarbonisation options for the Dutch waste incineration industry, The Hague: PBL Netherlands Environmental Assessment Agency and TNO Energy Transition.

In the absorber, excess flue gasses containing some undissolved CO2 need to be vented (9). This limits the CO 2 capture rate of the process to 85% (Personal communication, 2021).

The work estimated costs for three CCU and CCS variants that are applicable to the decarbonisation of WIPs. The amount of CO_2 captured for utilisation was based on an installation that operates only during the summertime, when greenhouse CO_2 demand (the assumed use) would be high. The costs presented in the study are shown in Table 11 below. The cost of capital is estimated using a 6% 'discount rate' and a lifetime of 15 years for the capture technology. The CCS facility has a cost of €176 per tonne CO_2 captured. It should be noted that the scale of operation is relatively small: if the capital costs, fixed operating costs, and transport costs are assumed to scale at the same exponent (0.7) as used above, the equivalent cost for a unit capturing 200,000 tonnes CO_2 would be €158 per tonne CO_2.

Table 11: Assumed technical and economic parameters of a reference CCU/CCS plant

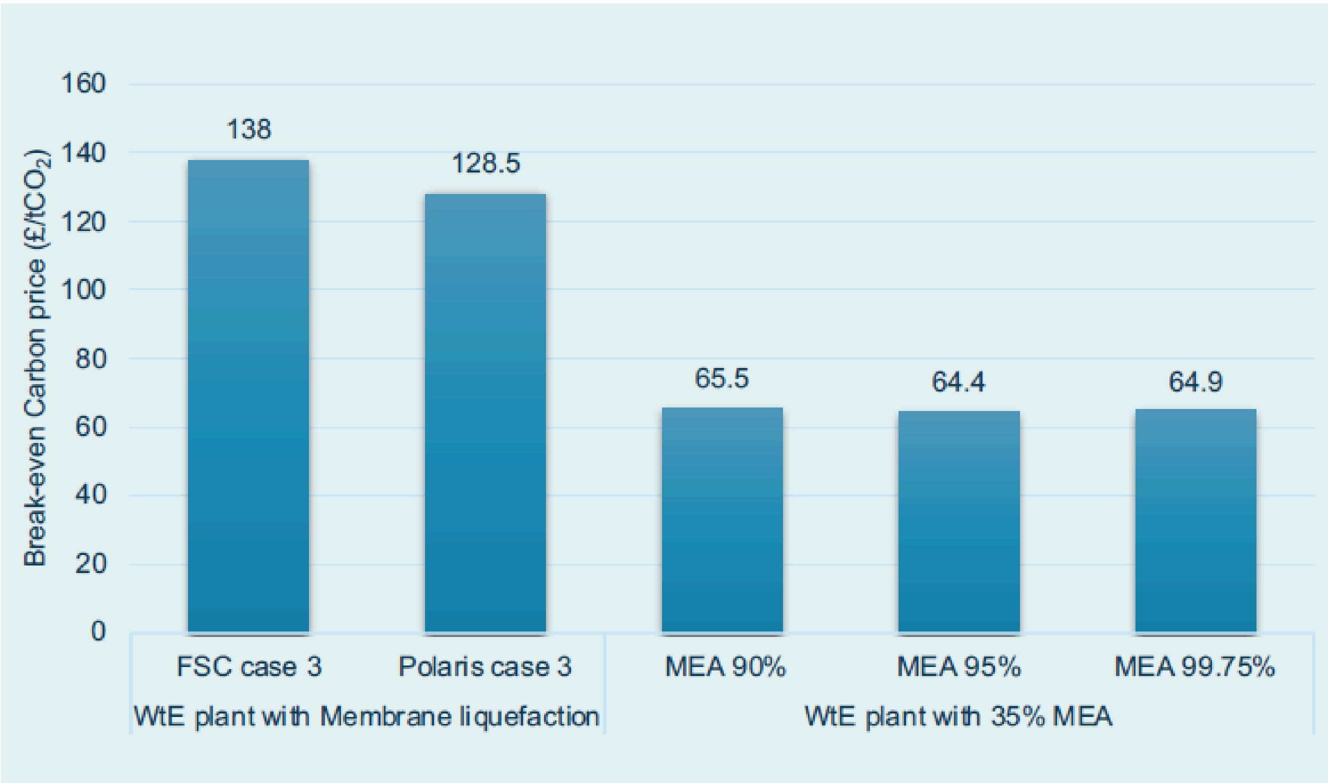
Reference plant parameters	CCU only (greenhouses)	CCS only	CCUS hybrid (greenhouses)
Operational hours (hours/year)	4000	8000	8000
Peak CO_2 capture rate (t CO_2 captured/hour)	13.75	13.75	13.75
Captured CO_2 for utilisation (kt CO_2 captured/year)	55	0	55
Captured CO_2 for storage (kt CO_2 captured/year)	0	100	45
CAPEX (M€)	56.38	56.38	56.38
Annual cost of capital (M€/year)	5.80	5.80	5.80
Fixed O&M cost (M€/year)	1.70	1.70	1.70
Variable O&M cost (M€/year)	1.26	2.29	2.29
Transport costs (M€/year)	1.16	2.10	2.10
Porthos processing charge (M€/year)	0	5.74	2.46
Revenue from CO_2 sales (M€/year)	3.30	0	3.30
Profit (M€/year)	-6.62	-17.63	-11.06
Cost per tonne CO_2 captured (€/t CO_2)	120	176	111
CO_2 avoidance rate (t CO_2 avoided/t CO_2 captured)	56%	76%	65%

Cost per tonne CO_2 avoided (€/t CO_2)	214	232	170

Source: De Leeuw, M. and Koelemeijer, R. (2022), Decarbonisation options for the Dutch waste incineration industry, The Hague: PBL Netherlands Environmental Assessment Agency and TNO Energy Transition.
Note – the Porthos processing charge refers to charges that are assumed to be levied by the Porthos project, a system of CCS that is planned to serve the Port of Rotterdam.

Work undertaken under the auspices of the NEWEST-CCUS project has also sought to understand the break-even CO_2 price that would be required to justify a cost-neutral implementation of CCS.[38] The costs appear to relate only to the capture process and gas compression, but not transport and storage, though this is not entirely clear. The work considers two broad technology types, and these have different break-even CO_2 prices, not least because they imply different energy penalties in running the process itself (see Figure 9 below). If it is right to assume the calculation excludes costs for transport and storage, then the break-even CO_2 prices would likely increase by, roughly, the cost of the transport and storage. Once this is factored in, the lower-end break-even price would then be of the order £80 (€92) per tonne CO_2, rising depending on the specifics of the facility, and the associated cost of the transport and storage.

Figure 9: Break-even carbon cost under business model for WtE with Carbon capture



Source: NEWESTCCUS (2023) Webinar 2: Carbon Capture and Storage for Waste to Energy: Evaluating climate impacts and technologies, 25 January 2023.
Note: MEA refers to monoethanolamine, a solution used in CCS facilities.

[38] NEWESTCCUS (2023) Webinar 2: Carbon Capture and Storage for Waste to Energy: Evaluating climate impacts and technologies, 25 January 2023.

Magnitude of energy penalty

We mentioned above that it was not clear whether Eunomia had accounted for the energy penalty, or alternatively, the costs of fuel use, associated with CCS. The study noted:

> *The size of this loss will depend on the efficiency of the capture process, but can be as much as 20% of the energy output from the facility.*

It referenced an IPCC report from 2005 as evidence.[39]

More recently, work under the NEWEST-CCUS project has sought to shed further light on this issue. A paper by Su et al uses the Aspen-Plus V10 model to estimate the energy penalty for conventional solvent-based CO_2 capture plants using 35 % monoethanolamine (MEA) aqueous solution.[40] They considered both power only and CHP incinerator configurations and two different capture rates (95% and 99.72%). Results for the power only configuration are shown in Table 12 below. The same study indicates that by using advanced heat recovery from the capture process itself, the energy penalty otherwise experienced in moving from95% to 99.72% capture can be offset. This work was undertaken as part of a wider project, which presented results for a range of technologies in a presentation in January 2023 (see Figure 10).

Table 12: Electricity output penalty as a result of deploying carbon capture at incineration plants

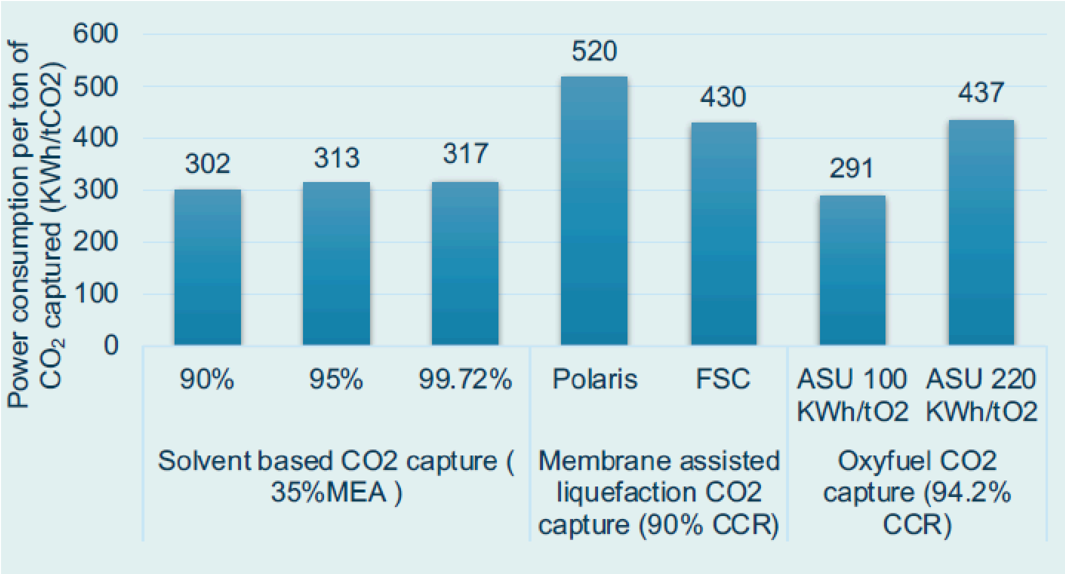
		Unit	Capture @ 95 %	Capture @ 99.72 %
Electricity output penalty	Basic heat integration	kWh elec/tCO_2	297	304
	Advanced heat integration	kWh elec/tCO_2	266	277

Source: Dan Su, Laura Herraiz, Mathieu Lucquiaud, Camilla Thomson, Hannah Chalmers, Thermal integration of waste to energy plants with Post-combustion C02 capture, Fuel, Volume 332, Part 1, 15 January 2023.

Figure 10: Modelled power use by different carbon capture technologies at incineration plants

[39] IPCC (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)], https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf

[40] Dan Su, Laura Herraiz, Mathieu Lucquiaud, Camilla Thomson, Hannah Chalmers, Thermal integration of waste to energy plants with Post-combustion CO_2 capture, Fuel, Volume 332, Part 1, 15 January 2023.



Source: NEWESTCCUS (2023) Webinar 2: Carbon Capture and Storage for Waste to Energy: Evaluating climate impacts and technologies, 25 January 2023.

The Dutch study considered above suggested that the energy penalty arises in the form of a sacrifice both in terms of electricity and heat generation:[41]

> *In total, the process consumes around 212 kWh of electricity and 670 kWh of heat per tonne CO_2 captured (Lensink & Schoots, 2020)*

Christensen and Bisinella, in a study of the GHG impacts of carbon capture and utilisation, assume the following:[42]

> *CC* [carbon capture] *induces an energy penalty, since the MEA process uses part of the steam originally used for electricity production. The penalty is around 250 kWh/tonne MSW for MSWI A* [MSW Incinerator A, an electricity only facility] *(reducing net electricity production by one-third) and around 300 kWh/tonne MSW for MSWI B* [MSW Incinerator B, a facility recovering both electricity and heat] *(reducing net electricity production by half). Plant B has in addition a small reduction in net heat production by 6%, although we assume that 60% of the heat associated with the carbon capture process can be recovered for district heating.*

The issue here is less to do with the climate-related benefits of exporting power and heat from incinerators: we have argued previously that these benefits are diminishing over time. Rather, from the perspective of an operator, it is the loss in income which is felt as a result of the reduction in power and/or heat export that affects the costs of introducing CC technology. This is not trivial in the economics of operating an incineration

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[41] De Leeuw, M. and Koelemeijer, R. (2022), Decarbonisation options for the Dutch waste incineration industry, The Hague: PBL Netherlands Environmental Assessment Agency and TNO Energy Transition.
[42] Christensen, T. H., & Bisinella, V. (2021). Climate change impacts of introducing carbon capture and utilisation (CCU) in waste incineration. Waste Management, 126, 754-770.

facility. The loss in electricity exported may be of the order 35% of electricity exported, and potentially more, depending on the nature of the waste being combusted and the net (of internal use) efficiency of power generation.

In this study, we assume that the energy penalty is either:

- 300kWh for electricity only facilities; or
- 212kWh of electricity and 670 kWh of heat at a CHP facility

These figures are expressed per tonne of CO_2 actually captured by the process (as opposed to being per tonne of CO_2 input to the CC facility). This is in line with the figures estimated in Su et al. [43]

Estimated costs

Based on the above reports, and in an attempt to synthesise the likely costs, we estimate costs below for facilities ranging from 100kt to 300kt and with different WACC's applied. These are estimates, and various 'ways of combining' costs are possible. The cost to the operator of the energy penalty has been estimated crudely by valuing the electricity at an average EU price for wholesale electricity, which at the time of writing was taken to be €0.09 per kWh.[44]

At the upper end of the scale, and with lower WACC applied, these are broadly in line with lower end costs in other studies, and the same applies with regard to upper end costs at lower scales, recognising that none of the studies reviewed appear to have applied a WACC above 7.5% (so our highest 'equivalent' cost – with a WACC of 8% - is €173 per tonne CO_2).

[43] Dan Su, Laura Herraiz, Mathieu Lucquiaud, Camilla Thomson, Hannah Chalmers, Thermal integration of waste to energy plants with Post-combustion CO_2 capture, Fuel, Volume 332, Part 1, 15 January 2023.
[44] Based on data from Ember (see https://ember-climate.org/data/data-tools/europe-power-prices/)

Table 13: Estimated costs for carbon capture, compression, rransport and storage, net of energy revenues foregone, for different scales of facility (all costs, except Capex outlay, are per tonne CO2 captured)

Scale	100kt			200kt			300kt		
Capex outlay (total, €)		€55,000,000			€80,000,000			€95,000,000	
Weighted average cost of capital	10%	8%	12%	10%	8%	12%	10%	8%	12%
Operating Lifetime of Facility		20			20			20	
Annualised Capital Costs	€65	€56	€74	€47	€41	€54	€37	€32	€42
Operating cost (excl energy penalty)		€20			€15			€12	
Transport and Storage, Low		€45			€40			€30	
Transport and Storage, High		€75			€60			€50	
Capture	@85%	@95%	@99%	@85%	@95%	@99%	@85%	@95%	@99%
Lost revenue from energy use	€19	€22	€22	€19	€22	€22	€19	€22	€22

Summary WACC	10%	8%	12%	10%	8%	12%	10%	8%	12%
Low	€149	€143	€161	€121	€117	€131	€99	€96	€107
High	€179	€173	€191	€141	€137	€151	€119	€116	€127
Mid	€164	€158	€176	€131	€127	€141	€109	€106	€117

GHG performance

The two different approaches to reducing carbon emissions function quite differently. The one effectively captures CO2 contained in materials, the other, in the gases emitted by the incinerator. Both the LMWS and the CCS processes rely on inputs of energy, the CCS more so than the LMWS, though in the CCS process, the energy is assumed to be provided by the facility itself.

The savings from either process have to be gauged against a baseline of incinerating materials directly (i.e., without either CCS or LMWS). Hence, in this Section, we review the effects of:

- Direct Incineration
- Incineration + CCS
- Incineration + LMWS; and
- Incineration + LMWS + CCS.

The functional unit is a tonne of LMW entering the different processes. The LMW has the composition and characteristics given in Table 1 above. Note that in this study, we consider the savings in lifecycle terms rather than from the perspective of a particular actor, or as it may be affected by a particular policy. Both fossil and non-fossil CO_2 are considered.

Direct to incineration (baseline)

Incinerating the LMW without any treatment leads to the emission of 841kg CO_2 per tonne of waste input and 40g N_2O, giving an equivalent emission of 853kg CO_2equ per tonne of waste input.[45] The energy generated gives rise to 'emissions reduction' which falls over time as the carbon intensity of energy generation declines. The resulting emissions for the 'electricity only' and 'CHP' modes are shown below. These figures include nominal amounts of fuel used at the facility itself.

Table 14: Greenhouse Gas Emissions in Baseline 'Incineration Only' (tonnes CO_2e per tonne of LMW Handled), Incinerator Generating Electricity Only or CHP

		Electricity	CHP
Incin Only	Short-term	0.707	0.608
	Energy decarb.	0.854	0.852

[45] These numbers do not simply 'sum' since the global warming potential of N_2O relative to CO_2 has to be taken into account.

Incineration + CCS

Depending on the efficiency of capture assumed, then emissions are abated, but also, there is an energy penalty associated with the deployment of CCS. We look at three cases for the 'capture efficiency' – where the proportion of CO_2 emitted which is captured is 85% (the maximum assumed by De Leeuw and Koelemeijer[46]), 95% and 99% (these being captures explored – in modelling – by Su et al[47]).

Incineration + LMWS

Based on the central composition used in the modelling, then applying the efficiencies of sorting of each fraction to the composition, 215kg per tonne of input LMW are removed by the sorting process. More generally, we would expect the type of future-proofed facility we have specified to achieve around 175-250kg per tonne of input LMW, the exact figures being dependent on the composition of the waste received.

The materials removed by the LMWS process can help reduce emissions elsewhere in the economy by facilitating the preparation of secondary materials. In the process, between the extraction of the materials from LMW, and their being recycled, we assume that there is a loss of material (see Table 5 above). Based on the materials extracted, the loss rates, and the assumed GHG benefit from recycling, the LMWS process delivers a reduction in CO_2 emissions of 231kg CO_2 per tonne of waste input to the process. The LMWS and the subsequent hot washing of sorted plastics require use of energy, accounted for in the assessment.

As regards the material remaining to be incinerated, not only is there less material to be incinerated, but the carbon content of that material is reduced relative to the baseline. That is because the LMWS is – in relative terms – more focussed on extracting materials whose carbon content, per unit of weight 'as received', is higher than the average for the waste as a whole. The characteristics of the waste to be incinerated are shown in Table 3 above, both per tonne of waste incinerated, and per tonne of waste input to the LMWS process, which is what remains to be incinerated, and what is modelled in our system.

Incineration + LMWS + CCS

In this configuration, the LMWS process above is then coupled with an incinerator equipped with CCS, modelled as described above, but with the material entering the incinerator being the residual waste that is the output from the LMWS process rather than the raw LMW.

[46] De Leeuw, M. and Koelemeijer, R. (2022), Decarbonisation options for the Dutch waste incineration industry, The Hague: PBL Netherlands Environmental Assessment Agency and TNO Energy Transition.
[47] Dan Su, Laura Herraiz, Mathieu Lucquiaud, Camilla Thomson, Hannah Chalmers, Thermal integration of waste to energy plants with Post-combustion CO_2 capture, Fuel, Volume 332, Part 1, 15 January 2023. Note this work was based on modelling as opposed to empirically observed outcomes.

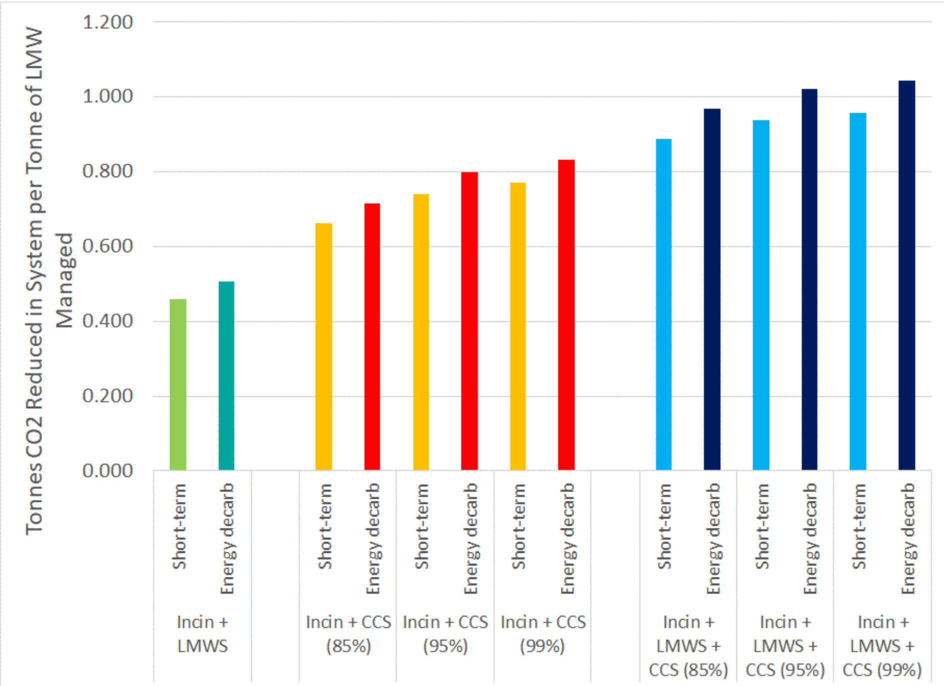
Key results

The key results, in terms of CO_2e savings are shown in Table 15 and in graphic form, for the electricity only incinerator, in Figure 11.

Table 15: CO_2 Reduction from Different Technologies (tonnes CO_2 per tonne of LMW Handled), Incinerator Generating Electricity Only or CHP

Savings		Electricity	CHP	Electricity	CHP
		Short-term		Energy decarbonised	
Incin + LMWS	Short-term	0.457	0.424	0.505	0.504
Incin + CCS (85%)	Short-term	0.661	0.593	0.713	0.711
Incin + CCS (95%)	Short-term	0.739	0.663	0.797	0.795
Incin + CCS (99%)	Short-term	0.770	0.691	0.831	0.829
Incin + LMWS + CCS (85%)	Short-term	0.885	0.807	0.967	0.965
Incin + LMWS + CCS (95%)	Short-term	0.936	0.853	1.020	1.020
Incin + LMWS + CCS (99%)	Short-term	0.957	0.872	1.042	1.043

Figure 11: Level of CO_2 reduction achieved using different technologies (tonnes CO2 per tonne of LMW handled), incinerator generating electricity only



The figures indicate that the LMWS gives close to two-thirds the level of CO_2 reduction that may be achieved by a CCS facility delivering 95% CO_2 reduction. The CCS process gives higher abatement, but it is the combination of LMWS + CCS that generates the greatest overall reduction.

In all cases, the absolute CO_2 reduction increases in the 'energy decarbonised' scenario as this assumes that the carbon intensity of energy falls, implying that the reduced level of energy generation – which affects all scenarios - carries with it a lower 'penalty'. The energy generated is least in the combined LMWS+CCS so the effect of the energy penalty is greatest, leading to the largest uplift in absolute terms from progressive decarbonisation.

What's missing?

In the above, the key aspect which is missing is the effect of including embodied emissions (associated with the materials and energy used to manufacture the technologies, and in the associated construction processes) within the analysis. Embodied emissions are frequently downplayed in studies of this nature because they are typically spread across the activity of a given facility over its useful lifetime. However, from the perspective of climate change, and the contribution by any capital items made to remaining on a net-zero trajectory, the embodied emissions imply an early 'drawdown' of what can be significant amounts of greenhouse gases. As such, they can make a significant dent in remaining carbon budgets. They have not been included in this analysis. In this assessment, all technologies would contribute to this 'drawdown'. The relative magnitudes of the drawdown are not known.

Similarly, the effect on auxiliary materials has not been modelled here. This includes those used in the technologies themselves, as well as reductions – likely in the Incin + LMWS and Incin + LMWS + CCS cases – in the use of auxiliary materials at the incinerator.

Finally, the benefit associated with materials recycling has been kept constant. It is to be hoped that the manufacture of materials decarbonises over time, though empirical evidence suggests this happening much slower than for (for example) power generation. Changes to the EU-ETS and the introduction of a carbon border adjustment mechanism may hasten this in future. As such, we would expect that the CO_2 credit from recycling would fall over time. Equally, to the extent that this is driven by carbon pricing, there may be an effect on prices for secondary materials (whereby secondary materials trade at higher prices in the interim period, reflecting their lower greenhouse gas emissions).

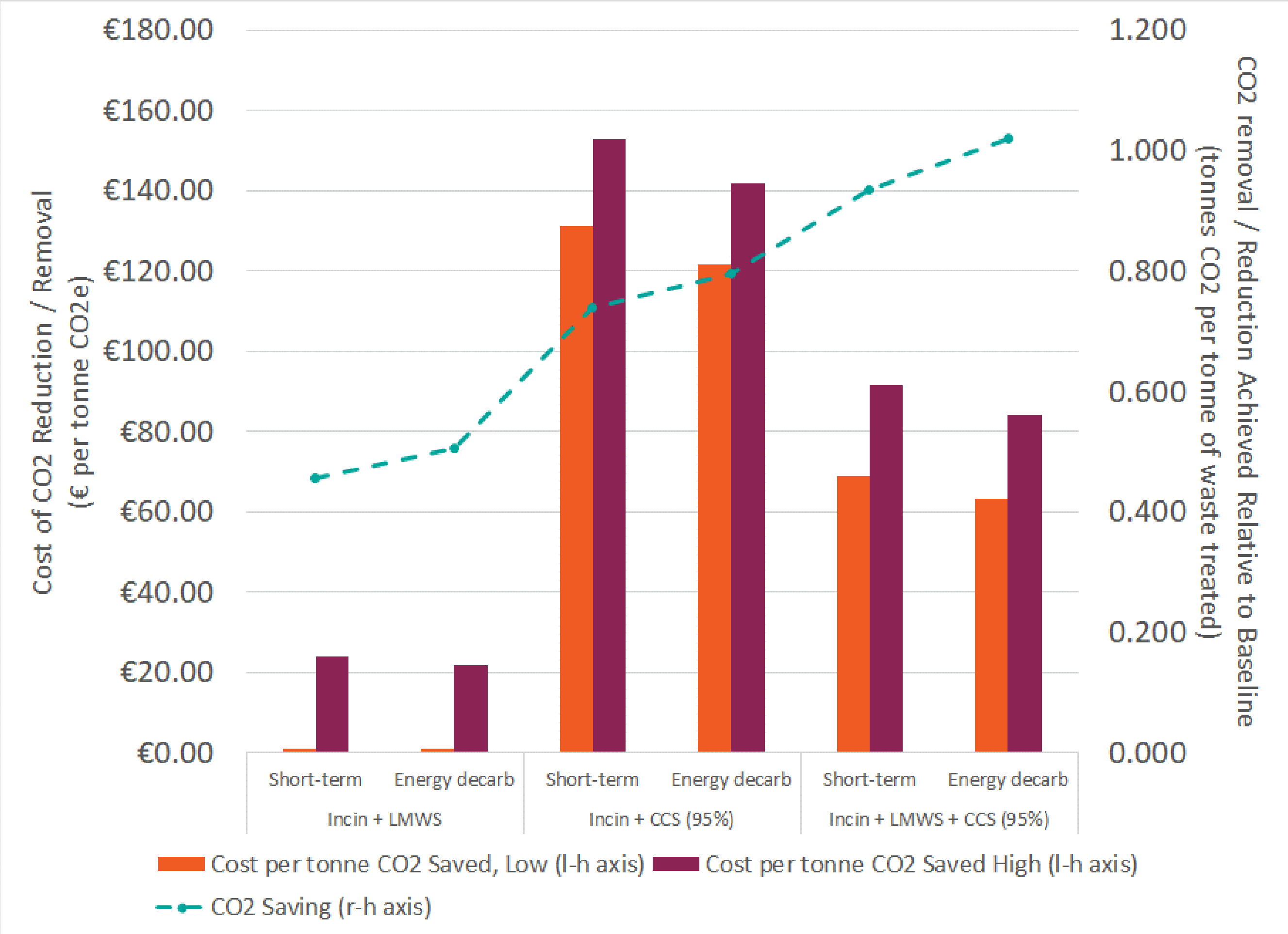
Cost effectiveness of abatement

Based on the costs of the different technologies, and the CO_2 reductions calculated above, we estimated the cost per unit of CO_2 reduction associated with the system. Note once again that in this study, we consider the savings in lifecycle terms rather than from the perspective of a particular actor, or as it may be affected by a particular policy.

The key outputs are shown for the 200kt situation in Figure 12. This shows the cost effectiveness of the CO_2 reduction achieved by different technologies for the case of an electricity only incinerator, and assuming the carbon capture and storage system achieves a 95% capture rate.

What this highlights is that although the level of abatement achieved (represented by the dashed line plotted on the right-hand axis) is lower for the LMWS system, the costs per tonne of CO_2 reduced (the bars, plotted on the left-hand axis) is, comparatively, very low. Costs are €1 – €24 per tonne CO_2 in the current case, falling to €1 – €22 per tonne CO_2 as energy is decarbonised. At the lower end, the costs are close to zero. This is dependent on revenues from material sales being as assumed in the central case. In earlier work, we flexed these values by +/- €9 per tonne of waste treated. In other words, although costs might increase, it is also possible that they could be lower still. Even if all revenues were lost, the costs would still be well below those where CCS is deployed alone.

Figure 12: System cost of GHG reduction (€ per tonne CO_2 reduction achieved), electricity only incinerator, 200kt capacity



Deploying CCS alone achieves a higher level of CO_2 reduction, but the costs are, comparatively, rather high at €132 – €153 per tonne CO_2 in the current case, falling to €122-€143 per tonne CO_2 as energy is decarbonised. Where CCS alone is deployed, the costs look to be somewhat above the prices at which EU allowances have been trading in the EU emissions trading scheme (see Figure 13).

The LMWS+CCS system achieves the highest level of CO_2 reduction of any of the scenarios, and its cost per tonne of CO_2 reduced is much lower – roughly half – that where CCS is deployed in isolation, although still much higher than the costs of deploying LMWS alone. Costs are €69 – €92 per tonne CO_2 in the current case, falling to €63-€84 per tonne CO_2 as energy is decarbonised. The costs per tonne of CO_2 reduced by the LMWS + CCS system are at levels at or below prices at which EU allowances have recently been trading (see Figure 13).

Figure 13: Recent prices for EU allowances (€ / tonne CO_2)

Source: https://ember-climate.org/data/data-tools/carbon-price-viewer/

Key observations

The suggestion from the above is that:

- The LMWS offers a potentially quick way to make significant reduction / removal of greenhouse gases from incineration. The costs of doing so at a 200kt facility are very low – of the order €1 - €22 per tonne of CO_2 reduction;
- Higher levels of reduction / removal are achieved by Incin + CCS, but the costs may be highly variable, depending on factors such as the cost of capital for capture equipment and local conditions. The costs are rather high at €132 – €153 per tonne CO_2 in the current case, falling to €122-€143 per tonne CO_2 as energy is decarbonised.; and
- The lower cost of CO_2 reduction from LMWS helps partially mitigate the much higher costs of CCS. Combining the two technologies – Incin + LMWS + CCS - offers a way to achieve the highest levels of removal / reduction (the highest of the technologies assessed) at a much lower *average* cost per unit of CO_2 reduction than where CCS is deployed alone (€69 – €92 per tonne CO_2 in the current case, falling to €63-€84 per tonne CO_2 as energy is decarbonised). The marginal costs of CO_2 reduction from CCS remain high if the steps are considered sequentially. Importantly, though, application of CCS would be compatible with LMWS, and complements its effect.

Some observations are that CCS would need to be implemented on-site, and as some studies of roll-out have considered, it might not always be possible to accommodate CCS on the site of an existing incinerator.[48] LMWS can, in principle, be implemented in a separate location from CCS, although there might (depending on the existing logistics) be additional costs involved in doing so. LMWS can, therefore, be implemented in such a way as to derive CO_2 reduction in circumstances where it might be difficult to apply CCS (it can, within reason, be separated spatially from the incineration facility). LMWS can also be implementable relatively swiftly and with lower capital requirement. It also contributes to meeting (and exceeding) waste recycling targets.

This suggests a sequential logic, in which LMWS is applied as widely and as early as possible (subject to relevance of the waste streams) with CCS being deployed in its wake at facilities deemed most likely to be needed in future. The future of incineration facilities may indeed be shaped by which factors are likely to make CCS deployment more favourable, though equally, it should be considered that the case for deploying CCS may be greater at co-incineration facilities (such as cement kilns), which have purposes beyond treating waste, and for which CCS may be a necessary component of a broader decarbonisation pathway.

An important point is that the deployment of LMWS is likely to be a 'lower regret' solution with much reduced potential for lock-in. The fact that it seems eminently *compatible with* CCS suggests, as per our previous paper, a need for a rational scaling-back of incineration capacity in those Member States with too much capacity in place.[49] LMWS can also help support in the phasing down of capacity by removing waste for recycling, and reducing the net calorific value of the waste remaining to be combusted (allowing more waste to be combusted at a facility of a given size).

In subsequent work, we plan to explore these issues in further detail, incorporating the perspectives of different stakeholders in the assessment, and considering the potential policy implications.

[48] Hasan Muslemani, Iain Struthers, Laura Herraiz, Camilla Thomson, Mathieu Lucquiaud (2023) *Waste Not, Want Not: Europe's untapped potential to generate valuable negative emissions from waste-to-energy (WtE) using carbon capture technology*, Oxford Institute for Energy Studies, March 2023.

[49] Equanimator (2023) Enough is Enough: The Case for a Moratorium on Incineration, Report for Zero Waste Europe, September 2023.

ZERO WASTE EUROPE

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