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A comparative techno-economic and life cycle assessment of energy-from-waste technology integrated with carbon capture and storage

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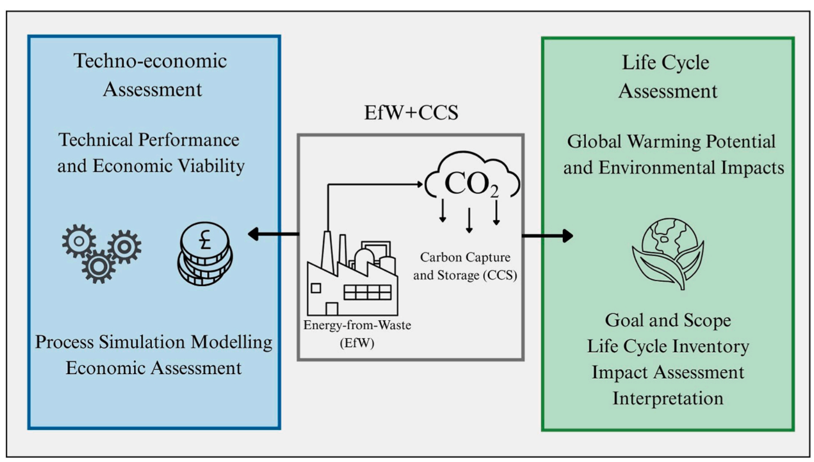
HIGHLIGHTS

- An 80% CO_2 capturerate imposes an energy penalty of 35% in EfW + CCS systems.
- EfW CAPEX and OPEX increased by 30% with the addition of CCS.
- EfW + CCS had a positive net present value and economic potential.
- The addition of CCS decreased GWP by 33% in EfW systems.
- Ammonia use for NO_x removal in EfW systems strongly influenced GWP and OPEX.

GRAPHICAL ABSTRACT



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ABSTRACT

Rising urbanisation and global population growth are projected to nearly double municipal solid waste (MSW) generation by 2050. Energy-from-waste (EfW) technologies recover energy from mixed waste streams, generating electricity and heat. However, for every tonne of MSW incinerated, 0.7–1.7 tonnes of CO_2 is emitted. Integrating carbon capture and storage (CCS) into EfW (EfW + CCS) presents a promising pathway to mitigate these emissions yet remains constrained by high costs and decreased energy efficiency. This study presents a comprehensive assessment of EfW + CCS, using a combined techno-economic and life cycle assessments approach. A thermodynamic steady-state model was developed in Aspen Plus to evaluate mass and energy balances for both standalone EfW and EfW + CCS. Results show that an EfW + CCS system with 250 ktpa capacity and 80% capture rate incurs a 35% energy penalty and increases capital (CAPEX) and operating expenditure (OPEX) both by 30%. Additionally, the system results in a positive net present value, 2.7% return on investment and a levelised cost of electricity of £163/MWh, but extended payback period from 4.5 to 8.3 years

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compared to standalone EfW. The life cycle assessment results showed a 33% reduction in global warming potential (GWP), though monoethanolamine production and carbon capture infrastructure increased other impacts. This study suggests that the current carbon price of £49.4/t CO_2 is insufficient to incentivise CCS deployment, with a required subsidy estimated at £178/t CO_2 captured. Furthermore, ammonia use for NO_x removal strongly influenced GWP and OPEX, with 60% NO_x removal resulting in a reduction of 41% in GWP and increasing OPEX by 19% compared to standalone EfW.

1. Introduction

Due to the rapid increase in urbanisation and population growth, global municipal solid waste (MSW) generation has been on the rise, with an estimated 2.1 billion tonnes generated in 2023 and projections reaching 3.8 billion tonnes by 2050 (United Nations Environment Programme, 2024). Energy-from-Waste (EfW) is a widely adopted energy recovery technology used to manage mixed waste streams, such as MSW, by generating electricity and heat through a combined heat and power (CHP) unit. In 2023, UK EfW facilities processed 16 million tonnes (Mt) of MSW, contributing 3.1% to national electricity generation (Tolvik Consulting Ltd, 2024). However, for every tonne of MSW incinerated, 0.7-1.7 tonnes of CO_2 are generated, with all UK EfW facilities contributing to 3.5% of UK territorial greenhouse gas (GHG) emissions (Muslemani et al., 2024). Carbon capture and storage (CCS) technologies offer the potential for a low-carbon alternative for waste management and energy production when integrated with EfW (EfW + CCS).

Recent literature indicates that EfW + CCS systems are a promising emerging technology, despite significant barriers to large-scale implementation. Boré et al. (2024) highlights that the energy penalties of post-combustion carbon capture (PCC) technologies are considerable with reductions in overall system efficiency ranging from 13 to 17%, varying due to capture efficiency (85-95%). Magnanelli et al. (2021) noted that, in EfW systems, increased capture efficiency further reduces overall efficiency, primarily due to energy demands for solvent regeneration, CO_2 compression and increased auxiliary power consumption.

From an economic perspective, Baltac et al. (2024) found that CCS capital expenditure, of £70–300/t CO_2, is highly dependent on scale with larger facilities benefitting from lower costs. Additionally, Lugal and Rowland (2021) indicated that EfW plant location further impacts CCS capital expenditure with retrofitted systems located near CCS clusters facing costs of £66–110/t CO_2, due to shared infrastructure (Gammer and Elks, 2020). While remote sites face elevated transport costs and may favour alternative technologies (Barlow et al., 2025; Dong et al., 2018). PCC technology has a TRL of 8-9 and is the cheapest when compared to other capture technologies as explored by Kheirinik et al. (2021). Furthermore, several studies (Ng et al., 2021; Ng and Phan, 2021) show that higher revenues are generated from integrated systems that combine waste valorisation with material recovery compared to conventional systems, at a cost of increasing initial investment. However, existing studies largely focus on retrofitting systems, with limited understanding of the technical and economic performance of new-build EfW + CCS systems.

Life cycle assessment studies indicate significant climate benefits with EfW + CCS. EfW technologies, including MSW incineration, can achieve a carbon footprint of 0.6-1.0 kg CO_2-eq/kWh as reported by Abedin et al. (2025). Gasification and pyrolysis exhibit comparable global warming potential of 0.4–0.7 kg CO_2-eq/kWh and 0.3–0.6 kg CO_2-eq/kWh respectively, with anaerobic digestion yielding the lowest warming potential 0.1-0.3 kg CO_2-eq/kWh (Abdallah et al., 2024; Abedin et al., 2025). Paulillo et al. (2024) found that EfW can achieve net-negative emissions of −195 kg CO_2/t MSW to −488 kg CO_2/t MSW for varying capture rates of 50-95% respectively, when integrated with CCS, significantly improving the environmental performance compared to the standalone system (Pour et al., 2018; Paulillo et al., 2024). Furthermore, Materazzi et al. (2024) reported that greater environmental impacts were found in waste-to-hydrogen systems with CCS than MSW incineration with CCS, with hydrogen production leading to reduced emissions of −700 kg CO_2-eq/t compared to −560 kg CO_2-eq/t in MSW incineration with CCS. Wider environmental impacts such as toxicity, eutrophication and acidification potential within EfW + CCS systems are often overlooked, limiting a comprehensive understanding of the environmental benefits and trade-offs associated with new-build EfW + CCS systems.

Consequently, there remains a research gap regarding the widespread deployment of new-build EfW + CCS systems in the UK, particularly in terms of understanding their technical, economic, and environmental impacts as a national decarbonisation strategy for the waste sector. To address this limitation, this study introduces a new case study that evaluates these dimensions through a holistic point of view combining techno-economic and life cycle assessments, offering a comprehensive evaluation of EfW + CCS systems. The study aims to assess the overall viability of EfW + CCS in the UK and its potential contribution to reducing emissions from the waste sector. The research seeks to achieve this through three key objectives: (1) to evaluate the technical and economic feasibility of EfW + CCS systems in comparison with standalone EfW; (2) to assess the environmental impacts of EfW + CCS relative to standalone EfW; and (3) to develop policy recommendations that can enhance the economic and environmental outcomes of EfW + CCS deployment.

The paper is structured as follows: Section 2 outlines the methodological framework and key assumptions. Section 3 presents process simulation models of standalone EfW and EfW + CCS. Techno-economic and life cycle assessments results are reported in Section 4, followed by discussion of widespread deployment of EfW + CCS systems in the UK in Section 5. Finally, Section 6 concludes the research and offers recommendations for future work.

2. Methodology

An integrated methodological framework, as illustrated in Fig. 1, was adopted in this study. The methodology begins with the development of a process simulation model using Aspen Plus to generate detailed mass and energy balances for both systems. These form the basis for assessing the technical performance and serve as the foundation for subsequent economic and environmental assessments. A comprehensive techno-economic and life cycle assessment was conducted to assess the economic costs and benefits, as well as the environmental impacts, of an integrated EfW + CCS system compared to a standalone EfW.

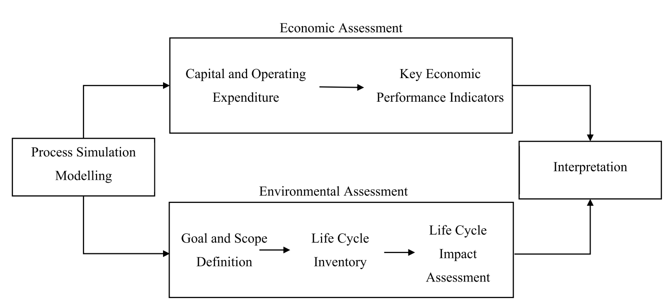


Fig. 1. An integrated techno-economic and life cycle assessment approach.

2.1. Economic assessment

The economic assessment considered capital expenditure (CAPEX) and operating expenditure (OPEX), revenues and key economic performance indicators. CAPEX includes all the upfront expenses related to the plant's construction, installation and commissioning. For EfW equipment cost data was collected from literature (Wheeler and Rome L de, 2003). These figures were subsequently scaled using the cost-capacity scaling factor from Equation (1) and adjusted to 2025 values using Chemical Engineering Plant Cost Index (CEPCI) from Equation (2). Total capital expenditure was based on standard cost engineering practices, with CAPEX calculation breakdown based on total direct cost (TDC), defined as the sum of all equipment costs (Hu et al., 2023). Calculations for the total indirect costs (TIC), bare erected costs (BEC), engineering and contractor (EC), engineering, procurement and construction (EPC), process contingency (PC), project contingency (PJC), total plant costs (TPC) and owner costs (OC) are shown in Table S1 in supplementary material. Total CAPEX is the sum of TDC, TIC, EC, PC, PJC and OC. Annual CAPEX ($CAPEX_{annual}$) is calculated using Equation (3). Key infrastructure for the EfW system consists of the combustion chamber, combined heat and power unit and air pollution control unit. The CCS unit includes a CO_2 capture unit, consisting of an absorber, stripper and other utilities, as well as a CO_2 compression unit comprised of a series of compressors and coolers. As this was a non-site-specific assessment, no explicit transport distance or storage site was assumed. Instead, the study adopted average CO_2 transport and storage cost assumptions from Eunomia (2021) to represent the full CCS chain at a UK level. CO_2 transport and storage CAPEX was assumed at £15/t CO_2 and £8/t CO_2 respectively, with CO_2 transport and storage OPEX both assumed at 5% of CAPEX values.

$$\frac{Cost_{capacity,b}}{Cost_{capacity,a}} = \left(\frac{Capacity_b}{Capacity_a}\right)^S \quad (1)$$

$Cost_{capacity,a}$: cost of EfW base system.
$Cost_{capacity,b}$: cost of EfW new system following scale up/down.
$Capacity_a$: capacity of EfW base system.
$Capacity_b$: capacity of EfW new system following scale up/down.
S: scaling factor

$$\mathrm{Cost_{new}} = \mathrm{Cost_{old}} \times \left(\frac{\mathrm{CEPCI_{new}}}{\mathrm{CEPCI_{old}}}\right) \quad (2)$$

$Cost_{new}$: The cost of EfW facility in current year.
$Cost_{old}$: The cost of EfW facility in previous year.
$CEPCI_{new}$: The Chemical Engineering Plant Cost Index from current year.
$CEPCI_{old}$: The Chemical Engineering Plant Cost Index from reference year

$$\mathrm{CAPEX_{annual}} = \mathrm{CAPEX} \times \mathrm{CRF} \quad (3)$$

$$\text{Capital Recovery Factor (CRF)} = \frac{(1+i)^n \times i}{(1+i)^n - 1}$$

i: discount rate
n: plant lifetime (years).

OPEX comprises of all recurring costs associated with running operations in the form of fixed and variable costs. Fixed costs include labour and maintenance costs and were calculated as 3% of total CAPEX (Hu et al., 2023). Variable costs include the costs of consumables including ammonia, sodium bicarbonate and monoethanolamine (MEA), water consumption and treatment of ash residues. The cost per unit for the variable costs of EfW + CCS system is shown in Table 1.

Revenue streams for both systems include gate fees and income from energy generation. Gate fees refer to the charges waste management companies incur for the treatment and processing of waste. In the UK, gate fees for 2024/25 were assumed at £117/t of waste (WRAP, 2025).

Table 1
Variable operating costs for EfW + CCS system (Amec Foster., 2015; Hu et al., 2023).

Component	Cost
Ammonia solution (£/tonne)	184.5
Sodium bicarbonate (£/tonne)	241.1
Water supply (£/m^3)	0.96
Bottom ash residues (£/tonne)	24.2
Fly ash residues (£/tonne)	205.5
MEA make-up (£/tonne)	1200.3

Energy sales were calculated based on electricity generation only, as this is the primary revenue stream for EfW plants in the UK, with heat exports contributing a minor share of total revenues and was therefore excluded. Electricity can be sold to the national grid, with unit prices of 18.5p per kWh used to calculate energy sales, based on the average quarterly prices paid for energy in the UK in 2025 (Department for Energy Security and Net Zero, 2025a). All electricity generated from the EfW facility was assumed to be exported in both systems. While both electricity and heat are produced by the CHP unit, heat production was not directly derived from the process simulation model. Instead, it was assumed based on the electricity-to-heat ratio from (MVV Energie AG, 2024). Energy penalty calculations were based on both electricity and heat consumption.

Economic indicators consist of economic potential (EcP), net present value (NPV), return on investment (ROI), and payback period calculated using Equations (4)–(7), respectively (Ng et al, 2024). Positive economic potential and NPV indicates that the project generates more revenue than its costs, making it a key indicator for economic profitability. ROI provides a percentage that reflects the efficiency of the investment. The payback period determines how long it will take to recover the original cost of the project. For this study, a discount rate of 8% was applied (Department for Business, Energy and Industrial Strategy (BEIS), 2019) assuming a plant design life of 25 years and plant availability of 87.4%, approximately 7700 operational hours per year, based on average UK EfW facilities in 2024 (Tolvik Consulting Ltd, 2025).

$$\text{Economic Potential (EcP)} = \text{Revenues} - (\mathrm{CAPEX_{annual}} + \mathrm{OPEX}) \quad (4)$$

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \quad (5)$$

R: net cash flow (cash inflow − cash outflow) during time period t

$$\text{Return on Investment (\%)} = \frac{\mathrm{EcP}}{\mathrm{CAPEX}} \times 100\% \quad (6)$$

$$\text{Payback Period (years)} = \frac{\mathrm{CAPEX}}{(\text{Revenues} - \mathrm{OPEX})} \quad (7)$$

Key performance indicators include the levelised cost of electricity (LCOE) used to assess the cost-effectiveness of power generating technologies. It was calculated by using Equation (8) whereby total lifetime costs including annual capital and operating costs were divided by total electricity generated over plant's operational lifetime (Department for Energy Security and Net Zero, 2023a). A lower LCOE indicates a more competitive and cost-efficient energy solution. As a renewable energy source, the LCOE of EfW allows for better comparison with fossil fuel-based power sources and other renewable energy technologies.

$$\text{Levelised Cost of Electricity, LCOE (£ / MWh)} = \frac{\mathrm{CAPEX} + \sum_{t=1}^{n} \frac{\mathrm{OPEX}_t}{(1+i)^t}}{\sum_{t=1}^{n} E_t} \quad (8)$$

E_t: electricity generated at period t (MWh).

2.2. Life cycle assessment (LCA)

The LCA followed ISO 14040:2006 and ISO 14044:2006 standards (International Organization for Standardization, 2006b; International Organization for Standardization, 2006a), consisting of four stages: (i) goal and scope definition (including, purpose of the study, the functional unit and the system boundaries of both systems), (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) interpretation. Life cycle inventory was determined by mass and energy balances derived from the process simulation model and supplemented by the Ecoinvent V3.11 database. Inputs included (raw materials and energy) while outputs included (emissions to air, water and soil and solid residues).

Environmental impacts were assessed using CML 2001 v2.5 baseline method including categories such as abiotic depletion potential (fossil fuels) (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), photochemical ozone creation potential (POCP), acidification potential (AP) and eutrophication potential (EP). SimaPro V9.5 software was used to conduct the LCA due to its comprehensive database and wide range of impact assessment methods, which facilitate comparative evaluations. The interpretation phase evaluated the results and drew conclusions on the environmental impacts of both the EfW + CCS and standalone EfW systems.

3. Process simulation modelling

A thermodynamic steady-state model was developed in Aspen Plus V14 to simulate both standalone EfW and EfW integrated with carbon capture (CC). This process simulation model generates mass and energy balances, enabling the evaluation of technical plant performance including impacts on CO_2 capture rate. As a result, CO_2 transport and storage were excluded from the process model, as they fall outside the system boundary and are site-specific. However, they were incorporated into the TEA and LCA assessments to capture the economic and environmental impacts across the full EfW + CCS chain. Table 2 shows the input variables of both EfW and CC systems. For this study, a 250 ktpa EfW capacity with 80% capture rate was assumed as the baseline case. This reflects UK average EfW capacities, as well as transitional standards for CO_2 capture rates.

A process flow diagram of the EfW + CC system is shown in Fig. 2. MSW is stored in a waste bunker to ensure a consistent feed rate to the combustion process. MSW (stream 1) is then combusted in the presence of excess oxygen (stream 2) at a temperature of 850-1100°C. Solid residues produced from combustion are released as incinerator bottom ash (IBA) (stream 3) which is considered non-hazardous after treatment and is commonly used as a secondary aggregate in the construction industry. The resulting exothermic reaction releases hot flue gas (stream 4), which is used to convert feedwater (stream 5) into steam (stream 6) to drive a CHP unit for heat and power generation, releasing hot water (stream 7) which can be reused. The flue gas (stream 8) generated from combustion contains various pollutants and is therefore treated with reagents (stream 9) in an air pollution control (APC) unit. This includes a scrubber using sodium bicarbonate and ammonia to remove sulphur dioxide (SO_2), hydrogen chloride (HCl), and nitrogen oxides (NO_x). This produces APC residues including wastewater discharge (stream 10) and fly ash (stream 11).

Table 2
Input feed variables for process simulation model of EfW and CC systems.

Input Variable	Flowrate (ktpa)
MSW	250
Air	2000
Sodium bicarbonate	71.7
Ammonia	118.8
Water	780
MEA solution make-up	13

With the integration of CC, using a post-combustion chemical absorption process with MEA, the flue gas (stream 12) is mainly composed of CO_2, H_2O, N_2 and O_2. Firstly, it is conditioned to the optimal temperature and pressure using a blower and cooler (streams 12-14), to ensure capture efficiency. An exothermic reaction takes place within the absorber between the CO_2 concentrated gas stream (stream 14) and the MEA liquid stream (stream 23). A rich MEA stream (stream 15) leaves from the bottom of the absorber, sent to a pump to maintain pressure levels (stream 16) and heated through a heat exchanger, before entering the stripper (stream 17). A lean MEA stream is released from the bottom of the stripper (stream 18). A pump is used to maintain pressure levels (stream 19) and the stream is cooled through the heat exchanger and cycled back into the absorber (streams 20, 22, 23). A MEA makeup stream (stream 21) is added to maintain solvent levels. The 'treated' gas stream with less CO_2 is sent to the stack (stream 24).

The captured CO_2 (stream 25) is cooled (stream 26) and sent to a flash unit, producing a liquid stream (stream 27) mainly composed of water. The captured CO_2 (stream 28) is directed to a series of compression stages (streams 28-33), including intercooling, to condense and compress the gas. The pressure outlets of each stage are 7.4 bar from stage 1 (stream 30), 27 bar from stage 2 (stream 32) and 100 bar from stage 3 (stream 34), with a pressure ratio of 3.7 in each stage. Once the gas stream is compressed, a high-purity stream of CO_2 (stream 34) is generated and ready to be transported to a storage site.

Assumptions considered for the standalone EfW system in the Aspen simulation model were.

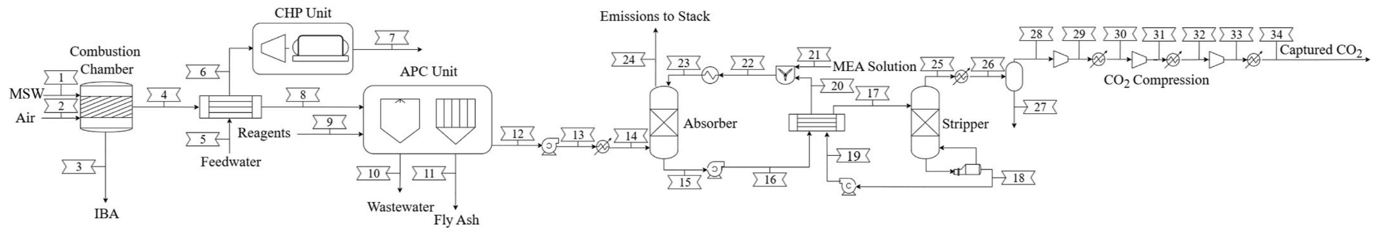
- MSW is composed of carbon, hydrogen, oxygen, nitrogen, sulphur, chlorine and ash. Complete combustion takes place whereby all MSW is fully oxidised, hence carbon monoxide formation is not considered.
- Air used in combustion is composed of 79% nitrogen and 21% oxygen by mass.
- The flue gas contains no particulate matter or dust particles.
- The higher heating value of MSW is 16.6 GJ/tonne.

The Peng-Robinson Equation of State (PENGROB) property method was used to model the EfW system, as it effectively accounts for non-ideal gas behaviour and is suitable for hydrocarbon mixtures such as those present in MSW, ensuring accurate modelling of combustion processes (Aspen Technology Inc, 2001). Tables S2 and S3 in the Supplementary Material present the specifications for unit operations for both EfW and CC units as well as the ultimate analysis for MSW respectively. The feedstock was assumed to have a biogenic and moisture content of 50% and 20% respectively, representing partially dried MSW. The completed EfW model was validated against data from Protos Energy Recovery Facility (ERF) (Cheshire West and Chester Council, 2025) and verified against data from (Sebastiani et al., 2023*)*, as presented in Table 3. Validation model was based on limited operational data from Protos ERF but included steam turbine and flue gas cleaning operating conditions and sodium hydroxide flowrate. Other key parameters including combustion temperature, MSW composition, combustion air supply were assumed, resulting in the observed discrepancies.

Furthermore, the CC unit was modelled and additional assumptions considered were.

- MEA concentration in the lean loading is 30%wt
- Absorption takes place at 30°C and 1.5 bar
- CO_2 loading is set at 0.2 mol CO_2/mol MEA using design specification based on the molar flow rates of lean MEA stream and rich CO_2 stream

Non-RandomTwo-Liquid (NRTL) property method was used to



Stream Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Temperature (°C)	25	25	150	1100	60	519	129	120	25	120	120	120	120	30	31	31	101
Pressure (bar)	1	1	1	1	54	54	2	1	1	1	1	1	1.5	1.5	1.5	2.1	2.1
Mass Flow (ktpa)	250	2000	53	2197	780	780	780	2197	30.3	95.8	7.5	2124	2124	2124	6925	6925	6925
Mass Fraction																	
Carbon	0.316																
Hydrogen	0.04																
Oxygen	0.212	0.21		0.033				0.033				0.015					
Nitrogen	0.012	0.79		0.680				0.680				0.777					
Sulphur	0.0024																
Chlorine	0.0056																
Ash	0.212		1								1						
Water	0.2			0.064	1	1	1	0.064		0.86		0.072	0.02	0.02	0.672	0.672	0.672
Carbon Dioxide				0.132				0.132				0.136	0.98	0.98	0.034	0.034	0.034
Sulphur Dioxide				0.001				0.001									
Nitrogen Oxide																	
Hydrogen Chloride				0.001				0.001									
Nitrogen Dioxide				0.012				0.012		0.04							
Nitric Oxide				0.078				0.078		0.05		Trace					
Ammonia									0.78			Trace					
Sodium Bicarbonate									0.22								
Sodium Sulphate										0.03							
Sodium Chloride										0.02							
Monoethanolamine (MEA)															0.295	0.295	0.295

Stream Number	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Temperature (°C)	126	126	53	25	53	30	30	62	30	30	30	117	30	126	30	224	30
Pressure (bar)	2.1	1.5	1.5	1	1.5	1.5	1.5	2.1	2.1	2.1	2.1	5	5	15	15	100	100
Mass Flow (ktpa)	6679	6679	6679	13	6692	6692	1891	246	246	10	236	236	236	236	236	236	236
Mass Fraction																	
Carbon																	
Hydrogen																	
Oxygen							0.019										
Nitrogen							0.948										
Sulphur																	
Chlorine																	
Ash																	
Water	0.694	0.694	0.694	0.695	0.694	0.694	0.002	0.044	0.044	0.93	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Carbon Dioxide	0.001	0.001	0.001		0.001	0.001	0.03	0.956	0.956	0.07	0.992	0.992	0.992	0.992	0.992	0.992	0.992
Sulphur Dioxide																	
Nitrogen Oxide																	
Hydrogen Chloride																	
Nitrogen Dioxide																	
Nitric Oxide																	
Ammonia																	
Sodium Bicarbonate																	
Sodium Sulphate																	
Sodium Chloride																	
Monoethanolamine (MEA)	0.305	0.305	0.305	0.305	0.305	0.305	0.001										

Fig. 2. Process flow diagram of EfW + CC.

Table 3
Validation results for EfW model compared to Protos ERF plant (Cheshire West and Chester Council, 2025) and model verification compared to (Sebastiani et al., 2023).

Output	Observed Value	Simulation Value	Deviation (%)	Source
EfW Turbine Power (MW)	17	17.7	3.9%	Protos ERF
CO_2 Emissions (t/t MSW)	0.80	0.77	3.3%	Protos ERF
CO_2 Concentration in Flue gas (%)	11.5	12.7	9.4%	Sebastiani et al. (2023)

model the CC unit as it accurately captures the non-ideal liquid phase behaviour of aqueous amine solutions, enabling more accurate vapour-liquid equilibrium predictions between CO_2 and MEA streams (Aspen Technology Inc, 2001). MEA degradation was excluded for model simplicity. The completed CC model was validated against data from Protos ERF Plant (Cheshire West and Chester Council, 2025), as shown in Table 4. Validation model was based on limited operational data from Protos ERF but included capture rate and amine solvent flow rate. Other key parameters including absorber and stripper operating conditions and CO_2 compression pressure ratio were assumed, resulting in the observed discrepancies.

A sensitivity analysis was conducted for the EfW + CC system, focusing on the capture efficiency. Figs. 3 and 4 present how the solvent flow rate and reboiler heat duty vary for capture efficiencies of 70%, 80% and 90%, indicating that increased capture efficiency leads to an increase in the reboiler heat duty and solvent demand. As a result, 80%

Table 4
Validation results for CC model compared to Protos ERF plant (Cheshire West and Chester Council, 2025).

Output	Observed Value	Simulation Value	Deviation (%)
CC Power Demand (MW)	7.1	7.4	4%
CO_2 Captured (t/t MSW)	0.74	0.73	0.9%
Reboiler Heat Duty (MW)	51.8	49.7	4%

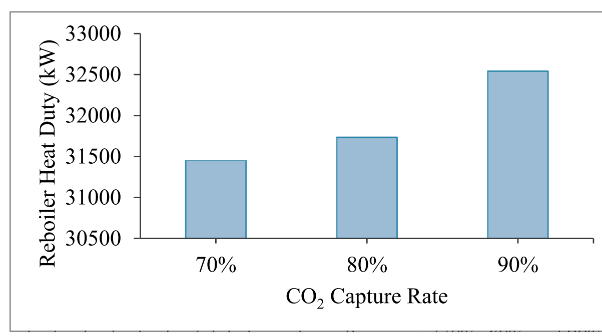


Fig. 3. Sensitivity of reboiler heat duty to capture efficiencies (70%, 80% and 90%) in the EfW + CC system.

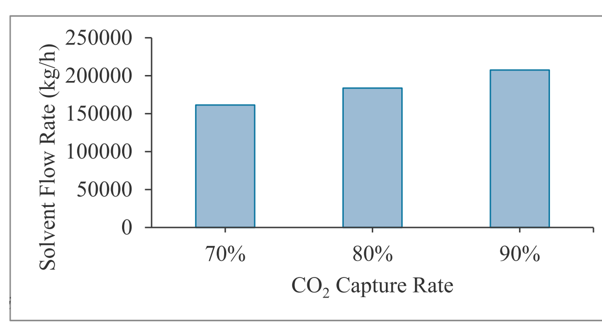


Fig. 4. Sensitivity of solvent flow rate to capture efficiencies (70%, 80% and 90%) in the EfW + CC system.

capture rate was set to ensure a minimum threshold for commercial scale whilst minimising energy demands and solvent costs.

The mass and power balances of EfW + CC and standalone EfW are presented in Fig. 2 and Table 5, respectively.

The net power output of the EfW system is 20.2 MW, corresponding

Table 5
Power balance for EfW and EfW + CC systems.

Power Balance		
EfW	Power Generated (MW)	
	Steam Turbine	20.2
	Power Consumed (MW)	
		0.00
	Net Power Output (MW)	**20.2**
CC	Power Generated (MW)	
		0.00
	Power Consumed (MW)	
	Blower	0.33
	Pumps	0.02
	Compression	4.47
	Net Power Output (MW)	**−4.8**
EfW + CC	**Net Power Output (MW)**	**15.4**

to 621.6 kWh/t MSW, aligning with the UK EfW average of 600 kWh/t MSW input (Tolvik Consulting Ltd, 2025). However, the integration of CC resulted in a 24% power penalty, with a net power output of 15.4 MW (473 kWh/t MSW). The CC unit imposed a parasitic electrical load of 24% due additional energy demands required for CO_2 compression, solvent circulation and auxiliary operations.

EfW reflects a reduction in useable heat due to the energy intensity of the reboiler for solvent regeneration, bearing a heat duty of 3.6 GJ/t CO_2 captured. The addition of CC resulted in an overall energy penalty of 35% including both heat and power on the EfW system, consistent with energy penalties reported for similar processes (Andersson, 2020; Vasudevan et al., 2016).

The environmental benefit of integrating EfW with CC is demonstrated through its reduction in carbon emissions with 0.23 t CO_2/t MSW released into the atmosphere, reflecting an 80% capture efficiency, equivalent to 234 kt CO_2 per year. In contrast, standalone EfW produced 1.16 t CO_2/t MSW released through stack emissions.

4. Results

4.1. Economic analysis

The economic viability of EfW + CCS was assessed by considering capital and operating costs, revenues and economic key performance indicators. As this was a non-site-specific assessment, no explicit transport distance or storage site was assumed. Instead, the study adopted average CO_2 transport and storage cost assumptions from Eunomia (2021), as mentioned in the methodology section, to represent the full CCS chain at a UK level.

The total CAPEX for standalone EfW was estimated using Equations (1)–(3), at £174.7 M (annual CAPEX of £16.4 M/y), with the cost breakdown presented in Table 6 and list of equipment costs in Table S4 of the Supplementary Material. This includes total direct costs of £55.5 M, total indirect costs of £27.8 M, engineering and contractor fees of £22.5 M, process contingency of £20.8 M, project contingency of £25.3 M and owner's costs of £22.8 M. The OPEX was estimated at £18.2 M/y including £5.2 M/y from fixed costs and £12.9 M/y from variable costs. EfW CAPEX estimated in this study is consistent with values reported in literature for facilities with comparable capacities, ranging from £141.5-247.6 M (Turley and Tooke, 2020).

On the other hand, the CAPEX of EfW + CCS system was estimated at £227.7 M (annual CAPEX of £21.3 M/y), where CCS costs £53.1 M (annual cost of £5.0 M). The inclusion of the CCS increased CAPEX by 30% compared to standalone EfW, primarily due to the blower and compressors used in the carbon capture unit. The OPEX for the EfW + CCS system was estimated to be £23.6 M/y. Of this, the CCS unit accounted for £5.4 M/y, representing a 30% increase in comparison to a standalone EfW. The full operating cost breakdown for EfW and CCS is shown in Table S5 of the Supplementary Material.

Revenues are derived from gate fees and energy sales. At a standardised rate of £117/t MSW (WRAP, 2025), the treatment of 250 ktpa of MSW yields a consistent gate fee revenue of £29.3 M/y for both systems. In contrast, energy sales exhibit a marked decline from £28.7 M/y to £21.9 M/y with the integration of CCS. As a result of the energy penalty associated with CCS, total annual revenue declines from £58 M/y in standalone EfW to £51.1 M/y in EfW + CCS.

EfW indicated a strong financial performance and value over the 25-year period with a NPV of £254 M and economic potential of £23.5 M/y, estimated with Equations (4) and (5). However, with the increase in capital and operating costs, the EfW + CCS system saw a drop in value with a NPV of £68.4 M and an economic potential of £6.2 M/y, a reduction in ROI from 13.4% to 2.7%, using Equation (6) and a prolonged payback period from 4.4 years to 8.3 years using Equation (7). Costs, revenues and economic indicators of EfW and EfW + CCS systems are shown in Table 7. Furthermore, economic performance is sensitive to electricity unit prices with higher unit prices significantly improving the economic viability of EfW + CCS systems as shown in Table S6 of Supplementary Material.

The LCOE of EfW and EfW + CCS were calculated using Equation (8). EfW illustrated a LCOE of £95/MWh as shown in Table 8. However, when integrated with CCS, the economic viability decreases significantly. As a result of higher costs and reduction in electricity output, the LCOE of EfW + CCS increased to £163/MWh, which is higher than the UK wholesale electricity price of £127/MWh, as shown in Fig. 5. However, this comparison is indicative only, as the revenue assumptions and market price are not directly equivalent. As a standalone technology, the LCOE of EfW is less than conventional fossil fuel-based power, such as gas-fired generation (£114/MWh), but remains higher than renewable sources like solar (£41/MWh) and offshore wind (£44/MWh) (Rogelj et al., 2024; Department for Energy Security and Net Zero, 2023a) due to higher capital and operating requirements of EfW systems. Over the 25 years plant lifetime, EfW produces 3.88 TWh at a discounted OPEX of £195.3 M, while EfW + CCS generates 2.96 TWh at £253.5 M, indicating the higher LCOE reflects both increased costs and lower net electricity output. Full cost breakdown of LCOE for both systems is shown in

Table 6
Capital and operating expenditure breakdown of EfW and CCS systems.

Capital Expenditure (£M)	EfW	CCS
Total Direct Cost (TDC)	55.5	15.2
Total Indirect Cost (TIC)	27.8	7.6
Engineering and Contractor (EC)	22.5	6.1
Process Contingency (PC)	20.8	5.7
Project Contingency (PJC)	25.3	6.9
Owner's Cost (OC)	22.8	6.2
CO_2 Transport	-	3.5
CO_2 Storage	-	1.9
Total Capital Expenditure (CAPEX)	**174.7**	**53.1**
Operating Expenditure (£M/y)	**EfW**	**CCS**
Fixed Costs	5.2	1.4
Variable Costs	12.9	3.7
CO_2 Transport	-	0.18
CO_2 Storage	-	0.09
Total Operating Expenditure (OPEX)	**18.2**	**5.4**

Table 7
Costs, revenues and economic indicators of EfW and EfW + CCS systems.

Indicators		EfW	EfW + CCS
Costs	Annual CAPEX (£M/y)	16.4	21.3
	OPEX (£M/y)	18.2	23.6
Revenues	Gate Fees (£M/y)	29.3	29.3
	Energy Sales (£M/y)	28.7	21.9
Economic Indicators	Economic Potential (£M/y)	23.5	6.2
	Net Present Value (£M)	254	68.4
	Return on Investment (%)	13.4	2.7
	Payback Period (y)	4.4	8.3

Table 8
Levelised cost of electricity calculation for EfW and EfW + CCS over 25-year plant lifetime.

Levelised Cost of Electricity (LCOE)	EfW	EfW + CCS
Discounted OPEX over plant lifetime (£M)	195.3	253.5
CAPEX at year 0 (£M)	174.7	227.7
Electricity generated over plant lifetime (MWh)	3885000	2959000
LCOE (£/MWh)	**95.2**	**162.6**

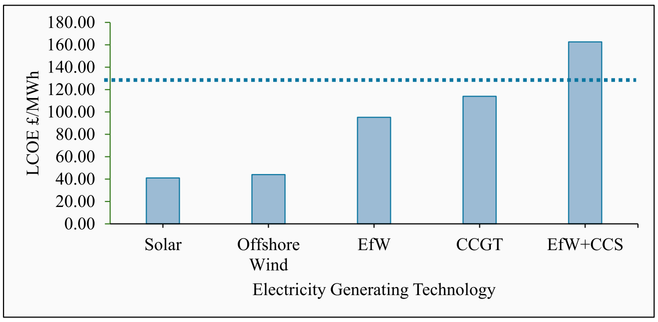


Fig. 5. Levelised cost of electricity of electricity generating technologies. CCGT (combined cycle gas turbine), solar and offshore wind values including grid connection costs reproduced from (Department for Energy Security and Net Zero, 2023a). Dotted line represents current wholesale price of electricity (£/MWh) in the UK (Rogelj et al., 2024).

Table S7 of the Supplementary Material.

For widespread deployment of EfW + CCS it is essential to understand the economic implications further. From 2028, EfW plants in the UK will be included in the UK Emissions Trading Scheme (UK ETS), resulting in carbon emissions being subject to a carbon price, currently at £49.4/t CO_2 emitted (Department for Energy Security and Net Zero, 2025b). Due to economies of scale, as EfW capacity increases the CCS CAPEX/t CO_2 decreases, as shown in Fig. 6. However, even with capacities near 1000 ktpa, CCS CAPEX is higher than the current carbon price, making it economically less viable. Therefore, for average UK EfW capacities of 200-300 ktpa with 80% capture efficiency, a government subsidy of £162-200/t CO_2 captured is required to incentivise EfW + CCS against UK ETS figures.

4.2. Life cycle assessment

4.2.1. Goal and scope

The aim of the LCA is to compare the life cycle environmental impacts of an EfW + CCS system, against standalone EfW within the UK. The system boundary includes a partial gate-to-gate with avoided burden starting from the deposition of MSW at the EfW facility and ends at the production of CO_2 as a product for the EfW + CCS system. This captures the direct environmental impacts of the EfW + CCS process including benefits of avoided emissions, whilst excluding upstream processes that have minimal impact on system's performance. The EfW system ends at emissions to stack. Previous studies (Cherubini et al., 2009; Rotthong et al., 2026) show that thermal treatment of MSW including flue gas cleaning is the main contributor to environmental impacts, while collection and transportation play a relatively smaller role. In line with the system expansion approach, system credits were applied for energy recovery including exported electricity and the recycling of bottom ash. Heat export was excluded due to uncertainty in its utilisation, which depends on actual heat demand and could otherwise lead to overestimation of environmental benefits. Fly ash is sent to landfill for hazardous waste treatment. The impacts of CO_2 transport and storage are not included in the system boundary but are calculated separately based on assumptions from (Chari et al., 2023) to account for the full CCS chain. System boundaries for EfW and EfW + CCS systems are shown in Fig. 7. For standalone EfW, this includes infrastructure for incineration and CHP units, inputs of sodium bicarbonate, ammonia, activated carbon and water, as well as electricity generation. Electricity consumption was assumed at 15% of electricity generated (Tolvik Consulting Ltd, 2025). Outputs comprise of emissions to air, water and soil, alongside bottom ash and fly ash.

Additional inputs in the EfW + CCS system include MEA, as a material, and carbon capture infrastructure. As data was unavailable, a standard chemical factory was used to represent the carbon capture unit. This represents a key uncertainty in environmental impacts where results should be interpreted accordingly. Additional outputs considered for EfW + CCS include reduced CO_2 emissions and the release of MEA into the atmosphere. CO_2 emissions from both EfW and EfW + CCS systems were assumed to comprise a 50/50 split between biogenic and fossil carbon, representing a simplified approximation of typical MSW composition. The energy required for CO_2 capture and compression was accounted for by reducing the electricity exported from the EfW + CCS system, as standalone EfW can meet the energy demands of the CCS unit. The functional unit was defined as 1 tonne of MSW incinerated to enable a consistent basis for comparison between the systems.

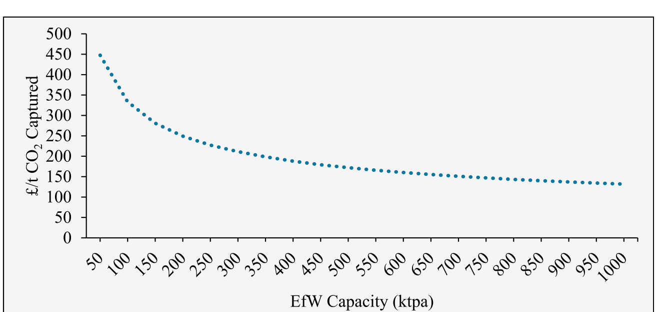


Fig. 6. CCS CAPEX per tonne of CO_2 captured for EfW capacities between 50 ktpa-1000ktpa.

4.2.2. Inventory analysis

Inventory data for both standalone EfW and EfW + CCS was taken from the mass and energy balance produced from the process simulation model. Where data was unavailable, literature values provided by Jeswani and Azapagic (2016) were used. The life cycle inventory per tonne of MSW for standalone EfW and EfW + CCS is shown in Tables S8 and S11 in Supplementary Material.

4.2.3. Impact assessment

The impact assessment was conducted using the CML 2001 (v2.5) methodology, a European-based approach. Ten baseline environmental impact categories were evaluated, including ADP, GWP, ODP, HTP, FAETP, MAETP, TETP, POCP, AP and EP. Summary of impact assessment results generated from SimaPro are shown in Table 9, with all results shown in Tables S9 and S10 in Supplementary Material. CO_2 transport and storage impact contributions were assumed at 11% for GWP and 12% for HTP and AP (Chari et al., 2023), all other impact categories had minor contributions and were therefore not included. Environmental impact assessment shows an increase in all impact categories with the integration of CCS, apart from GWP, whereby a decline of 33% is noted.

4.2.4. Interpretation

Environmental impacts for EfW and EfW + CCS systems are shown in Fig. 8. In the EfW system, ADP reached 4393 MJ/t MSW without considerations for system credits. This impact was contributed predominantly by ammonia (66%) and sodium bicarbonate production (14%), with smaller contributions from MSW incineration and CHP infrastructure. Credits from energy recovery (2546 MJ/t MSW) and bottom ash

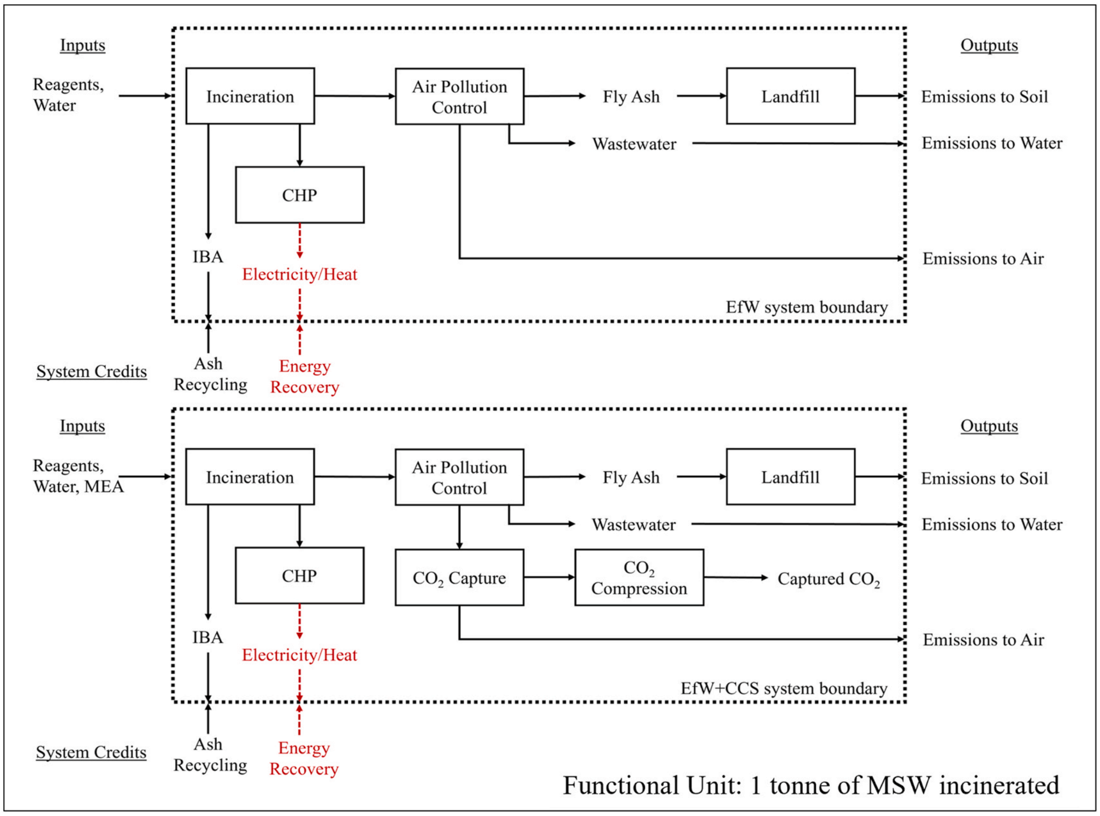


Fig. 7. System boundaries for EfW (above) and EfW + CCS (below) systems. Energy streams are indicated with red dashed line.

Table 9
Environmental impacts of EfW and EfW + CCS for 1 tonne of MSW incinerated.

Impact category	Unit	EfW	EfW + CCS
Abiotic Depletion Potential (ADP)	MJ	1839	4475
Global Warming Potential (GWP)	kg CO_2 eq	735	496
Ozone Layer Depletion Potential (ODP)	kg CFC-11 eq	0.0	0.0
Human Toxicity Potential (HTP)	kg 1,4-DB eq	299	2265
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg 1,4-DB eq	155	468
Marine Aquatic Ecotoxicity Potential (MAETP)	kg 1,4-DB eq	306,218	736,238
Terrestrial Ecotoxicity Potential (TETP)	kg 1,4-DB eq	1.8	8.1
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq	0.03	0.07
Acidification Potential (AP)	kg SO_2 eq	17.7	20.7
Eutrophication Potential (EP)	kg PO_4 eq	4.6	5.0

recycling (7.6 MJ/t MSW) are accounted as avoided burdens and substantially reduced ADP to 1839 MJ/t MSW. For GWP, the system impact was 912 kg CO_2-eq/t MSW, of which direct stack emissions from combustion accounted for 64%, while indirect upstream contributions from ammonia (23%) and sodium bicarbonate production (7%) made up most of the remainder. Energy recovery offset 177 kg CO_2-eq/t MSW, resulting in a net GWP of 735 kg CO_2-eq/t MSW for standalone EfW.

AP was estimated at 18 kg SO_2-eq/t MSW, dominated by stack emissions from combustion (95%), while reagents contributed only marginally. Energy recovery provided a negligible offset of 0.3 kg SO_2-eq/t MSW, bringing the net impact to 17.7 kg SO_2-eq/t MSW. Similarly, EP impact totalled at 4.6 kg PO_4-eq/t MSW, also dominated by direct stack emissions from combustion, with minor contributions from upstream ammonia and sodium bicarbonate production, and minimal offset from energy recovery. HTP, FAETP and MAETP impacts for standalone EfW (no system credits) were 340, 182, and 364,544 kg 1,4-DB-eq/t MSW, respectively. Sodium bicarbonate production contributed (47%, 40%, and 36%) of these impacts, followed by ammonia production (22%, 24%, 17%) and fly ash landfilling (14%, 31%, 31%), with the remainder from MSW incineration and CHP infrastructure. System credits from energy recovery and bottom ash recycling reduced these impacts by 13%, 15%, and 16%, resulting in net values of 299, 155, and 306,218 kg 1,4-DB-eq/t MSW. TETP was 1.8 kg 1,4-DB-eq/t MSW including system credits, mainly due to sodium bicarbonate and ammonia production, with energy recovery offsetting 0.6 kg 1,4-DB-eq. POCP was 0.03 kg C_2H_4-eq/t MSW, with reagent production contributing 0.04 kg C_2H_4-eq/t MSW and energy recovery providing a credit of 0.02 kg C_2H_4-eq/t MSW. No significant impacts were observed for ODP.

Integrating CCS into the EfW system reduced GWP by 33%, reducing it to 496 kg CO_2-eq/t MSW including system credits, demonstrating a significant environmental impact saving potential of carbon capture via MEA absorption. Main contributors include ammonia production (56%), direct stack emissions (26%), carbon capture infrastructure (12%) and MEA production (9%). Furthermore, energy recovery offset in GWP accounted to 135 kg CO_2-eq/t MSW, which was lower than standalone EfW due to CCS energy penalty. Additionally, in the EfW + CCS system, including system credits, all other impact categories increased in comparison to standalone EfW, due to the additional resource and energy demands of CCS. ADP increased to 4475 MJ/t MSW due to higher ammonia consumption for flue gas pre-treatment (77%), MEA production (20%), carbon capture infrastructure (12%), as well as lower credits from energy recovery (1939 MJ/t MSW) due to CCS energy penalty. HTP increased by 658% to 2265 kg 1,4-DB-eq/t MSW, FAETP by 202% to 468 kg 1,4-DB-eq/t MSW, and MAETP by 140% to 736,238 kg 1,4-DB-eq/t MSW, primarily driven by upstream MEA production, elevated ammonia use and carbon capture and pipeline infrastructure. TETP increased to 8.1 kg 1,4-DB-eq/t MSW, largely due to carbon capture infrastructure. POCP increased to 0.07 kg C_2H_4-eq/t MSW, reflecting

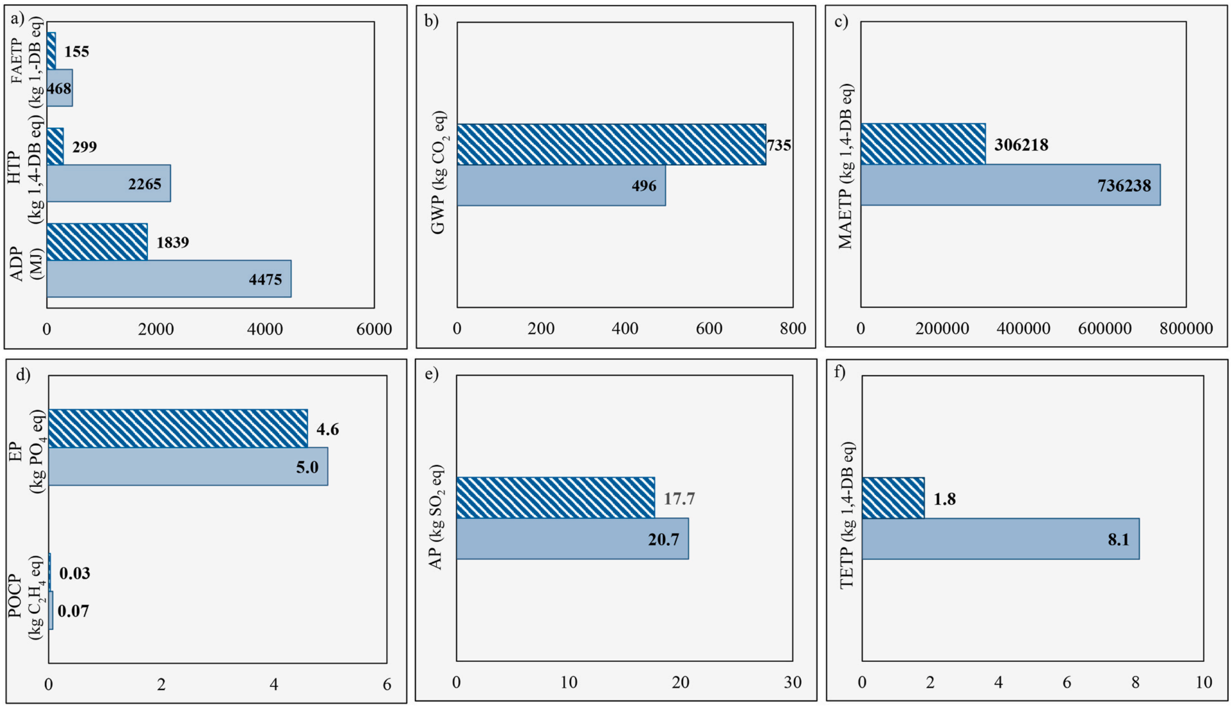


Fig. 8. Environmental impacts including a) ADP, HTP and FAETP b) GWP c) MAETP d) POCP and EP e) AP and f) TETP, of EfW (indicated by striped block) and EfW + CCS (indicated by solid block) systems including system credits with respect to 1 tonne of MSW incinerated.

increased ammonia use and MEA emissions to air. EP and AP increased by 9% and 19%, reaching 5.0 kg PO_4-eq/t MSW and 21.0 kg SO_2-eq/t MSW, respectively, due to additional ammonia production, MEA production and carbon capture and pipeline infrastructure.

Results indicate that upstream production of ammonia and sodium bicarbonate, along with fly ash landfilling, are major contributors to the environmental burdens of standalone EfW. This is due to the fossil fuel intensive synthesis requirements of reagents used, as well as landfill leachate contaminating aquatic and terrestrial ecosystems impacting ADP, GWP, HTP, MAETP, FAETP and TETP. Elevated AP and EP arise from nitrogen and sulphur oxides in combustion emissions, contributing to acid rain and nutrient enrichment that deplete oxygen in aquatic ecosystems. System credits including energy recovery offset some impacts, particularly ADP, GWP, HTP, MAETP and FAETP by displacing conventional fossil fuel energy. Bottom ash recycling offset impacts in ADP and MAETP, by displacing landfill impacts.

The integration of CCS into the EfW system resulted in a reduction in GWP compared to a standalone EfW, demonstrating the effectiveness of post-combustion carbon capture using MEA in mitigating direct stack emissions. However, production and disposal of MEA, higher ammonia consumption, and construction of carbon capture infrastructure increased impacts in all other categories. This is due to the formation of persistent organic compounds and degradation by-products, because of increased fossil fuel use and raw material extraction including metals and concrete. Furthermore, the reduction in energy recovery further diminished the system's potential to offset fossil fuel consumption, limiting the benefits typically associated with energy displacement in EfW systems. While CCS reduces GWP, it also raises chemical and energy demands, raising concerns for the overall environmental benefit of integrating CCS into EfW systems.

5. Discussion

There are opportunities and challenges for the deployment of EfW + CCS systems. On the one hand, there is a significant improvement in the climate performance of EfW systems with the addition of CCS with an 80% capture rate indicated by the 33% decline in GWP, with similar trends observed in previous literature (Paulillo et al., 2024). However, CCS imposes a 35% energy penalty resulting in reduced net electricity and heat output of EfW systems, comparable to 11–40% energy penalties observed in the power sector (House et al., 2009). Additionally, CAPEX and OPEX both increased by 30% in the EfW + CCS system compared to standalone EfW. CCS CAPEX of £227/t CO_2 captured aligns with literature ranges of £70-300/t CO_2 (Baltac et al., 2024). As a result of these higher costs, the LCOE of EfW + CCS increased to £163/MWh, which is higher than the UK wholesale electricity price of £127/MWh. However, this comparison is indicative only, as the revenue assumptions and market price are not directly equivalent. This suggests that electricity from the current UK energy mix, a combination of fossil fuels, renewables and nuclear, is generally cheaper than power generated by EfW + CCS. Despite this, the CCS unit within the EfW + CCS system is internally supplied but at the expense of reduced net export.

However, following further analysis for both economic and environmental impacts, suggestions can be made to strengthen the investment in EfW + CCS as a sustainable waste management strategy and a source of renewable energy. In the UK, the presence of an established EfW fleet presents an opportunity to leverage economies of scale, particularly by targeting larger facilities for CCS integration. Larger capacity facilities (>250 ktpa) can benefit from lower unit costs for CO_2 capture and compression, improving economic viability, as shown in Fig. 5. The present study shows that for an average UK EfW capacity of 200-300 ktpa, a government subsidy of £174-214/t CO_2, £162-200/t CO_2 and £152-188/t CO_2 captured is required for 70%, 80% and 90% capture efficiencies respectively, to incentivise initial investment in EfW + CCS against current UK ETS carbon price of £49.4/t CO_2 (Department for Energy Security and Net Zero, 2025b). These are consistent with existing government support mechanisms such as the Industrial Carbon Capture Business Model (Department for Energy Security and Net Zero, 2023b). For a 250 ktpa facility with 80% capture rate, the inclusion of the subsidy reduces payback period to 3.3 years and increases ROI to 21%. As an emerging technology, this would support initial costs and help encourage foreign investment. Although, CO_2 transport and storage

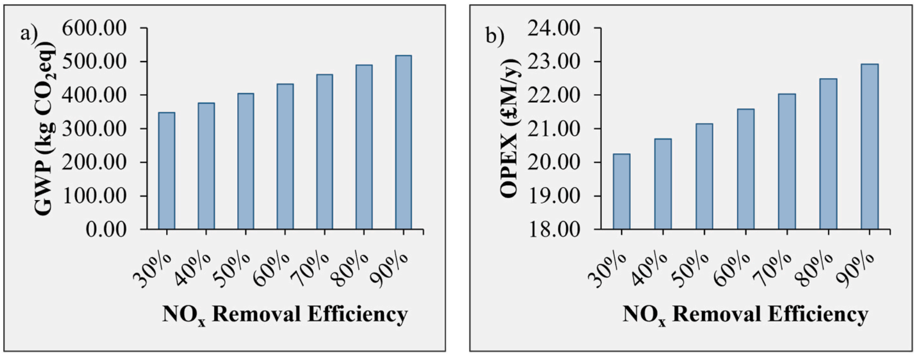


Fig. 9. Sensitivity of NO_x removal efficiency of EfW + CCS system including a) GWP and b) OPEX.

costs are assumed based on literature values and are not site-specific. Additionally, the LCOE of standalone EfW is comparable to current gate fees of £117/t MSW. Therefore, to support the deployment of EfW + CCS systems, it is recommended to raise gate fees in line with the higher LCOE to incentivise investment.

From an environmental perspective there is a trade-off between lower GWP and overall life cycle environmental impacts. The integration of CCS leads to an increase in the use of reagents including ammonia for flue gas cleaning. Sensitivity analysis, as shown in Fig. 9a with full inventory in Table S12 of Supplementary Material, indicates that GWP values vary with NO_x removal efficiencies in the EfW + CCS system. Higher NO_x removal results in a greater GWP impact due to increased ammonia use. The lowest GWP values occur consistently at 30% NO_x removal efficiency, driven by reduced ammonia demand. However, this environmental benefit is offset by increased NO_x emissions, which elevate HTP by 3%, AP by 252% and EP impacts by 246% compared to the present study of just above 80% NO_x removal efficiency, due to additional nitric oxide and nitrogen dioxide emissions. On the other hand, the present study also shows that ammonia use contributes to 23% of total operating costs in EfW + CCS system. Fig. 9b shows the relationship between NO_x removal efficiency and OPEX, with a reduction of 6% (£1.3 M/y) in OPEX from 60% to 30% NO_x emissions removal. APC units typically achieve 30-60% efficiency in EfW systems (Asghar et al., 2021; Van Caneghem et al., 2016). Therefore, for 60% NO_x removal efficiency, GWP reduces to 433 kg CO_2-eq/t MSW with an OPEX of £21.6 M/y for EfW + CCS systems. This, in combination with the government subsidy of £178/t CO_2 recommended from this study for EfW + CCS systems of 250 ktpa capacity and 80% capture rate, results in an economic potential of £49.9 M/y, a ROI of 22% and payback period of 3.2 years. This highlights the importance of government support and the optimisation of EfW + CCS systems to ensure economic viability and sustainable long-term implementation.

6. Conclusions

This study comprehensively assessed the techno-economic performance and environmental impacts of the integration of EfW with CCS as a potential pathway for decarbonising the UK waste management sector. The technical implementation of CCS introduces an energy penalty due to the additional energy required for CO_2 capture and compression. Furthermore, the EfW + CCS system incurs higher capital and operational costs and generates lower revenues but has an overall positive economic potential. Additionally, EfW + CCS offers environmental benefits, including an 80% capture rate and 33% reduction in GWP compared to standalone EfW. Environmental impacts, including ADP, MAETP, FAETP, HTP and TETP, increased due to MEA production and carbon capture infrastructure in the EfW + CCS system. Recommendations are made to reduce initial CCS investment costs by introducing a subsidy of £178/t CO_2 for EfW + CCS capacity of 250 ktpa and 80% capture rate. Furthermore, NO_x removal efficiency plays a role on GWP and OPEX of the integrated system due to ammonia use for flue gas cleaning, with 60% NO_x removal efficiency reducing GWP by 41% in comparison to standalone EfW.

Further research is required to evaluate alternative EfW technologies, particularly gasification, for its potential to enhance the performance of EfW + CCS systems and to reduce the associated energy penalty. In addition, the role of carbon pricing mechanisms should be explicitly incorporated into the assessment of standalone EfW facilities, enabling a more robust comparison with EfW + CCS configurations, particularly under future scenarios of the UK Emissions Trading Scheme. Additionally, alternative carbon capture technologies should be evaluated to provide a deeper understanding of system-wide feasibility. Such efforts are necessary to advance EfW + CCS as an economically viable and sustainable solution for waste management.

The limitations of this study include assumptions regarding CO_2 transport and storage costs andenvironmental impacts, as well as carbon capture infrastructure within the LCA. As these assumptions influence the results, particularly ecotoxicity impacts in EfW + CCS systems, the findings should be interpreted with caution. In addition, uncertainty in the process simulation model was not propagated into the TEA and LCA assessments. While the results remain valid under the assumed conditions, this limits the ability to fully characterise uncertainty and may influence the robustness of the conclusions. Therefore, the recommendations to incentivise EfW + CCS systems, including the proposed subsidy, should be considered in light of these limitations.

Rights retention statement

CRediT authorship contribution statement

Janna Aljoubory: Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Eleni Iacovidou:** Conceptualization, Validation, Writing – review & editing. **Kok Siew Ng:** Conceptualization, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.148920.

Data availability

The data have been provided in the Supplementary Materials.

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