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

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Supplementary Material

Table S1 CAPEX breakdown for EfW and CC

Capital Expenditure (£M)	Calculations
Total Direct Cost (TDC)	Sum of Equipment Costs
Total Indirect Cost (TIC)	50% TDC
Bare Erected Cost (BEC)	TDC+TIC
Engineering and Contractor (EC)	27% BEC
Engineering Procurement and Construction (EPC)	127% BEC
Process Contingency (PC)	25% BEC
Project Contingency (PJC)	20% EPC + 5% BEC
Total Plant Cost (TPC)	120% EPC + 30% BEC
Owner's Cost (OC)	15% TPC
Total Capital Expenditure	TDC+TIC+EC+PC+PJC+OC

Table S2 Specifications for unit operations for EfW and CC systems used in process simulation model

System	Block Name	Aspen Block Model	Block Properties	Value
EfW	Combustion Chamber	RStoic	Temperature	1100 °C
			Pressure	1 bar
	Heat Exchanger	HeatX	Hot stream outlet temperature	120 °C
	CHP Unit	Compr	Type	Isentropic
			Discharge pressure	2 bar
			Isentropic efficiency	0.9
	APC Unit	RStoic	Temperature	120 °C
			Pressure	1 bar
CC	Absorber	RadFrac	Temperature	30 °C
			Pressure	1.5 bar
			Stages	10
	Heat Exchanger	HeatX	Cold stream outlet temperature	70 °C
	Stripper	RadFrac	Temperature	100 °C
			Pressure	2.1 bar
			Stages	12
			Condenser	Partial-Vapour
			Reboiler	Kettle
			Reflux Ratio	1.5
			Bottoms to Feed Ratio	0.98 mole
	CO_2 Compression	Compr	Isentropic Efficiency	0.9
			Mechanical Efficiency	0.8
			Pressure	Stage 1: 7.4 bar Stage 2: 27 bar Stage 3: 100 bar

Table S3 Ultimate Analysis of MSW reproduced from (Becidan, Sørum and Lindberg, 2010)

Component	% w.t based on dry basis
Carbon	39.5
Hydrogen	5.0
Oxygen	26.5
Nitrogen	1.5
Sulphur	0.3
Chlorine	0.7
Ash	26.5

Table S4 Full list of equipment costs of EfW and CC systems

List of Equipment		Cost (£M)
EfW	Waste Handling	0.04
	Incinerator	8.77
	Flue Gas Treatment Plant	21.7
	CHP Plant	25.0
	Total EfW Direct Cost (£M)	**55.5**
CC	Absorber	0.62
	Blower	8.41
	Compressors	3.60
	Lean Solvent Pump	0.01
	Rich Solvent Pump	0.22
	Wash Pump	0.01
	Wash Column	0.48
	Wash Heat Exchanger	0.04
	Separator	0.03
	Stripper	1.26
	Heaters	0.40
	Flashes	0.07
	Total CC Direct Cost (£M)	**15.2**

Table S5 Operating cost breakdown of EfW and CCS systems

EfW and CCS Operating Costs		Cost (£M/y)
EfW	Ammonia	3.7
	Sodium Bicarbonate	1.6
	Water Supply	0.7
	Bottom Ash Management	1.3
	Fly Ash Management	1.5
	Total Variable Costs (£M/y)	8.8
	Total Fixed Costs (£M/y)	5.2
	Total EfW Operating Costs (£M/y)	**14.0**
CCS	Ammonia	1.1
	MEA Make-up	2.6
	Water Supply	0.02
	Total Variable Costs (£M/y)	3.7
	Total Fixed Costs (£M/y)	1.4
	CO_2 Transport (£M/y)	0.18
	CO_2 Storage (£M/y)	0.09
	Total CCS Operating Costs (£M/y)	**5.4**

Table S6 Sensitivity analysis of cost of unit of electricity (per kWh) on economic indicators including EcP, NPV and ROI for EfW and EfW+CCS systems

Electricity Price		**EcP (£M)**		**NPV (£M)**		**ROI (%)**	
		EfW	EfW+CCS	EfW	EfW+CCS	EfW	EfW+CCS
12.95 p/kWh	Low (-30%)	24.0	12.0	147.3	-15.5	13.7%	5.3%
18.50 p/kWh	Central	32.6	18.5	240.0	55.1	18.7%	8.1%
24.05 p/kWh	High (+30%)	41.2	25.1	332.7	125.7	23.6%	11.0%

Table S7 Levelised cost of electricity breakdown for EfW and EfW+CCS systems

Year	EfW Electricity Generated (MWh)	EfW Discounted OPEX (£M)	EfW+CCS Electricity Generated (MWh)	EfW+CCS Discounted OPEX (£M)
1	155393.7	18.2	118318.2	23.6
2	155393.7	15.6	118318.2	20.2
3	155393.7	14.4	118318.2	18.7
4	155393.7	13.4	118318.2	17.3
5	155393.7	12.4	118318.2	16.1
6	155393.7	11.5	118318.2	14.9
7	155393.7	10.6	118318.2	13.8
8	155393.7	9.8	118318.2	12.7
9	155393.7	9.1	118318.2	11.8
10	155393.7	8.4	118318.2	10.9
11	155393.7	7.8	118318.2	10.1
12	155393.7	7.2	118318.2	9.4
13	155393.7	6.7	118318.2	8.7
14	155393.7	6.2	118318.2	8.0
15	155393.7	5.7	118318.2	7.4
16	155393.7	5.3	118318.2	6.9
17	155393.7	4.9	118318.2	6.4
18	155393.7	4.6	118318.2	5.9
19	155393.7	4.2	118318.2	5.5
20	155393.7	3.9	118318.2	5.1
21	155393.7	3.6	118318.2	4.7
22	155393.7	3.3	118318.2	4.3
23	155393.7	3.1	118318.2	4.0
24	155393.7	2.9	118318.2	3.7
25	155393.7	2.7	118318.2	3.4
Total	**3884842.5**	**195.3**	**2957955.0**	**253.5**

Working example:

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

a) $\text{EfW LCOE (£/MWh)} = \frac{£(174.7+195.3)\text{M}}{3884842.5\ \text{MWh}} = \frac{£(370\times1000000)}{3884842.5\ \text{MWh}} = 95.2$

b) $\text{EfW+CCS LCOE (£/MWh)} = \frac{£(227.7+253.5)\text{M}}{2957955.0\ \text{MWh}} = \frac{£(481.2\times1000000)}{2957955.0\ \text{MWh}} = 162.7$

Table S8 Life cycle inventory of EfW and EfW+CCS systems based on 1 tonne of MSW incinerated.

Inputs	Units	EfW	EfW+CCS	Source of Data
Sodium Bicarbonate	kg	26.0	26.0	Simulation Model
Ammonia	kg	79.6	95.2	Simulation Model
Water	kg	3120.0	3120.0	Simulation Model
Monoethanolamine	kg	-	15.9	Simulation Model
Emissions to Air				
CO_2 (Fossil)	kg	580.9	114.5	Simulation Model
CO_2 (Biogenic)	kg	580.9	114.5	Simulation Model
CO	kg	0.024	0.024	(Jeswani and Azapagic, 2016)
NO_2	kg	16.9	16.9	Simulation Model
NO	kg	16.9	16.9	Simulation Model
HCl	g	32.9	32.9	(Jeswani and Azapagic, 2016)
SO_2	g	75.0	75.0	(Jeswani and Azapagic, 2016)
HF	g	1.1	1.1	(Jeswani and Azapagic, 2016)
NH_3	g	0.4	0.4	(Jeswani and Azapagic, 2016)
MEA	kg	-	8.2	(Jeswani and Azapagic, 2016)
Energy Consumed				
Electricity	kWh	95.7	95.7	(Tolvik Consulting Ltd, 2025)
Energy Recovered				
Electricity	kWh	621.6	473.4	Simulation Model
Ash/Residues				
Bottom Ash	kg	212.0	212.0	Simulation Model
APC Residues	kg	30.0	30.0	Simulation Model
Infrastructure				
Incineration	p	2.50×10^{-7}	2.50×10^{-7}	Simulation Model
CHP Unit	p	5.0×10^{-6}	5.0×10^{-6}	Simulation Model
Carbon Capture Infrastructure	p	-	4.0×10^{-7}	Simulation Model

Table S9 Total environmental impacts of EfW from SimaPro

Impact Category	Total Emissions (inc. system credits)	EfW Emissions to Air	Ammonia	Water	Sodium Bicarbonate	Incineration Infrastructure	CHP Infrastructure	Electricity Consumption	Electricity Generated	Ash Recycling	Flyash Landfill
ADP (MJ)	1839.30	0.00	2907.48	2.58	629.08	41.45	8.47	796.11	-2546.06	-7.60	7.79
GWP (kg CO_2 eq)	735.14	580.91	210.57	0.16	67.64	4.16	0.87	47.84	-176.71	-0.59	0.28
ODP (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTP (kg 1,4-DB eq)	298.67	43.86	73.87	0.10	160.78	5.46	5.06	4.11	-40.99	-0.10	46.51
FAETP (kg 1,4-DB eq)	155.28	0.01	43.20	0.12	72.01	5.32	2.27	2.79	-26.23	-0.07	55.86
MAETP (kg 1,4-DB eq)	306218.38	44770.00	61882.35	128.45	131713.32	6707.83	2481.59	4044.80	-58191.03	-134.67	112815.75
TETP (kg 1,4-DB eq)	1.82	0.00	0.82	0.00	1.39	0.08	0.14	0.03	-0.64	0.00	0.00
POCP (kg C_2H_4 eq)	0.03	0.00	0.02	0.00	0.02	0.00	0.00	0.00	-0.02	0.00	0.00
AP (kg SO_2 eq)	17.67	17.05	0.24	0.00	0.66	0.01	0.00	0.04	-0.33	0.00	0.00
EP (kg PO_4-eq)	4.59	4.41	0.07	0.00	0.18	0.01	0.00	0.01	-0.10	0.00	0.02

Table S10 Total environmental impacts of EfW+CCS from SimaPro

Impact Category	Total Emissions (inc. system credits)	EfW+CCS Emissions to Air	Ammonia	Water	Sodium Bicarbonate	Incineration Infrastructure	CHP Infrastructure	CC Infrastructure	MEA	Electricity Consumption	Electricity Generated	Ash Recycling	Flyash Landfill
ADP (MJ)	4500.00	0.00	3477.29	2.58	629.08	41.45	8.47	552.91	906.01	796.11	-1939.13	-7.60	7.79
GWP (kg CO_2 eq)	448.87	114.45	251.84	0.16	67.64	4.16	0.87	53.72	41.14	47.84	-134.59	-0.59	0.28
ODP (kg CFC-11 eq)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HTP (kg 1,4-DB eq)	2023.17	43.86	88.35	0.10	160.78	5.46	5.06	670.02	1029.29	4.11	-31.22	-0.10	46.51
FAETP (kg 1,4-DB eq)	468.70	0.01	51.66	0.12	72.01	5.32	2.27	282.18	15.77	2.79	-19.98	-0.07	55.86
MAETP (kg 1,4-DB eq)	738803.35	44770.00	74010.04	128.45	131713.32	6707.83	2481.59	376560.21	27460.59	4044.80	-44319.44	-134.67	112815.75
TETP (kg 1,4-DB eq)	8.12	0.00	0.98	0.00	1.39	0.08	0.14	5.74	0.24	0.03	-0.49	0.00	0.00
POCP (kg C_2H_4 eq)	0.07	0.00	0.02	0.00	0.02	0.00	0.00	0.03	0.01	0.00	-0.02	0.00	0.00
AP (kg SO_2 eq)	18.49	17.05	0.28	0.00	0.66	0.01	0.00	0.57	0.11	0.04	-0.25	0.00	0.00
EP (kg PO_4-eq)	4.95	4.41	0.08	0.00	0.18	0.01	0.00	0.22	0.10	0.01	-0.07	0.00	0.02

Table S11 Inventory used from Ecoinvent database for life cycle inventory of EfW and EfW+CCS

Inputs	Ecoinvent database inventory
Ammonia	Ammonia, anhydrous, liquid {RER w/o RU}| ammonia production, steam reforming, liquid | Cut-off, U
Water	Water, decarbonised {GB}| market for water, decarbonised | Cut-off, U
Sodium Bicarbonate	Neutralising agent, sodium hydroxide-equivalent {GLO}| sodium bicarbonate, to generic market for neutralising agent | Cut-off, U
Incineration Infrastructure	Municipal waste incineration facility {GLO}| market for municipal waste incineration facility | Cut-off, U
CHP Infrastructure	Heat and power co-generation unit, organic Rankine cycle, 1000kW electrical {GLO}| heat and power co-generation unit construction, organic Rankine cycle, 1000kW electrical | Cut-off, U
Carbon Capture Infrastructure	Chemical factory, organics {RER}| chemical factory construction, organics | Cut-off, U
MEA	Monoethanolamine {RER}| ethanolamine production | Cut-off, U
Electricity Consumed	Electricity, high voltage {GB}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U
Electricity Generated	Electricity, high voltage {GB}| electricity, high voltage, production mix | Cut-off, U
Ash Recycling	Process-specific burdens, slag landfill {Europe without Switzerland}| process-specific burdens, slag landfill | Cut-off, U
Flyash Landfill	Hard coal ash {RoW}| treatment of hard coal ash, residual material landfill | Cut-off, U

Table S12 Inventory data for sensitivity analysis of NO_x removal efficiencies (30-90%) on GWP and OPEX in EfW+CCS systems

NO_x Removal Efficiency	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**
EfW Ammonia Consumption (kg/t MSW)	29.0	38.7	48.4	58.0	67.7	77.4	87.1
EfW+CCS Ammonia Consumption (kg/t MSW)	44.6	54.3	64.0	73.6	83.3	93.0	102.7
EfW Ammonia Consumption (t/y)	7254.6	9672.8	12091.0	14509.2	16927.4	19345.6	21763.8
EfW+CCS Ammonia Consumption (t/y)	11154.6	13572.8	15991.0	18409.2	20827.4	23245.6	25663.8
NO_x Emissions (kg/t MSW)	129.2	110.7	92.3	73.8	55.4	36.9	18.5
NO_x Emissions (t/y)	32291.9	27678.8	23065.7	18452.5	13839.4	9226.3	4613.1
GWP (kg CO_2 eq/t MSW)	348	376	405	433	461	490	518
AP (kg SO_2 eq /t MSW)	74	64	53	43	33	22	12
EP (kg PO_4- eq /t MSW)	17.3	14.9	12.5	10.1	7.7	5.3	2.9
HTP (kg 1,4-DB eq /t MSW)	2340	2326	2311	2296	2281	2267	2252
Ammonia Cost (£M/y)	2.1	2.5	3.0	3.4	3.8	4.3	4.7
Total EfW+CCS OPEX (£M/y)	20.3	20.7	21.1	21.6	22.0	22.5	22.9

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