



**Programme Area:** Bioenergy

**Project:** Energy From Waste

**Title:** UK Benefits Case Report – Compatibility with CCS

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### Abstract:

Energy can be recovered from waste through either direct mass burn in a waste-to-energy (W2E) process or through the combustion in an engine or gas turbine of syngas or biogas generated through thermochemical or biochemical treatment (Energy from Waste, EfW). In general, EfW plants offer higher conversion efficiencies and correspondingly improved environmental performance (reduced emissions to atmosphere). However, the composition of the available waste types is derived from a mix of biogenic and fossil sources, making the CO<sub>2</sub> emitted a potential problem in the future if it is not treated as fully renewable, and hence avoids carbon taxes. At the current time, the energy from all 'advanced conversion' processes are favoured within UK support measures for the introduction of renewable energy schemes, but this also may not continue in the future.

This report provides a preliminary review of the issues surrounding the introduction of carbon capture technologies to EfW plants. If viable, this approach would offer means of eliminating the fossil-derived CO<sub>2</sub> emissions, providing 'negative' CO<sub>2</sub> emissions through the parallel removal of biomass derived CO<sub>2</sub>, although the benefits from this are not currently recognised by EU legislation.

### Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: <http://www.eti.co.uk/insights>

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**ETI**

**UK Benefits Case Report – Compatibility with CCS**

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**August 2011**

## **1 Introduction**

Energy can be recovered from waste through either direct mass burn in a waste-to-energy (W2E) process or through the combustion in an engine or gas turbine of syngas or biogas generated through thermochemical or biochemical treatment (Energy from Waste, EfW). In general, EfW plants offer higher conversion efficiencies and correspondingly improved environmental performance (reduced emissions to atmosphere). However, the composition of the available waste types is derived from a mix of biogenic and fossil sources, making the CO<sub>2</sub> emitted a potential problem in the future if it is not treated as fully renewable, and hence avoids carbon taxes. At the current time, the energy from all 'advanced conversion' processes are favoured within UK support measures for the introduction of renewable energy schemes, but this also may not continue in the future.

This report provides a preliminary review of the issues surrounding the introduction of carbon capture technologies to EfW plants. If viable, this approach would offer means of eliminating the fossil-derived CO<sub>2</sub> emissions, providing 'negative' CO<sub>2</sub> emissions through the parallel removal of biomass derived CO<sub>2</sub>, although the benefits from this are not currently recognised by EU legislation.

The report focuses on the technical issues surrounding the application of carbon capture and transport to suitable storage locations; with the impact of this approach on capital and operating costs is beyond the scope of the current work. Before exploring the available capture technologies and their compatibility with EfW schemes, it is worthwhile to review the availability of waste resources and the split between the fossil- and biomass-derived components now and in the future. Following this analysis, the report reviews the available technologies and summarises the benefits and constraints from their application, followed by consideration of the transport options from the distributed network of EfW plants as described in the main project.

## **2 CO<sub>2</sub> emissions and biogenic fraction**

The carbon content of the waste streams considered in for EfW project is from a mixture of biological and fossil sources. The biogenic content of the waste is viewed as available for the generation of renewable energy. Table 1 provides the proportions of qualifying biogenic carbon content for the waste material used in the EfW project with future projection out to 2050. The methodology for estimating the biogenic content was based on the criteria provided by OFGEM in their recent guidance document (2011). The waste materials used in the calculations are based on average UK compositions, with that from food and other organics being treated as main source of the biogenic content.

The qualifying biogenic percentage in the waste streams was calculated based on gross CV and weight percentage of each component in the waste stream. Table 2 provides the worked example for a municipal waste mix in the OFGEM report. This shows that even if the component would normally be considered as 100% biomass-derived (giving it a biodegradable content of 1), the qualifying percentage is not same as its wt % in a mixed waste composition due to its lower CV.

The biogenic carbon releases from EfW plants, whether or not included in greenhouse gas accounting is controversial. The IPCC (2006) guidelines for national greenhouse gas (GHG) inventories concludes that biogenic CO<sub>2</sub> released from incinerators should not be included in the energy section of GHG accounts. Similarly, it could be argued that biogenic releases of CO<sub>2</sub> from EfW plants should also not be included in the total emissions.

The waste flow model presented in the main EfW project reports takes account of the annual growth of waste arisings and provided simulated composition variations based on future recycling targets. As the recycling rates increase, the composition of the residual stream changes accordingly. The impacts on the percentage content of potentially recyclable materials such as paper, card, metals, glass and plastics are significant. For example, paper and card materials currently comprise a relatively high proportion of residual wastes (~14%), and as such represent large quantities of material which could be removed with effective recycling schemes. Food wastes are also being targeted under recent recycling schemes, as these are increasingly attractive for treatment in biological processes such as anaerobic digestion (AD). The

paper, card and organics components of residual wastes are the major contributors to the qualifying biomass fractions for energy recovery; the reduction of these components by future recycling activities subsequently reduces the biomass fraction of residual wastes which are shown in Figure 1. This illustrates that the overall amount of waste available for energy generation will fall in the future and the proportion of biogenic materials in the mix is also likely to fall. These factors have a direct impact on the overall benefits to the UK in applying COP2 capture to such schemes, in the context of the general increase in electricity and heat use expected in the future.

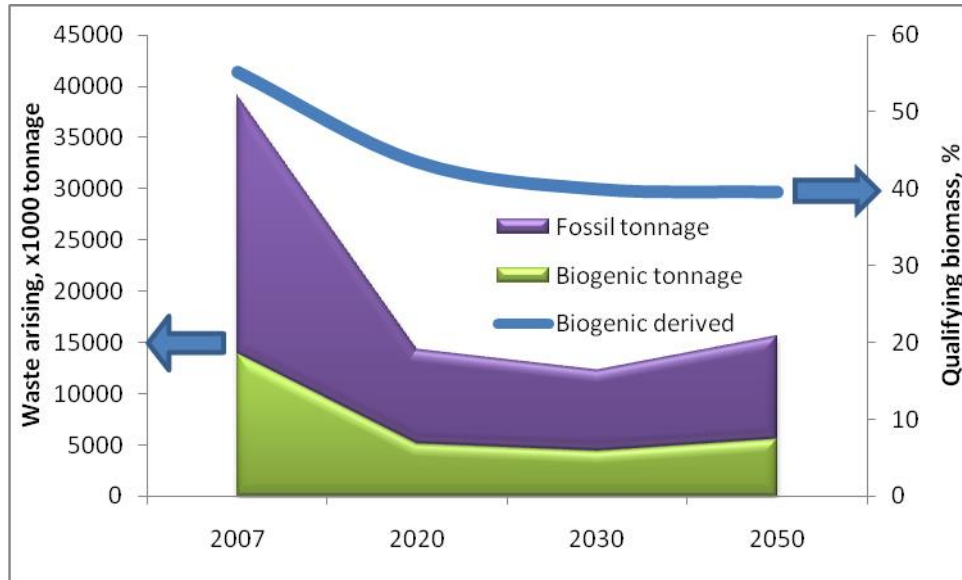


Figure 1: Future projections of qualifying biomass percentage and tonnage in average waste arising in UK.

Table1: Proportions of qualifying biogenic carbon content for future projections based on EfW report.

Material	Biodegradable content	GCV MJ/Kg	% composition				Qualifying biogenic %				Fossil tonnage x1000			
			2007	2020	2030	2050	2007	2020	2030	2050	2007	2020	2030	2050
Paper & card	1	15.6	32	14.02	8.6	8.06	35.44	15.53	9.53	8.92	5207.36	1386.02	851.84	1030.36
Film plastics	0	41.3	7	14.63	16.9	17.17	0.00	0.00	0.00	0.00	1764.40	1712.61	1852.81	2411.10
Dense plastics	0	35.2	8	3.51	2.2	2.01	0.00	0.00	0.00	0.00	2016.46	410.20	235.39	282.82
Textiles	0.5	20.7	2	4.18	4.8	4.91	1.47	3.07	3.56	3.60	496.71	474.28	510.56	664.06
Other combustibles	0.8	10	16	33.45		39.24	9.09	19.00		22.29				
					38.7				21.98		3666.45	3170.86	3304.03	4282.86
Glass	0	0	4	1.75	1.1	1.01	0.00	0.00	0.00	0.00	1008.23	205.10	117.70	141.41
Other non-combustibles	0	0	6	12.54		14.72	0.00	0.00		0.00				
					14.5				0.00		1512.35	1467.95	1588.12	2066.65
Food	1	8.1	13	5.70	3.5	3.27	7.48	3.28	2.01	1.88	3031.80	644.74	374.83	450.93
Other organics	1	8	2	4.18		4.91	1.14	2.37		2.79				
					4.8				2.75		498.39	477.70	514.83	669.69
Metal	0	0	4	1.75	1.1	1.01	0.00	0.00	0.00	0.00	1008.23	205.10	117.70	141.41
Household hazardous	0	0	1	2.09		2.45	0.00	0.00		0.00				
					2.4				0.00		252.06	244.66	264.69	344.44
WEEE	0	0	1	0.44	0.3	0.25	0.00	0.00	0.00	0.00	252.06	51.28	29.42	35.35
Fines	0.5	4	4	1.75	1.1	1.01	0.57	0.25	0.15	0.14	1002.51	204.59	117.52	141.21
<b>Total</b>							55.18	43.50	39.98	39.62	13907.38	5090.25	4374.30	5564.60

Used specification standard: CEN/TS 15747:2008

Table 2 Example calculation for qualifying % for waste stream

Primary category	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
	% Contribution by weight	Gross CV	Weight X GCV	% by GCV	Biodegradable content	Qualifying %
Paper and card	30	12.5	375	25.2	1	25.2
Textiles	70	15.9	1113	74.8	0.5	37.4
<b>TOTALS</b>	100	-	1488	100	-	62.6

### 3 The Application of CO<sub>2</sub> capture technologies to EfW Plants

Energy from waste greenhouse gas emissions could be easily reduced by the implementation of CO<sub>2</sub> capture technologies on EfW plants, but that would increase costs significantly, as it will for all fossil-fuel electricity generation technologies. However, the pro-rata increase would be even higher for EfW plants if 90% capture were assumed as the target due to their relatively small size and distributed nature.

Among the technologies used for separating and capturing CO<sub>2</sub> are methods based on absorption (using, for example, amine-based absorbents), adsorption, membrane separation, cryogenics, compression, etc. An overview of CO<sub>2</sub> capture technologies is illustrated in the following flow chart (Figure 2). Hybrid technologies also exist that integrate carbonate or amine based absorbents with membrane separation units as well as other possibilities such as biological units using enzymes or the use of ionic liquids. Table 3 provides the main characteristics of the technologies used in Figure 2, relevant to the issues being considered in this report.

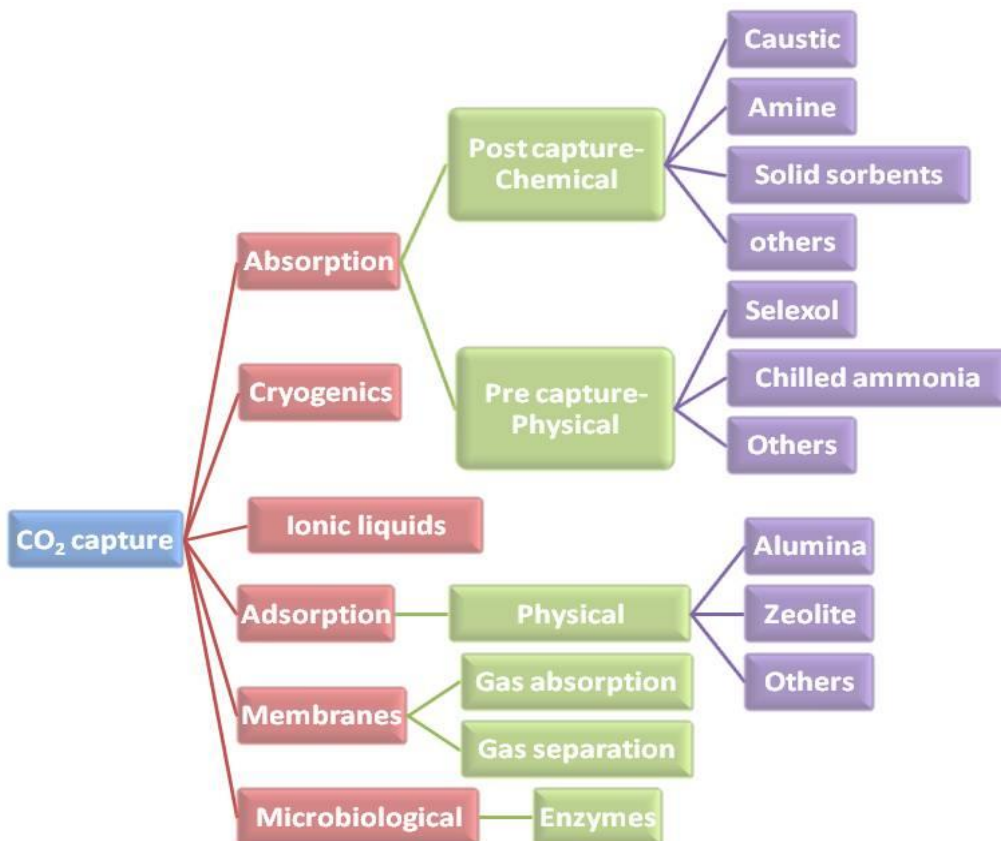


Figure 2: overview of CO<sub>2</sub> capture processes based on unit operations

**Table3: Review of CO<sub>2</sub> capture technologies and the characteristics**

	Temperature, deg	Pressure, bar	Energy, GJ/t	Scale/maturity
Post-combustion capture				
Amine	20 - 50	>1	1.0 – 1.8	Demo/pilot plant
Other & hindered amines	110	>1		Long history of commercial applications
Hot potassium carbonate	120	>2		Demo
Ionic liquid	40-110	>1	3.4-4.2	Small pilot plant
Ca looping	>600	>1		Demo/pilot plant
Pre-combustion capture				
Chilled ammonia	0-10	>20		Demo plant
Selexol	30 - 45	>20	0.5 – 1.2	Demo/pilot plant
Membrane	30	>20		No commercial application
Activated carbon, MOF's	30	>40		Novel methods
Oxy capture	5–35	1.1 – 110	0.5 – 0.8	Pilot plant
Chemical looping	>800			2 <sup>nd</sup> generation technology

It is technically possible for EfW plants to be configured to work with CO<sub>2</sub> removal using any of the main options. Pre-combustion capture is essentially equivalent to a gas upgrading process and so could be used to provide a syngas with an increased CV; this could be stored if necessary for future use (as could the raw syngas) to help even out demand cycles. The likely CO<sub>2</sub> removal integration approaches are shown in Figure 3.

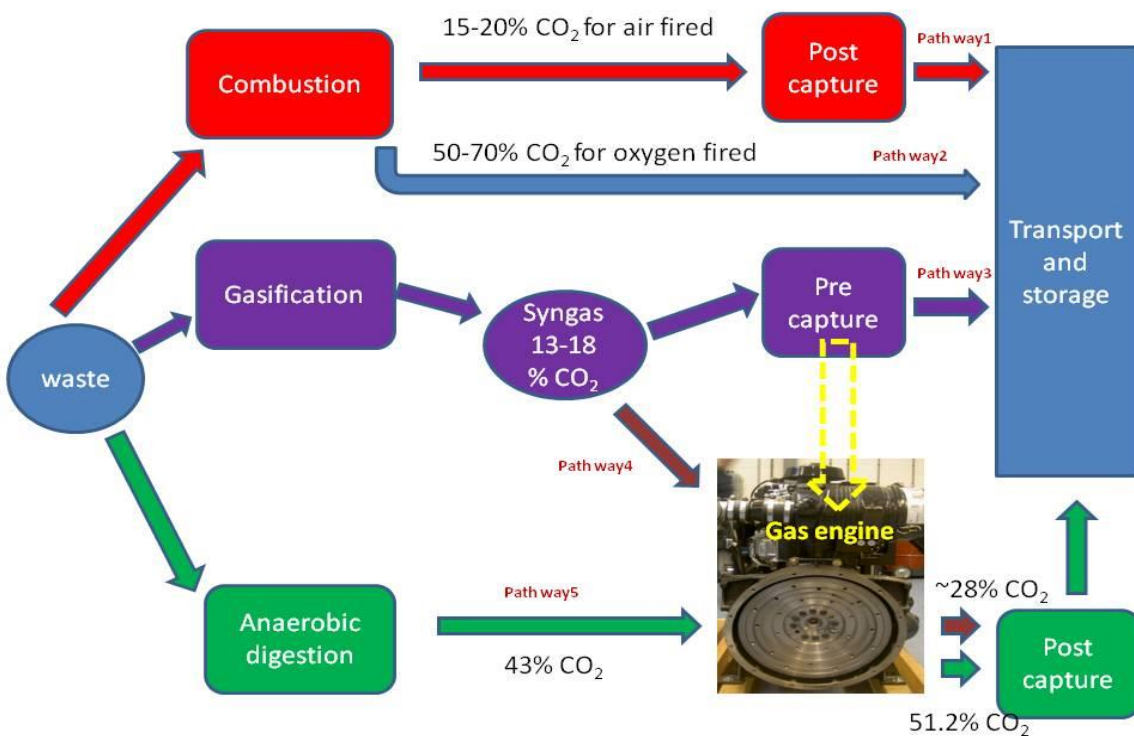


Figure 3: Options for the integration of CO<sub>2</sub> removal technologies in EfW plants.

Based on different pathways identified for CO<sub>2</sub> capture processes for different technologies, the Table 4 provides a summary of gas compositions for syngas and flue/exhaust gases related to the pathways. The calculations were performed based on thermodynamic equilibrium models with excess air of 10 % in a combustion engine and 400 % in a gas turbine

**Table 4: Typical flue gas compositions of different technologies**

Technologies	Gas Composition [%v/v]					Burned gas [%v/v]	
	CO <sub>2</sub>	CO	CH <sub>4</sub>	H <sub>2</sub>	N <sub>2</sub>	CO <sub>2</sub>	N <sub>2</sub>
<b>Incineration</b>						8.5	79.2
<b>Fluidised Bed gasifier</b>	17.3	10.6	4.7	3.8	61.6	Engine Gas Turbine	26.0 6.4 62.4 80.2
<b>Downdraft gasifier</b>	13.8	9.4	2.4	4.2	69.1	Engine	27.5 63.2
<b>Anaerobic Digestion</b>	43		57			Engine	51.2 48.8

The issues associated with each of the pathways highlighted are presented below.

Pathway 1 – Post-combustion capture following mass burn incineration: Using current technology, the flue gas from the combustion process (15-20 % CO<sub>2</sub>) must first be cleaned of impurities such as SO<sub>x</sub>, NO<sub>x</sub>, trace metals, etc using scrubbers, cyclones, electrostatic precipitators, bag filters, etc in order to comply with the Waste Incineration directive. This will leave the flue gas sufficiently clean for an amine scrubber or an equivalent post-combustion approach to work and the flue gas CO<sub>2</sub> concentration is within the normal range for such processes. Other approaches to post-combustion capture are also likely to be viable, although it is not clear whether any option is likely to be economic. The main issues here are for the application of amine scrubbing are the somewhat low concentration of CO<sub>2</sub> in the flue gas and the steam requirement for the stripper, which while only being at a modest temperature would have a large impact on the overall power output from an already low efficiency incineration plant.

Pathway 2 – Oxy-combustion of the waste: The mass burn incineration process is not suited to this approach, which has only been developed so far for pulverised coal combustion and gas- or oil-fired processes. The cost of the oxygen supply plant will be a significant extra capital cost and it is also not clear how the gas recycle (to replace the missing nitrogen in the combustion air) would be handled. The benefits of the approach would be high flue gas CO<sub>2</sub> concentrations and simplified separation processes using a condenser and compressor. Overall, it is highly unlikely that this approach would be economic for a variable, heterogeneous fuel such as waste without major development.

Pathway 3 – Pre-combustion capture from syngas: The removal of CO<sub>2</sub> from syngas using a physical solvent such as selexol is seen a preferred option for large-scale IGCC plants due to the reduced separation costs for the high pressure/high CO<sub>2</sub> concentration gas streams in such plants. While the syngas from a waste gasification scheme would have a reasonable level of CO<sub>2</sub> concentration (13-18 % CO<sub>2</sub>), it is highly unlikely that such plants will be working at high pressures due to the scale of the plant involved. However, there would be an added benefit of this approach as the resultant cleaned syngas would have a higher CV and this may be better suited for storage and subsequent use in engines or gas turbines. Partial CO<sub>2</sub> separation, rather than full separation (as may be required if the objective were to transport and store the CO<sub>2</sub>, may be worth further investigation as the separated CO<sub>2</sub> could be used in the gasification process to further



improve the gas quality. To achieve this, a capture process which could work with the relatively dirty syngas to avoid expensive pre-capture clean-up would be needed, such as the use of a solid sorbent.

Pathway 4 – Post-combustion from the flue gas exhaust from a syngas-burning engine or gas turbine: The CO<sub>2</sub> level in the syngas entering the gas engine or turbine would be as described for Pathway 3, but the levels in the exhaust gases would be very different due to the levels of excess air used in gas engines and turbines. Estimates of these exhaust gas CO<sub>2</sub> concentration are presented in Table 4. The CO<sub>2</sub> level in the exhaust gas from an engine is high at around 26%, significantly above that for which amine-based scrubbing technologies are being developed for coal-fired plants, where it would be in the range 12-15%. Consequently, an amine plant attached to such a system would be handling a lower volume of gas in order to capture the same amount of CO<sub>2</sub>, reducing the capital cost and making it a relatively attractive option. However, if the syngas were burned in a gas turbine, the higher excess air level used would mean the exhaust gas CO<sub>2</sub> concentration would be around 6%, and so an amine plant would be handling 4 times the volume of gas for the same level of capture, making it a much less attractive option.

Pathway 5 – Pre- or post-combustion capture of the CO<sub>2</sub> in biogas. A high level of CO<sub>2</sub> (around 43%) is present in biogas, clearly at a level that would make either pre- or post- combustion capture a reasonable option. Table 5 suggests that if the post-combustion route were used, allowing the capture of the CO<sub>2</sub> from the methane burned as well as that present in the syngas, the concentration in the exhaust would be over 50%, favouring most post-combustion technology options. Even if the gas were in sufficient quantity for a gas turbine to be used, the CO<sub>2</sub> level would be high enough for amine scrubbing to be used. The pre-combustion route would provide a better gas fuel for an engine or turbine, but would not capture any methane-derived CO<sub>2</sub>.

Of the CO<sub>2</sub> capture technologies, those developed to work on gases with a reasonable level of CO<sub>2</sub> at close to atmospheric pressure are the most likely options which could be used in EfW plants. Most of these are focussed on post-combustion applications but some (e.g. Ca looping) are already being developed for pre-combustion/gas upgrading applications. Conversely, those technologies developed for high pressure systems (e.g. pre-combustion capture using selexol or membranes) are unlikely to be viable for EfW plants, as the syngas would have to be cooled and compressed before separation, incurring a large energy penalty. The gas would then have to be brought back to close to atmospheric pressure in order for it to be used in a current combustion engine or gas turbine of a size suitable for EfW use. As discussed above, the oxy-combustion option is also likely to be uneconomic as well as having significant technical challenges for EfW applications.

Table 5 provides a summary of the key issues associated the application of the major CO<sub>2</sub> capture technologies to EfW plants, using a traffic light approach to indicate the most likely viable options.

**Table 5: Technological capture options for EfW plants.**

	Pre-capture				Post capture			oxy fuel/chemical looping
	Selexol	Chilled NH <sub>3</sub>	Membrane	Activated carbon	Amine	Hindered amines	Potassium carbonate	
<b>Incineration</b>	Not applicable				Very clean gas, no pre-treatment required			Expensive to produce O <sub>2</sub>
<b>FB Gasifier</b>	High concentration & compression required	Medium pre-treatment required	Compressor required	Practically feasible for high CO <sub>2</sub> concentration	Low pre-treatment required	Medium pre-treatment required		
<b>Downdraft</b>	High concentration & compression required	Medium pre-treatment required	Compressor required	Practically feasible for high CO <sub>2</sub> concentration	Low pre-treatment required	Medium pre-treatment required		
<b>AD</b>	Not applicable				Pre-treatment required			

As post-combustion technologies are the most likely way forward, if proven to be economic, the next section reviews the technical challenges associated with gas borne impurities in the flue/exhaust gases from which the CO<sub>2</sub> may be captured. For this purpose, only the most developed, amine-based system is

considered. Other systems which are also likely to be technically viable, such as solid sorbents/adsorbents, ionic liquids, membranes, will all have similar issues affecting implementation. Discussion of these in detail is beyond the scope of this report.

#### **4 Effect of impurities for amine based capture plants**

Amine based processes have been used commercially for the removal of acid gas impurities (CO<sub>2</sub> and H<sub>2</sub>S) from process gas streams for many decades; several commercial post-combustion pilot plants are in operation around the world. Impurities/contaminants in process streams such as oxygen, sulphur oxides, nitrogen oxides and particulate matter create special challenges during the separation process. The effects of these impurities are described below - similar types of impurities would be identified from EfW plant gas streams.

**Oxygen:** the solvents applicable for EfW plant gas systems degrade to varying degrees in oxidizing atmospheres. This leads to either high solvent losses or expensive reclaiming processes. Oxygen also causes corrosion problems which can lead to failures. The use of inhibitors in the amine based solvent could reduce degradation and corrosion problems.

**Sulphur oxides:** the element sulphur in the waste fuel could convert into sulphur oxides in EfW plants. The sulphur oxides react with amine solvents to form heat-stable corrosive salts that cannot be reclaimed. The process limits the sulphur oxides to less than 10 ppm level from the EfW plant gases. This can be achieved if some form of flue gas desulfurization unit is installed before the capture process to alleviate the problem.

**Nitrogen Oxides:** A typical EfW plant product gas contains some amount of NO<sub>x</sub>. The main component NO performs as inert gas and would not affect the amine based solvent. However, NO<sub>2</sub> could lead to the formation of a heat stable salt. Reduction of nitrogen oxides is acceptable to alleviate the problem by oxygen fired process rather than air fired. But this option may not be cost effective for EfW plants.

**Particulate matter:** Fly ash in the product gas can cause foaming and degradation of the amine solvent, as well as plugging and scaling of the process reactors. A filtering mechanism has to be implemented to reduce the fly ash content to appropriate levels to abate the aforementioned problems.

In summary, the capture of CO<sub>2</sub> from EfW gases requires a significant amount of pre-treatment processing in order to avoid operational problems in the solvent capture stage, adding to the cost of CO<sub>2</sub> capture.

#### **5 CO<sub>2</sub> volumes and the impact on transport options**

Table 5 provides the CO<sub>2</sub> emission volumes from the various plant options, using the same plant scales as in the main EfW project. This summarises the relative amounts of fossil and biogenic CO<sub>2</sub> as each would be viewed differently in the context of the applicable regulations and support measures, such as ROCs. The figures presented relate only to the gas phase species, i.e. the carbon in tars and solid process residues were not considered as CO<sub>2</sub> producers in the calculations. The table also shows the likely trend in these volumes up to 2050.

The issue here is whether the application of CO<sub>2</sub> capture technology with EfW plants would be viable in terms of scale/volumes collected and whether these volumes are compatible with the available transport options.

Table 6: Proportion of C in waste fuel passing to gas, liquid and solid in several conversion processes

Components	Technologies	Scale [tonnes/y]	C content [%]	C <sub>IN</sub> [tonnes/y]	C <sub>GAS</sub> [%]	C <sub>RES/TAR</sub> [%]	Maximum CO <sub>2</sub> produced [tonnes/year]	CO <sub>2</sub> Fossil/Biogenic [tonnes/y]			
								2007	2020	2030	2050
Paper, plastics, textiles, organics, combustibles, glass & food	Incineration	500,000	49.4	247,000	98	2	887,553	397,801/ 489,751	501,467/ 386,085	532,709/ 354,844	535,905/ 351,648
	Fludised Bed Gasifier	50,000	49.4	24,700	75	25	67,925	30,444/ 37,481	38,378/ 29,547	40,769/ 27,156	41,013/ 26,912
	Downdraft Gasifier	5,000	49.4	2,470	80	20	7,245	3,247/ 3,998	4,093/ 3,152	4,348/ 2,897	4,375/ 2,870
Food	Anaerobic Digestion	5,000	53.5	2,675	15	85	1,471	0/ 1471	0/ 1471	0/ 1471	0/ 1471

There is a clear economy of scale with respect to the use of CO<sub>2</sub> capture, with the likely volumes from waste incineration offering the biggest opportunity as well as being relatively large point sources which would simplify the transport issues and make connection to a pipeline network a possible option. However, if the technologies involved can be simplified for use at smaller scales, other transport options may prove viable.

Once the CO<sub>2</sub> is captured and compressed, the waste derived CO<sub>2</sub> can be transported by land via pipelines, road, barge or rail tankers, or by sea via ships.

In general, pipelines are the most economical method of transporting large quantities of dense phase/supercritical CO<sub>2</sub>. The cost per mile within a given diameter indicates that the longer the pipeline, the lower the unit cost (per mile) for construction. For EfW plants, the pipelines would need to be built near populated areas and these would tend to have higher unit costs. For EfW scenario (incineration) the annual CO<sub>2</sub> flow rates are approximately one million tonnes per year per plant. At these flow rates, transport costs are less and it should prove economic to use pipelines.

Liquefied CO<sub>2</sub> can be transported in tanks conveyed by road/rail/barge in a liquid form using cryogenic storage vessels. These vessels are available in various sizes ranging from 2 to 30 tonnes. Tankers are a flexible, adaptable and reliable means for transporting CO<sub>2</sub>, but much more expensive than pipelining. For downdraft and anaerobic digestion scenarios, tankers would be the best options for transporting the collected CO<sub>2</sub>.

The railway system has a large carrying capacity that enables it to handle large volumes of bulk commodities over long distances. For liquid transport, the net weight a single tank car can load is about 60 tonnes, so several tanks per transfer would be needed depending on the available storage capacity at the source location and the required regularity of removal. Rail transport will only become a competitive transport option for EfW plants if the logistics can fit the volumes in the existing railway system.

Ships can be used for long distance transport of CO<sub>2</sub> across the sea or round the coast of the UK. The size of a ship is typically up to 1500 m<sup>3</sup> (approximately 1000 tonnes), and there is no large ship suited to carrying CO<sub>2</sub> at low pressure. However, liquid petroleum gas tankers could be used for CO<sub>2</sub> transport. This option is more feasible once the captured CO<sub>2</sub> from each EfW scenarios could transport via tanks or railways to nearest port, acting as a hub for the collection of CO<sub>2</sub> from various locations in a region. However, loading and unloading infrastructure and temporary CO<sub>2</sub> storage would have to be included and would be costly.

The overall summary options for transporting CO<sub>2</sub> for EfW plants are given in Table 7.

**Table 7: Transport options for ETI scenarios from EfW plants.**

Technologies	Total emissions 2050, t/yr	CO <sub>2</sub> for	Transport options				Fluid characteristics
			Pipeline	Road tanker	Rail	Ship	
Incineration	887,553		Pipeline				Supercritical or dense phase
Fluidised bed gasifier	67,925			~3 times per year (2X30 & 1x10 tonnes)			Liquefied 17bar, -30 deg
					~1 x60 tonnes system per year		Liquefied 26 bar
Downdraft gasifier	7,245			1 x10 tonnes tank per year		~8 ships per year	Liquefied 17bar, -30 deg
Anaerobic digestion	1,471			1 x2 tonnes tank per year		~ 2 ships per year	Liquefied 17bar, -30 deg

## 6 Conclusions

This concise report provides a preliminary review of the issues associated with the possible application of CO<sub>2</sub> capture technologies with EfW plants.

The main conclusion from this study is that post-combustion options are the most likely to be successful, particularly from waste incineration schemes where large volumes will be available, although for amine scrubbing the most developed technology, the CO<sub>2</sub> concentration in the flue gas is somewhat lower than ideal and the steam requirements for stripping would impose a significant penalty on the plant efficiency. Alternative capture approaches may provide better solutions.

For the smaller scale plants, the use of simplified post-combustion schemes aimed at less than 90% capture may be viable, particularly as waste has a significant biogenic content. The regulatory regime and the available support measures are likely to have a major impact on this option.

## 7 References

1. Renewables Obligation: Fuel measurement and sampling guidance, OFGEM guidance document, 2011
2. ETI EfW project reports
3. IPCC Guidelines for national greenhouse gas inventories, 2011
4. N. Verdone, P. De Filippis, Chemosphere 54(2004) 975–985