Sustainable Development Commission Scotland

Energy from Waste Potential in Scotland

Quantifying the contribution Energy from Waste could make to Scotland's energy needs

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Abbreviations

AD	Anaerobic Digestion
CHP	Combined Heat and Power
C&I	Commercial and Industrial (waste)
CV	Calorific Value
EfW	Energy from Waste – generic term to include all technologies for recovering energy from waste streams. In this report: Combustion technologies and anaerobic digestion
LCA	Life Cycle Assessment
MBT	Mechanical and Biological Treatment
MSW	Municipal Solid Waste
MW	See Watt (MWe = Megawatt electric; MWth = Megawatt thermal)
ODT	Oven Dried Tonne (woodfuel)
ROC	Renewables Obligation Certificate
SEPA	Scottish Environment Protection Agency
SDC	Sustainable Development Commission (Scotland)
SG	Scottish Government
W	Watt – a unit of *capacity*. 1,000W = 1kW. 1,000kW = 1MW. 1,000MW = 1GW. 1,000GW = 1TW. In this report we have sought to display figures using the most appropriate form to avoid large number strings
Wh	Watt Hour – a unit of energy. 1,000Wh = 1kWh. 1,000kWh = 1MWh. 1,000MWh = 1GWh. 1,000GWh = 1TWh. In this report we have sought to display figures using the most appropriate form to avoid large number strings

1. Executive Summary

1.1 Project Summary

The Sustainable Development Commission Scotland (SDC), on behalf of the Scottish Government, has been investigating the potential for energy from waste (EfW) to provide for electricity and heat demand in Scotland.

This work follows on from our 2009 study *Renewable Heat in Scotland*,[1] which provided background data to the Scottish Government's Renewable Heat Action Plan.[2]

Renewable Heat in Scotland also drew on *A Burning Issue*; the SDC's earlier advice to Government on the sustainability of energy from waste.[3] *A Burning Issue* concluded that EfW could be considered a part of a sustainable waste policy for Scotland, but set conditions for how it should be developed. These conditions included setting caps on the level of municipal waste that should be treated through EfW, setting minimum thermal performance standards, and doing more to support and encourage anaerobic digestion.

Renewable Heat in Scotland highlighted that currently use of renewable heat equated to 1.4% of Scotland's forecast heat demand, but that this was set to rise significantly over time. We estimated that projects then in construction would double the level of renewable heat, and that there were sufficient projects in development to take renewable heat output to 4.7% of the total. Included within this total are domestic and commercial plants that use or plan to use renewable waste sources to generate heat.

Renewable Heat in Scotland also assessed the potential for thermal treatment of municipal waste to contribute to renewable heat needs. However, these initial estimates highlighted that further study was needed to provide Government with clear recommendations on what the likely energy generation would be per tonne of available waste.

The Scottish Government has therefore commissioned the SDC to provide clear guidance on the potential of waste sources to contribute to renewable heat and renewable electricity targets.

1.2 Summary of Key Findings

Scotland has significant medium term targets for renewable energy: **11% of all heat by 2020, and 50% of all electricity**. This study analyses existing data on controlled waste streams in Scotland to assess how much energy (heat and/or electricity) might be available from waste-to-energy technologies.

The findings demonstrate that energy from waste could make a contribution to these targets, though it should be noted that not all energy produced by energy from waste plants would necessarily be classified as renewable.

Our study shows that EfW in Scotland could **contribute approximately 2.0 TWh of useful heat and 0.90 TWh of electricity per year. This is equivalent to approximately 3% of Scotland's total heat demand and total electricity demand**.

The study takes existing and planned waste targets (Scotland's 'Zero Waste Plan', currently under consultation) as a baseline. Thus a 25% cap on combustion of Municipal Solid Waste (MSW) is taken as a given. Waste diversion scenarios from the Scottish Government Waste Team are used to estimate proportions of all waste streams that might potentially be used to recover useful energy.

Direct **combustion** of solid wastes (aka 'incineration') and **anaerobic digestion (AD)** with biogas capture are the main energy from waste (EfW) technologies considered.

This report contains outputs from the modelling (energy and capacity) and a discussion of these findings.

The highest energy output could be achieved from EfW plants if all thermal output is used for heat production because overall efficiency is potentially 80% or more. The thermal-only output from waste streams identified as potentially suitable for combustion or AD would add up to around **3.5 TWh of useful heat per year**, which equates to around **440 MW of thermal capacity.**[4] This is around 6% of Scotland's existing heat demand.

Without market support, most large EfW plants are likely to generate electricity as this is more valuable commodity. Typically two to three times as much fuel is used to produce a kWh of electricity than a kWh of useful heat. The 60% overall efficiency minimum recommended in the Zero Waste Plan consultation[5] effectively ensures that all plant is CHP. The potential CHP output from identified controlled waste streams amounts to around **2.0 TWh of useful heat** and **0.90 TWh of electricity** per year (**245 MWth** and **112 MWe capacity**). This electrical output corresponds to around 7% of Scotland's current renewable electricity output; and the thermal output is two and a half times Scotland's current renewable heat output (note that energy from combustion of waste is not 100% renewable). **Potential CHP output would contribute approximately 3% of Scotland's total heat demand and total electricity demand**, as shown in Figure 1.

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Figure 1: Potential CHP Energy from Waste in Scotland

	CHP thermal capacity MWth	CHP thermal output pa MWh	CHP electrical capacity Mwe	CHP electrical output pa MWh	CHP overall capacity MW	CHP Overall output MWh
Total Capacity/ Output	245	1,960,224	112	897,434	357	2,857,658

Note: CHP overall output is heat output plus electricity output

Existing landfill gas sites in Scotland are estimated by Scottish Renewables to have a capacity of **90 MWe** (the vast majority is electric only generation), which equates to around **0.7 TWh per year**. This is expected to tail off with a 15 year lag as landfilling of organic matter ends. EfW could, therefore, more than double all current generation from landfill gas, while also contributing significant quantities of low carbon heat.

2. Methodology

Baseline controlled waste figures for 2007/8 and 2008/9 have been received from the Scottish Government Zero Waste Team. These form the basis for this report. The basic methodology involves making assumptions on a) the quantities and energy content of different waste streams that could potentially be used for EfW (informed by the Zero Waste Plan currently under consultation); and b) the technologies that could be used to recover useful energy from those waste streams. This enables us to assess how much **energy (MWh)** could be generated each year from EfW in the future, and what generation or heat-raising **capacity (MW)** this equates to.

2.1 Information Sources

Various datasets on waste in Scotland were received from the Scottish Government Waste Team. These included:

- Total waste arisings, municipal solid waste (MSW) and commercial and industrial waste (C&I Waste) (original data from SEPA)
- Landfill Allowance Scheme data for MSW, 2008-9 (original data from SEPA)
- Compositional analysis of household waste in England (Scottish equivalent work not yet completed)
- Report from ReMade Scotland to SEPA on waste wood arisings in Scotland: *Arisings of Waste Wood from the Scottish Waste Management Industry* (Remade 2009)
- Report from Jacobs to SEPA on *Development of a policy framework for the tertiary treatment of commercial and industrial wastes* (Jacobs 2008)
- Modelling data for Annex J of the Zero Waste Plan for Scotland consultation[6]
- Unpublished SEPA lifecycle assessment of waste disposal opportunities - includes breakdown of waste arisings (SEPA 2009).

2.2 Technologies

Two technologies have been modelled: direct combustion and anaerobic digestion. Other technologies - such as various Mechanical Biological Treatments (MBT) - could be used to recover energy from waste, but the overall energy output is likely to be lower than from direct combustion. (For example, when Refuse Derived Fuel from an MBT process is combusted in an EfW plant total energy output is lower than for direct combustion of waste – although MBT may be more desirable for other reasons.)

Direct combustion of waste (also known as incineration with energy recovery) involves incineration of waste materials on a fluidized bed or grate, with energy recovery from steam boilers. Mixed wastes can be burned, but combustion of segregated waste streams, or residual waste after separation, is more likely under current plans. We assume a combustion efficiency of 80% for all waste streams except wood, for which we assume 85%.

Energy from combustion is considered renewable in proportion to the organic component of the waste stream burned. For reference the minimally sorted MSW burned in the Lerwick incinerator is 71% organic.[7] In practise in the UK, EfW plants generating electricity are eligible for ROCs if the plant is considered good quality CHP – as modelled here – or if advanced conversion techniques (such as pyrolysis gasification) are used, or if solid wastes are converted to liquid form before combustion.

Anaerobic Digestion of waste streams in an enclosed tank creates a methane rich biogas as a primary output, as well as various solid and/or liquid secondary outputs. The biogas can be burned onsite in boilers to raise heat, or, once cleaned, in reciprocating engines or gas turbines. Cleaned biogas could be used offsite in vehicles to meet transport renewable targets; or fed into the gas pipeline network to displace fossil gas for heating and cooking. Onsite electricity generation and export to the grid is assumed in this report.

All energy from anaerobic digestion is considered renewable.

2.3 Assumptions

Assumptions on proportions of each waste stream were developed from Scottish Government Waste Team and SEPA literature,[8] and via discussion with a reference group. A draft of this report has also been circulated to the reference group for comment. The group contains individuals from:

- Scottish Government Waste and Pollution Reduction Division, and Renewables Strategy and Onshore Renewables Team
- SEPA
- WRAP Scotland
- Scottish Enterprise
- Scottish Renewables
- Highland Council
- Keep Scotland Beautiful
- Remade Scotland.

Of 15.5 million tonnes 5.5 million tonnes is theoretically available because it contains either organic or otherwise combustible matter. Significant proportions of these waste streams could (and should, according to the Zero Waste Plan) be re-used, recycled or composted. Quantities of each waste stream considered as potentially suitable for EfW – *given expected statutory and logistical constraints* - are shown in Figure 2. (Note, for MSW the base case assumes 25% of the total is suitable for combustion *and* 11.9% is suitable for AD).

Figure 2: Waste Streams potentially suitable for EfW (Base Case)

	Tonnes Waste pa	% incineration	% AD	Tonnes Waste for EFW
Total MSW Scotland		25.0%		850,000
	3,400,000		11.9%	404,600
Total Construction Waste	9,500,000			
Of which: wood		0.7%		66,500
Residual C&IW Scotland				
Unspecified paper	496,000	50.0%		248,000
Packaging card	437,000	40.0%		174,800
Unspecified dense plastic	480,250	0.0%		
Unspecified wood	68,500	0.0%		
Furniture	5,250	0.0%		
Garden waste	12,000		90.0%	10,800
Food waste	418,000		90.0%	376,200

A number of technical assumptions needed to be made. These were developed from discussions with technology experts, and reference examples of each technology (where possible sites in Scotland, such as the combustion facilities in Lerwick, Dundee and Stevenscroft, and Anaerobic Digestion in Stornoway).

Main technological assumptions are shown in Appendix 1. Assumptions on efficiency and energy content of fuels have been taken where feasible from existing plant. This means that there is certainly scope for technology improvements to increase the total outputs, particularly of electricity. (Although basic sensitivity analysis suggests that changing the assumptions on quantities of waste used for EfW has more impact on results than assuming technical improvements.) All assumptions and waste inputs can be changed within the spreadsheet that accompanies this report.

Total potential energy from each waste stream can be calculated by using these assumptions. For each waste stream and technology (combustion or anaerobic digestion) three alternative potential energy outputs (MWh thermal or electric) have been calculated:

- Thermal only output, or
- CHP thermal output and CHP electrical output, or
- Electric-only output.

Thermal-only output will generate a higher total MWh of energy from waste, but the energy will be less valuable from an environmental and economic point of view than CHP heat and electricity.[9] Three scenarios have been modelled, reflecting different proportions of thermal-only, CHP and electric-only EfW plants, as well as altered assumptions on quantity and quality of waste going to EfW plants.

The **base case** assumes that all waste streams will be sorted, with proportions of materials being diverted to re-use, recycling or composting according to the proposed Zero Waste Plan for Scotland. Remaining proportions of suitable wastes are shown in Figure 2. In this case the 25% of MSW used in combustion plant is assumed to have a calorific value of 10MJ/Kg (this, coincidentally, is the CV of both unsorted MSW and sorted waste paper) and the 11.9% of MSW used for AD is assumed to be food waste (which outputs more biogas than unsorted MSW). The base case assumes that all EfW plants will be CHP – this reflects the 60% minimum overall efficiency threshold proposed in the Zero Waste Plan, and the higher value of electricity compared to heat.

The **maximum energy** case assumes that combustion plant will be thermal-only plant (like the Lerwick combustion plant, which feeds a community heating scheme). Overall efficiency of a thermal-only incinerator supplying low-grade heat suitable for district heating schemes can be over 80%, compared to around 65% for CHP or 23% for electric only. The maximum energy case also assumes that 50% of 'unspecified dense plastic', 'unspecified wood', and 'furniture' from the C&I waste stream is combusted (these are not used for EfW in the base case).

The **electricity-only** case assumes that all EfW plants will be electricity only (this could be taken as a business-as-usual case, if the 60% overall efficiency limit is not preserved). This case keeps all other assumptions the same as the base case. It is included to give an indication of the very significant resource-use efficiency advantage of CHP over electricity-only generation.

3. Energy Available

Energy output per waste stream is given for the base case (CHP thermal output and CHP electrical output), and for the maximum energy case and electricity-only energy case.

3.1 Base Case

Figure 3 shows the total energy available from each controlled waste stream considered. Total energy potentially available per year from these waste streams is around **1.96 TWh of CHP thermal output**, and **0.90 TWh of electrical output**. The combined total (heat and electricity) is around **2.86 TWh** per year.

Figure 3: Total EfW available under Base Case

	Tonnes Waste pa	% incineration	% AD	CHP thermal capacity MWth	CHP thermal output pa MWh	CHP electrical capacity Mwe	CHP electrical output pa MWh	CHP overall capacity MW	CHP Overall output MWh
Total MSW	3,400,000	25.0%		133	1,062,203	53	424,881	186	1,487,084
			11.9%	13	105,331	13	100,064	26	205,395
Total Construction Waste	9,500,000								
wood		0.7%		20	163,590	8	65,436	29	229,026
C&I Waste									
Unspecified paper	496,000	50.0%		39	309,913	15	123,965	54	433,878
Packaging card	437,000	40.0%		27	218,493	11	87,376	38	305,814
Unspecified dense plastic	480,250	0.0%							
Unspecified wood	68,500	0.0%							
Furniture	5,250	0.0%							
Garden waste	12,000		90.0%	0.4	2,812	0.3	2,671	0.7	5,483
Food waste	418,000		90.0%	12	97,937	12	93,041	24	190,978
TOTALS	14,817,000			245	1,960,224	112	897,434	357	2,857,658

Note: The table is a replication of the spreadsheet provided to Government for the calculation of EfW potential. Light Green denotes variables that can be changed by the user (total tonnes of waste, and percentages used for EfW; as well as all assumptions). Pink denotes thermal output, yellow electrical output, and orange overall output (the sum of thermal and electrical outputs)).

Landfill gas

Scottish Renewables maintains a database of all renewable electricity generation in Scotland. As of October 2009, this includes **90.035 MWe** of landfill gas electricity generating capacity.[10] Assuming these plants run for 8,000 hours (this is probably a slight underestimate, as gas buildup can cause problems if there is any downtime at landfill gas sites) this equates to **720,000 MWh** of electricity per year.

Existing landfill gas sites have a planned life of at least 15 years, so something close to this level of generation is likely to continue to 2020 before tailing off as the level of organic waste being landfilled declines substantially. Operators report, however, that as the organic content of waste falls landfill gas sites are already seeing less gas output per tonne of waste landfilled.

Agricultural and Forestry Wastes

Only controlled waste streams, which come under the auspices of the Environmental Quality Directorate of the Scottish Government, have been considered in this work. There is undoubtedly potential for some electricity and/or heat production from other 'waste' organic matter, particularly wood-processing (in-forest residues and processing residues) and agriculture.

Agricultural wastes – manures, straw, and unmarketable food produce – are generally disposed of on-farm,[11] ensuring that at least some of the nutrients are returned to the soil. For some farms it is feasible to recover useful energy from these wastes via anaerobic digestion while still returning nutrients to the soil via the digestate sludge. On-farm digesters are common in Germany (4,700 installed up to 2008, with total capacity of 12,000 MWe[12] – more or less four times Scotland's total installed renewable electricity capacity), and Scottish Enterprise reports some interest from farms in Scotland. On-farm anaerobic digester plants would in most cases combine uncontrolled farm wastes with controlled food wastes, perhaps brought in from outside. Farm wastes could therefore add to the 200GWh per annum of anaerobic digestion electricity identified in this work.[13]

Remade Scotland's (2009) report for the Scottish Government (*Arisings of Waste Wood from the Scottish Waste Management Industry*) suggests a theoretical maximum of 602,000 tonnes of wood waste could be recovered by the waste management industry in Scotland per year. This compares to a total of 305,000 tonnes of wood waste in Figure 2 (assuming wood is 5% of MSW, as in England), suggesting there may be significantly more potential for EfW from wood wastes than this modelling suggests.

A significant amount of uncontrolled wood-waste (mostly sawmill and papermill wastes) is already used for energy production; indeed boilers at wood processing sites deliver around 75% of renewable heat used in Scotland, and E.ON's Locekerbie power station takes waste wood streams as well as virgin wood.[14]

3.2 Maximum Energy Case

Figure 4 shows that the maximum energy potentially available from EfW (still broadly following Zero Waste Plan objectives) could be as much as **4.86 TWh** of thermal energy. This is around 70% higher than total (thermal and electric output) of 2.86 TWh under the base case.

Base case total CHP output is shown for comparison.

Figure 4: Total EfW available under Maximum Energy and Base Cases

Maximum Energy	Thermal only capacity MWth	Thermal only output MWh
	607	4,857,941

Base Case	CHP overall capacity MW	CHP Overall output MWh
	357	2,857,658

The increase is explained by the overall efficiency improvement of using thermal plant, rather than CHP plant (this change on its own would equate to around 25% increase in output); and the addition of plastic, wood and furniture waste streams from C&I Waste (this would equate to around 35% increase).

Heat-only plant is simpler and cheaper to build than CHP plant. The output is less valuable, however, both financially and environmentally, than CHP output. Significant heat-use from EfW plants will only be a realistic possibility if there is a step-change in the way heat is planned for and regulated. For example, EfW plants would need to be sited near to long-term heat loads (homes, swimming pools, some industry) and significant investment and intervention would be needed to build heat delivery infrastructure.

3.3 Electricity-only Case

Figure 5 shows that the total energy available if electric-only plants are used to recover energy is a little more than a TWh per year. The Electricity-only Case is identical to the base case, except that electricity-only plant is used instead of CHP.

The electrical output is around 20% higher in the electric-only case than for the base case. But the total (CHP) output in the base case is nearly three times the total output in the electricity-only case. This is as expected, due to the much higher overall efficiency of CHP compared to electric-only generation. Figure 5 compares the total energy output of the electricity-only case and the base case.

It is worth noting that the difference in output between CHP and electricity-only plant is more marked for combustion than for anaerobic digestion: combustion CHP plant recovers around 2.8x more energy in CHP mode (with around 20% reduction in electricity output), while anaerobic digestion recovers around 2.0x as much energy in CHP mode (with marginal reductions in electricity output). This is primarily because the anaerobic digestion plant uses almost half of the output heat from the gas engine to maintain digestion temperatures.

Figure 5: Total EfW available under Electricity-only and Base Cases

Electricity Only	Electrical only capacity MWth	Electricity only output MWh
	134	1,073,502

Base Case	CHP overall capacity MW	CHP Overall output MWh
	357	2,857,658

3.4 Sensitivity

Composition of MSW

We have assumed in the base case that MSW combusted has an energy content of 10 MJ/kg. This is a mid case from various references. Sorted wood or paper/card streams have a similar calorific value, and would produce around the same amount of energy as minimally-sorted MSW if burned in boilers designed for mixed waste. Sorted waste streams could be burned in custom designed boilers, though, which *might* recover up to 10% more energy – and all the heat and electricity produced would be considered renewable for organic waste streams.[15]

Sorted plastics have a significantly higher CV than MSW (or paper) – SEPA's life cycle assessment of options for C&I waste disposal suggests 22 MJ/kg. If the 25% of MSW used for combustion EfW was 100% plastic then the total output (under otherwise base case assumptions) would be around **4.6 TWh** of heat and electricity (580 MW combined CHP capacity). This is more than 1.5x the base case CHP output of 2.9 TWh.[16] Assessments of household waste composition in England, however, suggest that plastics make up just 7% of MSW – and none of the additional heat or electricity would be considered renewable.

Proportions of waste

Figure 2 showed the size of the waste streams technically suitable for EfW, and our estimates (developed with the Scottish Government) of the proportions that *might* be politically and logistically suitable. Obviously, increasing the total tonnage or the percentages available for EfW would increase the total energy output per year.

Assessments of household waste stream content suggest that 17% of all MSW is food waste. If all of this was processed in anaerobic digestion plants (instead of the 70% assumed in the base case) the total CHP output would be 2.95 TWh instead of 2.86 TWh. In fact assessments in England suggest that another 20% of MSW is garden waste. Including this in the anaerobic digestion line could take the total to 3.29 TWh. Doing so would, of course, change the likely energy content of the MSW allowed for combustion, possibly reducing the combustion output, and almost certainly reducing its renewable proportion.

Similarly, increasing the proportion of 'packaging card' from 40% to 90% and 'unspecified paper' from the C&I Waste stream from 50% to 90% would increase the total energy output per year from 2.86 TWh to 3.59 TWh (this calculation is included for demonstration only – Scotland is committed to recovering and recycling 60% of C&I packaging card).

Technical Efficiency assumptions

Assumptions on technical efficiency were taken from existing plant in the UK, and from discussions with experts about the current state of best practise. We do not expect the electrical or total efficiency of combustion plants to increase by more than 5% before 2020. Increasing the electrical efficiency of combustion plant by 5% (keeping parasitic energy consumption and thermal efficiency constant, thereby increasing overall efficiency by 5%) would increase CHP electrical output from 0.90 to 1.07 TWh. Total CHP output would increase from 2.86 to 3.03 TWh.

Efficiencies of biogas generators could increase significantly if fuel cell generators become more efficient and more affordable. If electrical efficiencies of anaerobic digestion plant increased from 33% to 50%[17] - with a corresponding reduction in thermal efficiency from 35% to 15% - then CHP electrical output would increase to from 0.90 TWh to 1.00 TWh, and overall CHP output drop slightly from 2.86 to 2.84 TWh (with combustion plant efficiencies remaining at base case level). If higher proportions of waste streams were processed through anaerobic digestion (or a MBT that produced a biogas output) then the electricity output increase would be correspondingly higher.

4. Context

4.1 Comparisons

Baseline energy from waste that could be available is around **3 TWh: 1 TWh electric and 2 TWh thermal.**

Taking electricity output and demand figures from the 2008 Scottish Energy Study,[18] and Scottish Government figures on total heat demand, proportions of total energy demand which could be met by base case EfW output are as follows:

	Demand	Potential EfW output	% EfW contribution
Electricity	35 TWh	0.90 TWh	2.6%
Heat	60.1 TWh	1.96 TWh	3.3%

Comparisons with current renewable energy output may also be interesting, and suggest that EfW's contribution could be far from insignificant. (Note: combustion EfW is not 100% renewable.) The current renewable heat figure of 0.85 TWh comes from SDC Scotland's work for the Scottish Government on Renewable Heat (2009). The comparison highlights that the potential level of EfW from heat is 2.3 times the current renewable heat output.

	Output	Potential EfW output	% EfW contribution
Renewable Electricity[19] (2005)	12.4 TWh	0.90 TWh	7.3%
Renewable Heat (2008)	0.85 TWh	1.96 TWh	230%

4.2 Existing diversions

To give some context to the feasibility of diverting this much waste into sorted streams for EfW, only 254,000 tonnes of card and paper and 54,000 tonnes of wood are currently recycled in Scotland, compared to a theoretical maximum identified in Table 2 of over a million tonnes. Even if EfW does become a preferred waste disposal method for all wastes up to the planned Zero Waste Plan levels the logistical challenges should not be underestimated.

4.3 Future change?

Reducing the total quantities of waste (while keeping the proportions used for EfW steady) would reduce the yearly energy output very nearly proportionally. We assume that as Scotland moves towards a Zero Waste society in the wider sense, waste streams available for EfW will therefore reduce.

4.4 Alternative uses of biogas

Biogas from anaerobic digestion, if cleaned, is a high-quality fuel and may in future be more valuable as a transport fuel than as a CHP fuel. Basecase anaerobic digestion biogas production could displace some 0.5 TWh worth (equivalent to around 50 Gigalitres of petrol, assuming petrol has an energy content of 10 kWh/litre) of fossil transport fuel. For comparison, Scotland's total oil demand in 2010 is estimated at 4.2 TWh.[20]

Similarly cleaned biogas might be used in fuel cells with electrical efficiencies of 50% or more (perhaps having been fed into the gas network to enable maximum use of CHP heat). This would double the amount of electricity available from basecase anaerobic digestion, as mentioned in section 3.4.

Appendix One: Technical Assumptions

Technical Assumptions:		Source	Notes
Running time per year hrs	8000	assumed	
Thermal plant efficiency - COMBUSTION	80%	Adrian Judge, Juniper/ other literature / estimate	
CHP plant efficiency, heat - COMBUSTION	45%	Adrian Judge, Juniper/ other literature / estimate	
CHP plant efficiency, electric - COMBUSTION	18%	Adrian Judge, Juniper/ other literature / estimate	Includes 10% parasitic
Electric plant efficiency - COMBUSTION	23%	Adrian Judge, Juniper/ other literature / estimate	Includes 10% parasitic
MWh per tonne MSW/paper - COMBUSTION	2.78	Adrian Judge, Juniper/ other literature / estimate	from CV of 10MJ/kg
MWh per tonne plastic - COMBUSTION	6.11	SEPA LCA of C&I W options / derived	From CV of 22MJ/kg
Biogas yield (60% methane) m3 / tonne food waste	125	Jacobs report.	CV of methane 35.7MJ/m3.
Biogas yield (60% methane) m3 / tonne unsorted MSW	75	As above, with AJ proportions between food waste ouput and MSW output	
MWh per tonne food waste - AD	0.74	From above, CV of methane 35.7 MJ/m3	
MWh per tonne MSW - AD	0.45	From above, CV of methane 35.7 MJ/m3	
Biogas plant efficiency, heat – AD	72%	Assumed 90% with 20% parasitics	
Biogas CHP plant efficiency, heat - AD	35%	Jacobs report.	Includes 30% parasitics (digester)
Biogas CHP plant efficiency, electric - AD	33%	Jacobs report.	Includes 5% parasitics
Biogas plant efficiency, electric only - AD	33%	Jacobs report.	Includes 5% parasitics
Thermal plant efficiency - WOOD COMBUSTION	85%	Renewable heat work; checked Jacobs	
CHP plant efficiency, heat - WOOD COMBUSTION	50%	Renewable heat work; checked Jacobs	
CHP plant efficiency, electric - WOOD COMBUSTION	20%	Renewable heat work; checked Jacobs	
Electric only plant efficiency - WOOD COMBUSTION	25%	Stevens Croft reference: 28% when burning waste wood	Assumes 10% parasitic
MWh per tonne wood/cardboard - WOOD COMBUSTION	4.92	Renewable heat work	Assumes wood waste has same CV as ODT wood

References & Endnotes

1. Sustainable Development Commission (2009) Renewable Heat in Scotland. Report to the Scottish Government.
2. Scottish Government (2009) Renewable Heat Action Plan: a plan for the promotion of the use of heat from renewable sources.
3. Sustainable Development Commission (2007) A Burning Issue. Report to the Scottish Government.
4. This result is the heat-only output of modeling the base case scenario. The 'maximum energy' case also adds additional quantities of waste (see the Methodology section for explanation of these scenarios).
5. See footnote 6 of the Zero Waste Plan consultation:

   Annex II to the Waste Framework Directive then gives a non-exhaustive list of recovery operations. This "includes incineration facilities dedicated to the processing of municipal solid waste only where their energy efficiency is equal to or above:
   - 0,60 for installations in operation and permitted in accordance with applicable Community legislation before 1 January 2009.
   - 0,65 for installations permitted after 31 December 2008".
6. See: www.scotland.gov.uk/Publications/2009/08/19141153/55.
7. A published figure, but sourced from personal communications with Jim Grant of Lerwick Heat Energy & Power Ltd
8. Based on discussions with Scottish Government on EfW potential.
9. Until we have a 100% renewable electricity supply, with over-supply, electricity from fuel will always be more valuable than heat from fuel. This is because heat raising boilers use fuel at around 90% efficiency, while electricity-only generators use fuel at around 30% efficiency. This explains why electricity prices in the UK are typically 3x gas prices; and why CHP is all other things being equal - a better solution for EfW than heat-only plant. However, the market is complex and access to the Renewables Obligation (Electricity), Renewable Transport Fuels Obligation and the forthcoming Renewable Heat Incentive, mean that developers must also consider what stimulus to seek support under.
10. Scottish Government Waste Team has quoted a SEPA estimate of 67.5 MWe, but this appears to be out of date
11. Farms are exempt from certain restrictions on waste disposal – including restrictions on burning waste with energy recovery.
12. Numbers from the German Biogas Association, reported by Delta Energy & Environment, personal communications
13. This number for AD electricity is the electric output of AD CHP under the base-case (this would be very similar if all AD plant was electric-only).
14. Remade Scotland (1999), and Forestry Commission Scotland woodfuel usage surveys.
15. We initially assumed that paper and card had energy content similar to oven-dried wood. This would have doubled the output from the 'unspecified paper' and 'packaging card' streams of C&I Waste, and increased the total yearly energy output in the base case from 2.86 TWh to 3.57 TWh.
16. The output from just the 25% MSW output (row 3 of the spreadsheet) is 3.27 TWh, compared to 1.49 under the base case.
17. At least one CHP engine developer is targeting electrical efficiency of 50% for an SOFC fuel cell: Wärtsilä with Topsoe Fuel Cells.
18. See: www.scotland.gov.uk/Publications/2008/11/14093227/7 Table 13.
19. Renewable electricity includes large hydro and does not include nuclear.
20. See: www.scotland.gov.uk/Publications/2008/11/14093227/6.

Sustainable
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The Sustainable Development Commission is the Government's independent watchdog on sustainable development, reporting to the Prime Minister, the First Ministers of Scotland and Wales and the First Minister and Deputy First Minister of Northern Ireland.

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