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Energy recovery for residual waste

A carbon based modelling approach

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Contents

1. Summary

1. This analysis set out to identify the critical factors that affect the environmental case for energy from waste (EfW) in comparison to landfill from a carbon perspective and the sensitivity of that case to those factors. In particular the aim was to examine the influences that the biogenic carbon content of the waste and the thermal efficiency of the EfW process have on the relative benefits of EfW and landfill.

2. It is recognised that there are a wide range of other practical, environmental and economic factors that need to be considered in assessing the benefits of different waste management approaches and that carbon cannot be the sole consideration. However, as the relative carbon impacts are often used as justification for adopting different approaches it is important to understand how they vary in the context of this wider decision process. The intention is to identify the key factors necessary to maximise the benefits of EfW over landfill in carbon terms in line with the hierarchy rather than indicate a preferred management route for waste of a certain composition.

3. A model was developed that considered the carbon emissions from a tonne of mixed residual waste depending on whether that waste were to go to energy recovery or landfill.

4. Energy from waste was considered to produce emissions from combustion of all the carbon in the waste and to produce energy related to the calorific value of that waste. The net energy generated (total energy reduced by the modelled net efficiency) was assumed to offset fossil emissions from an alternative generating source (the baseline being electricity only generation and the alternative source being the marginal generation mix). It did not directly account for any carbon left in the ash or the potential carbon benefits of metal recycling. These would be additional carbon benefits for EfW. Similarly nitrous oxide (N_2O) emissions have not been included in the calculation which would be a small disbenefit. If desired these factors could be accounted for by creating an 'apparent net efficiency' of a plant.

5. Landfill was considered to produce no gaseous[1] emissions from fossil waste and a proportion of the biogenic carbon was also assumed to be sequestered. The remaining biogenic carbon was assumed to decompose to form landfill gas made up of 50:50 (by volume) CO_2 and methane. This gas was assumed to be either released into the atmosphere or converted to CO_2 through: being captured and used to generate energy, which was assumed to offset the same fossil source as EfW; flared with no energy offset; or oxidised in the cap. CO_2 from these processes was assumed to be all biogenic. Methane released into the atmosphere was converted into carbon dioxide equivalents for direct comparison with EfW emissions.

[1] There are some non-gaseous emissions from the fossil component of the waste, particularly leachate.

6. The model was used to identify the ‘balance’ or point between energy from waste and landfill for a given composition of waste - the overall net efficiency of EfW plant required for a tonne of waste going to EfW to have the same carbon impact as that same tonne of waste going to landfill.

7. This balance point was examined for a range of theoretical waste compositions. It was found there was a very good, slightly non-linear, correlation (R^2 >0.99) between the biogenic carbon content of the waste and minimum efficiency of EfW plant required to match landfill. This allowed the sensitivity to underlying assumptions to be examined using a limited range of example compositions.

8. The sensitivity of the model output to the input assumptions was tested. As might be expected it was found to be highly sensitive to the marginal energy mix used to calculate carbon offset from generation and the level of landfill gas capture. It was sensitive to other parameters but these two were clearly the key factors.

9. Decreasing the carbon intensity of the background electrical energy mix was found to increase the biogenic content of waste required for a plant operating at a given efficiency, or alternatively increase the minimum efficiency of plant required to operate with a waste of a specific biogenic content. The sensitivity diminished with increasing biogenic content and there is a limiting value of biogenic content beyond which EfW is always superior to landfill in carbon terms regardless of efficiency (although high efficiency should still always be favoured for resource efficiency and economic reasons).

10. The limiting value of biogenic content was found to be dependent on the level of landfill gas capture. High capture rate required higher biogenic content for EfW to be superior to landfill. For a plant of given efficiency, increasing the level of landfill gas capture again led to a higher biogenic content being required for EfW to be superior. The marginal impact of a change was greatest at high capture rates. For a given biogenic content, increasing capture level increased the minimum efficiency of plant required.

11. Covariance of the two parameters showed there is no complex interaction between them.

12. Three scenarios were developed for electricity only EfW to look at the sensitivity of carbon outcomes to different assumptions over time. The carbon intensity of the offset energy was varied in line with DECC predictions for the marginal energy mix, which see a decarbonisation towards 2030, this was kept the same across the scenarios. The three scenarios were then developed based on the initial level of methane released from landfill as dictated by the capture rate. High methane (50% capture), central (60% capture) and low methane (75% capture). In all three scenarios the level of capture was modelled to increase asymptotically over time towards 80%.

13. Under all three scenarios, in the long term (by 2050), a high proportion of biogenic content (in the region of >70%) was required for electricity only generation. This could only be achieved by pre-treating the waste or much greater fossil plastics collection and recycling than is currently seen.

14. The average annual CO_2 savings over the plant lifetime for an EfW plant using waste with biogenic content of 61% were calculated for electricity only plants with efficiency ranging from 15% to 30%. For this comparison a 100 year window was considered, assuming the same waste was going to either management option for the first 25 years and that emissions from EfW would occur only during this period (planned plant lifetime) while during the overall 100 year period all potential emissions from landfill would occur.

15. In all scenarios there was an apparent cut off point beyond which an electricity only plant would have a lifetime carbon disbenefit. This occurred later and at lower efficiencies the lower the assumed methane capture rate.

16. Similarly there were cut off points where, despite overall lifetime benefits, at the end of the plant's lifetime it would be a net carbon emitter relative to landfill and therefore there would be a carbon disbenefit in extending its life. These transitions happened earlier and at higher efficiencies than the overall lifetime disbenefits.

17. The nature of this analysis means that some net emissions in later years are being offset by earlier carbon savings. This means that while a 25 year plant lifetime might be valid, extension beyond this may not. An analysis of net emissions relative to landfill shows that higher biogenic content is required to extend a plant's life beyond 25 years.

18. By convention biogenic carbon has been ignored in the modelling, however, some biogenic carbon that would be released in energy recovery is sequestered in landfill. We have modelled an approach that aims to reflect this sequestered component.

19. Including sequestered carbon significantly increases the efficiency of plant required for a given biogenic content. This conclusion is highly sensitive to the level of sequestration assumed. Reducing the assumed level of sequestration results in a significant drop in the biogenic content required for a given efficiency. This is due to its impact on three interlinked parameters – increasing the amount of methane assumed released from landfill; reducing the amount of biogenic carbon from EfW that should be counted; and reducing the apparent landfill gas capture rate. All of which favours EfW over landfill.

20. Comparison with other energy outputs gives different results due to the differing carbon intensity of the energy source being offset.

21. The carbon intensity of heat depends on the fuel source being displaced - oil or gas. In both cases this is lower than the current marginal electricity mix, however, unlike electricity it is expected to decarbonise much more slowly.

22. While earlier carbon benefits may be lower, heat continues to provide these for the lifetime of the plant.

23. As the model accounts for all of the carbon produced against electricity generation any additional heat use is 'carbon free'. As such it was found that relatively little additional heat use (through combined heat and power) was sufficient to offset any disbenefits from later years of electricity production.

Giving overall lifetime benefits under all but the most challenging set of assumptions for EfW.

24. Transport fuels likewise offset higher carbon intensity fuel sources. Therefore transport fuels form waste can potentially provide lifetime carbon benefits with lower overall efficiencies/biogenic content than electricity alone provided the energy use during production is properly accounted for.

2. Aims

25. To develop a simple model that allows variation of the critical factors and assumptions which impact on the carbon based environmental case for using energy from waste, relative to the alternative of landfill, for residual waste.

26. Identify the balance point for this choice and understand how it is reliant on underlying assumptions.

27. Help determine what factors may need to be considered in order to ensure recovery of energy from residual waste remains environmentally superior to landfill (i.e. in line with the hierarchy) in the long term.

28. Other drivers such as practicality, economics or fuel security are important in determining the overall case for waste treatment choices, this model will not take these into consideration.

3. Introduction

29. It is recognised that there are a wide range of practical, economic and environmental factors that need to be considered in assessing the benefits of different waste management approaches. The carbon case is just one of the considerations in this decision making process but is an important one that tends to dominate the environmental case for energy from waste relative to landfill. Carbon will therefore be the focus of this report.

30. The carbon case for energy from waste being superior to landfill is based on the premise that the climate change impact, in terms of CO_2 equivalents, of producing energy from the waste is less than the potential impact from methane emitted if the waste were to go to landfill. The model can therefore be thought of as being in two parts:

- the potential carbon impact of producing energy from waste
- the potential carbon impact of landfilling that same waste

31. If the latter is greater then there is a carbon case that the waste should go to energy recovery rather than landfill and vice versa. The difference between the two halves of the model for a given set of circumstances determines which is the better choice in terms of greenhouse gas emissions. There are of course a number of other environmental issues to be taken into account when selecting between the two routes - some of which may tip the balance in the opposite direction depending on the relative magnitude of the carbon case and these other factors.

32. The discussion that follows considers energy recovery only from residual waste. For this purpose, residual waste is considered to be waste which cannot be beneficially recycled (or reused) for economic, environmental or practical reasons. We recognise that the ultimate goal is to minimise residual waste and that as a function of this, waste volumes and composition may change over time, but this does not fundamentally impact on the analysis below, although it may impact on the case for building residual waste infrastructure.

33. Although the model could potentially apply to residual waste of any type, our primary consideration is in relation to municipal solid waste (MSW) as the majority of plants in the UK currently burn this type of waste, or RDF derived from it. For ease we will refer to this type of waste as 'black bag' in reference to how it has been historically collected from households in the UK. However, in reality we are considering all residual municipal solid waste[2] however sourced.

34. A typical black bag of residual MSW will contain a mixture of different things, such as paper, food, plastic, clothes, glass and metal. Some of these wastes, e.g. food, will originally have come from biological sources, i.e. plants, and the carbon stored in them is known as biogenic carbon. Some of the waste materials, e.g. plastics[3], will have been made from fossil fuels such as oil and the carbon stored in them is known as 'fossil carbon'. Some of the wastes, e.g. clothes, will contain a mixture of biogenic and fossil carbon (e.g. cotton/polyester mixes), while other wastes will contain little or no actual carbon (e.g. metals). We need to understand if the carbon in the waste is biogenic or fossil in origin for two reasons: (i) they behave differently in landfill (plastic does not generally decompose) and (ii) biogenic and fossil carbon are counted differently in terms of how they are calculated to contribute to global warming[4]. Of the waste in our typical black bag, currently[5] somewhere between one half and two thirds of the carbon in waste is of biogenic origin.

35. Considering the energy from waste route, if our black bag of waste were to go to a typical combustion-based energy from waste plant, nearly all of the carbon in the waste would be converted to carbon dioxide[6] and be released immediately into the atmosphere. Conventionally the biogenic carbon dioxide released is ignored in this type of carbon comparison as it is considered 'short cycle', i.e. it was only relatively recently[7] absorbed by growing matter. In contrast, the carbon dioxide released by fossil-carbon containing waste was absorbed millions of years ago and would be newly released into the atmosphere if combusted in an energy from waste plant.

36. The energy from waste plant will generate some energy (in addition to whatever it uses to run itself). This energy substitutes for energy that would otherwise

[2] We are also considering the current broad EU definition of MSW to include household and household like C&I waste.
[3] A small but increasing proportion of plastics are being made from biogenic sources. The model could in future be adapted to account for these releasing biogenic rather than fossil carbon in EfW and the likelihood of their decay to produce methane in landfill. However, as the output of the model depends on total biogenic carbon rather than its specific source this does not affect the conclusions. For simplicity where we refer to plastic this should be assumed to be fossil plastic.
[4] The atmosphere cannot distinguish between CO_2 released from a biogenic source versus a fossil source. However, in terms of considering overall climate impacts it is important they are accounted for and treated differently to avoid double counting. The IPCC have agreed conventions for doing this which are applied here.
[5] The composition of waste changes over time as consumption patterns, reuse, recycling and separate collection practices change.
[6] <3% would remain in the ash.
[7] In this context 'relatively recently' is considered to be decades (or for wood centuries) as opposed to the millennia which fossil materials have been locked underground.

need to be generated[8], thereby saving any fossil carbon dioxide that would have been released by that alternative generating source. This means that in our comparison some of the fossil carbon dioxide released by the energy from waste plant can be offset by the saving from the alternative generating source, reducing the overall impact. The more efficiently the energy from waste plant converts the waste to useful energy, the greater the carbon dioxide being offset and the lower the net emissions.

37. Alternatively, considering the landfill route, all the fossil carbon stays in the ground and doesn't break down. The fossil carbon is sequestered, as is potentially up to half of the biogenic carbon depending on the exact conditions in the landfill. However, some of the biogenic material does break down with the carbon converted to a mixture of carbon dioxide and methane, known as landfill gas. A large proportion of this landfill gas would be captured and burned, generating energy and offsetting alternative generation emissions. Burning landfill gas produces biogenic carbon dioxide which, as for energy from waste, is considered short cycle. Crucially however, some of the methane would escape into the atmosphere. As a very potent greenhouse gas even a relatively small amount of methane can have dramatic effect and be equivalent to a much larger amount of carbon dioxide (methane is around 25 stronger than CO_2 as a greenhouse gas[9]).

38. The carbon (equivalent) emissions from the two different routes are summarised in Diagram 1 below.

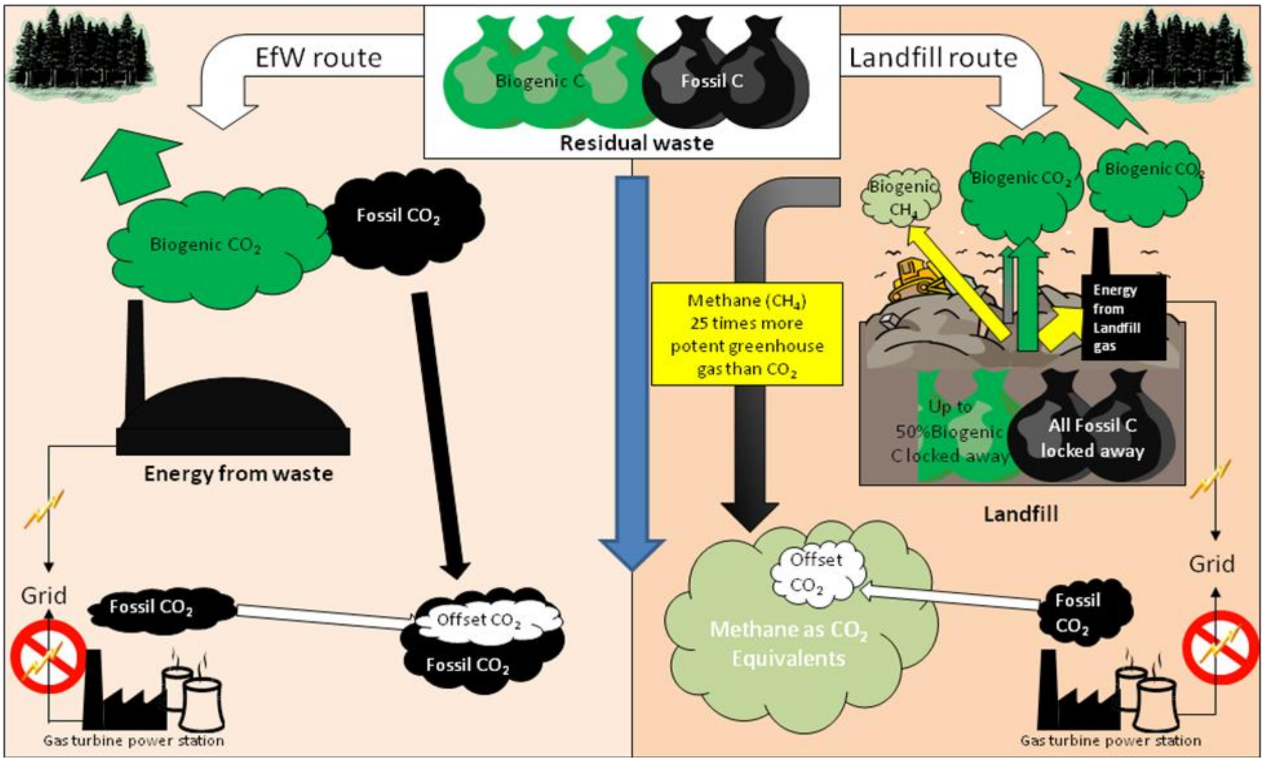
39. Crucially the negative carbon impacts of energy from waste come from the fossil component of the waste, while those from landfill originate from the biogenic material. Hence the relative proportions of fossil and biogenic material will have an important impact on which route is better and result in a balance point where the theoretical emissions are equal. The other key factor is clearly the carbon impacts of the energy being offset. The benefits of offsetting high carbon fossil energy will be greater than offsetting low carbon renewable energy.

40. This can be illustrated by considering the extreme cases. An energy from waste plant burning 100% fossil material, releasing its fossil CO_2, and offsetting only renewable energy would produce more CO_2 equivalents than landfilling the same 100% fossil waste where all the carbon would be locked away (i.e. zero emissions). Similarly an energy from waste plant burning 100% biomass producing only biogenic CO_2, which is conventionally discounted, while also offsetting a high fossil carbon generating source would clearly be better than that same biomass producing methane in landfill.

[8] The amount of energy offset is determined by what is considered to be the marginal energy mix at the time.

[9] The very latest update from IPCC has revised this value up to 34 times (http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf). The majority of the modelling was conducted with the earlier figure of 25. This does have some impact on the numeric output of the model but does not dramatically affect the conclusions. The sensitivity of the model to this factor is discussed below.

Diagram 1. Emissions routes from landfill and EfW



41. This illustrates that if you could perfectly separate residual waste (that by definition cannot be beneficially recycled) into biogenic and fossil components, you would aim to recover energy from the biogenic component and landfill or otherwise sequester the fossil component[10]. In reality this is not possible hence the need to understand the impact of mixed waste.

42. A number of issues complicate both sides of the model but the fundamental point remains that residual waste is generally a mixture of biogenic and fossil. Therefore the balance of these components and the efficacy of how they are treated will determine whether energy recovery or landfill is the most appropriate solution for the waste.

43. Metal recovered and recycled from bottom ash can significantly add to the environmental benefits of EfW. It is beyond the scope of this model to consider this especially as, while it is commonplace, it is not necessarily always done. This should perhaps be considered as an additional route by which the balance point can be shifted.

44. Equally, both landfill and EfW emit greenhouse gases other than CO_2 and methane e.g. N_2O, again these have not been considered in this model and are more suited to detailed lifecycle analysis. The simplifications used mean that

[10] This is assuming there were not mechanisms which allowed environmentally sound recovery of the embedded carbon in the fossil component at the molecular level e.g. through depolymerisation (i.e. making new polymers from the waste was less carbon intensive than using virgin materials). There would then be the separate issue of whether this is recovery or ‘molecular recycling’.

the values identified in the model should be considered illustrative rather than definitive. However, it would be expected that the trends demonstrated by the model would be maintained and it is from these that conclusions may be drawn.

4. Model development

45. As discussed above the model consists of an energy recovery side and a landfill side, with the overall output being determined by the balance of the two.

4.1. Assumptions

46. In developing the model we have had to make a number of assumptions. The rationale for these is described in the method below but they are listed here for ease.

47. For each waste material *stream* that make up the overall composition we have used values from the "Carbon Balances[11]" report and assumed constant:

- proportion biogenic carbon
- proportion fossil carbon
- calorific value

48. For wastes with a biogenic content:

- proportion of dissimible decomposable carbon (DDOC) – the proportion of the waste which is carbon that will actually decompose to landfill gas is taken from MelMod[12]
- all gases released from landfill are biogenic in origin

49. Default values for variables

- Carbon intensity of marginal energy mix: 0.373t/MWh (equivalent to CCGT)
- Landfill gas capture rate: 75%
- Waste composition: 2011 figures from MelMod, gives 61% biogenic

50. Fixed input values

- Proportion of methane in landfill gas: 50%
- Calorific value of methane: 50MJ/t = 13.89MWh/t
- Efficiency of landfill gas engine: 41%
- Proportion of methane oxidised in the cap: 10%

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[11] Fisher K, Collins M, Aumônier S and Gregory B (2006), Carbon Balances and Energy Impacts of the Management of UK Wastes *Defra R&D Project WRT 237* Final Report, Table A1.61

[12] Brown K, Conchie S, Leech A (2012) MELMod-UK (Methane Emissions from Landfills Model - UK) 2012v1.1

- Proportion of landfill gas used in energy generation (not flared): 50%
- Equivalent warming potential of 1t of methane: 25 CO_2eq

51. In addition to these numerical assumptions it has been necessary to make a number of simplifications in order to keep the model manageable. The assumptions are listed in Table 1 below along with their potential impact on application of the model to the real world.

Table 1. Assumptions

Assumption	Implication
Metal recycling from EfW incinerator bottom ash is not occurring (this does occur in the majority of plants but to different levels).	The impact will be to underestimate the carbon benefits of EfW where recycling does occur. Recycling of metal from IBA can have a significant impact on the global warming impacts of EfW. For example, Burnley and Coleman (2012) estimated that recovering aluminium from IBA doubled the reduction in greenhouse gas emissions of the EfW system. Taking account of these impacts would have the effect of moving the "balance point" in favour of EfW.
The volumes of N_2O and other emissions have a negligible greenhouse impact relative to CO_2.	The impact will be to underestimate the negative impact of EfW. Detailed results data in the WRATE model indicates that with a typical UK residual waste composition approximately 4.5% of total direct greenhouse gas emissions from EfW are attributable to N_2O and there are no significant N_2O emissions from landfill. Taking these into account would move the balance point in favour of landfill.
All carbon is converted to CO_2 in EfW.	This will overestimate emissions as up to 3% of carbon can remain in the ash.
The carbon impacts of ash handling (negative from transport or positive from recycling to aggregate) are not considered.	The impact will depend on handling method.
The same total volume of CO_2 equivalents released will have the same impact regardless of the timescale over which release occurs.	Landfill emits CO_2e of methane over a much longer period of time than EfW releases CO_2 so this is likely to overestimate the relative impact of landfill.

4.2. Composition of waste

52. The key commonality between both sides of the model is the composition and mass of waste involved. The composition of the waste is one of the key variables to be examined, and the dependency on mass was removed by basing the calculations on 1 tonne of waste. Like-for-like composition was compared between the two sides of the model.

53. Care needs to be taken if considering refuse derived fuels. Comparing the relative benefits of burning or landfilling the fuel itself then the model is valid. However, comparing the fate of 1 tonne of residual waste where it undergoes some further separation to create the refuse derived fuel before burning, the loss of mass needs to be considered along with any carbon benefits of additional recycling. This requires a more life cycle approach and is beyond the scope of this model.

54. One tonne of waste does not have a constant carbon content as it varies depending upon the waste components. The relative proportions of biogenic and fossil carbon also depend upon the waste components, as do other important factors such as the calorific value.

55. One of the difficulties in developing this model was finding data sources that provide all of the information required in a single place based on a single set of assumptions and analysis. Unfortunately this was not possible and as a result, key data on composition, carbon content and calorific values had to be taken from two different sources. While the data where comparisons can be made between the two sources seem relatively self consistent, this is recognised as a weakness in the model.

56. For a simple model it is necessary to consider some average values of waste composition. Defra uses a model called MelMod to consider the potential carbon impacts of waste management. This model is also used by DECC for the Greenhouse Gas Inventory, so for consistency, average compositional data was taken from this model. The base case used was for predicted residual municipal waste in England 2011, though to a degree the starting point does not matter as one of the key purposes of the model is to enable variation of these components.

57. Unfortunately MelMod does not include information on the carbon content and calorific value of fossil waste components so a different data source was required for this information. This is provided by the report "Carbon Balances and Energy, Impacts of the Management of UK Wastes December 2006 (Annex A Table A1.26)[13]". While this is a relatively old report it is unlikely the

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[13] Fisher K, Collins M, Aumônier S and Gregory B (2006), Carbon Balances and Energy Impacts of the Management of UK Wastes *Defra R&D Project WRT 237* Final Report, Table A1.61

http://www.fcrn.org.uk/sites/default/files/ERM_Carbon_balances_and_energy_impacts_of_waste.pdf
Original source material: AEA Technology, National Household Waste Analysis Programme NHWAP (1992/3), Phase 2 Volume 2. Department of Environment 1995.

carbon content and calorific values of the individual materials has changed significantly.

Table 2. Baseline residual waste composition

Waste stream	Predicted residual waste for England 2011 kt	Proportion of total residual waste	Proportion of total residual waste revised categories
Paper	1459.89	0.104	
Card	680.91	0.049	
Mixed Paper and Card	0.00	0.000	0.153
Plastics	1751.87	0.125	0.125
Textiles (and footwear)	567.17	0.041	0.045
Miscellaneous combustibles	593.48	0.042	0.063
Miscellaneous non-combustibles	1278.05	0.091	0.091
Food	4318.42	0.308	0.308
Garden	423.27	0.030	0.030
Soil and other organic waste	478.49	0.034	0.034
Glass	665.37	0.048	0.048
Metals, White Goods and Other Non-biodeg Products	228.62	0.016	0.016
Non-organic fines	207.93	0.015	0.015
Wood	373.77	0.027	0.027
Sanitary / disposable nappies	628.80	0.045	0.045
Furniture	285.34	0.020	
Mattresses	62.63	0.004	
Bulky household items	0.00	0.000	
	0.00	0.000	
Total	14004.00	1.000	1

58. To effectively utilise data from both reports some of the waste stream categorisations needed to be merged to provide a single set. The changes implied by this are set out below, and the revised compositional data shown in the final column of the table above.

- Paper and card are considered under a single mixed heading
- Furniture is included under miscellaneous combustible
- Mattresses have been added to textiles[14]

[14] While it is recognised that a major component of the weight will be metal the major combustible component will be textile.

4.3. Energy recovery model

59. The energy recovery model needs to consider a number of factors:

Calorific value of the waste

60. The calorific value of the waste is how much (chemical) energy is stored in the waste per tonne that could potentially be converted into useful electrical or heat energy when burned. Waste such as plastic has a high calorific value whereas other wastes such as kitchen waste that is very wet have much lower values. This is due to the water adding significantly to the weight while adding nothing in energy terms. Energy is used to convert all the water to steam during combustion. The data available uses gross calorific value (higher heating value). More details on comparison of gross and net calorific values can be found in **Annex 1**.

The efficiency of conversion of that calorific value into energy

61. In reality, not all of the energy stored in the waste can be practically realised. Each step in the system of burning waste, using the resultant heat to make steam and using this steam to drive a turbine results in significant loss of energy. The efficiency of conversion takes account of this. For the purpose of the model the efficiency is considered to be the proportion of the energy stored in the waste that actually gets converted into energy (heat and/or electricity) useable outside of the plant i.e. net of any parasitic loads[15]. It important to know how much useable energy is generated, as this energy can be considered to substitute for energy that would have been generated using other means.

Energy (EfW) = mass of waste x calorific value x efficiency

62. All EfW efficiencies presented in the report have been calculated from the Gross CV (GCV) of the waste input. It is more usual to use net CV (NCV) to show efficiency, because this reflects the fact that the latent heat of condensation for water vapour is not utilised. For example, considering a high-performing electricity-only plant with a net CV efficiency of 30%. This equates to a gross CV efficiency of 25%. The difference that this makes is set out in more detail in **Annex 1**, together with information as to how an approximate conversion could be made between plant efficiencies calculated using NCV and GCV. Any comparison between the model and real plants needs to be based on efficiencies also calculated using gross CV (higher heating value).

63. This report and the model consider a wide range of potential plant efficiencies that would have lower net greenhouse gas emissions than landfill. However, in

[15] Parasitic load will primarily be the energy required to run the plant, but the concept could also easily be extended to include, for example, the energy required in a pre-treatment step for example to produce RDF.

reality EfW facilities will have to meet Best Available Techniques (BAT) derived on a case by case basis from the European BAT Reference Document (BREF Note) which covers the detailed technical requirements and which was published in 2006. Work on an update is not planned to start until 2014[16].

64. In 2009, the Environment Agency published guidance[17] for waste incineration based on the IPPC Directive. This has not been updated for the Environmental Permitting Directive. Whilst the efficiency figures apparently required are not particularly onerous for new build, there are several factors to consider including that BAT has to apply to existing as well as new plants. The Environment Agency sets out indicative BAT.

65. Importantly, recent planning inquiries have shown that for electricity only, a plant that is not classified as recovery (R1 status[18]) is unlikely to receive planning permission.

66. An efficiency of approximately 25.5%[19] is required to be classified as recovery (R1). The recovery of energy from waste is limited by boiler temperatures, steam pressures etc. to a potential maximum efficiency of approximately 33%, so there is a very narrow band of realistic efficiency values. If a higher thermal efficiency is required, useful heat will have to be provided, either alone or as combined heat and power (CHP), and the actual efficiency will be dependent on the heat load.

67. Therefore, while it is necessary for the model to include a wide range of theoretical efficiencies, in reality the window of attainable efficiencies in electricity only generation mode is quite narrow.

CO_2 offset through generation

68. It is assumed that the source of energy being replaced would have been generated using a plant with the carbon intensity (emissions factor) of the marginal energy mix[20] in line with HMT Green Book[21] guidance on appraisal

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[16] http://eippcb.jrc.ec.europa.eu/reference

[17] How to comply with your environmental permit Additional guidance for: The Incineration of Waste (EPR 5.01); Environment Agency, March 2009.

[18] European Union, (2008), Waste Framework Directive https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/218586/l_31220081122en00030030.pdf

[19] Based on net CV and equivalent to approximately 21.4% efficiency based on gross CV using the conversion factor calculated in Annex 1.

[20] The marginal energy factor relates to the generation of an additional unit of grid electricity. There will be a range of different plants generating so the carbon intensity will be a mix of these. As this mixture will change with time so will the emissions factor. An alternative way of considering it is the carbon intensity of the plant you would build to deliver that same energy if you didn't use EfW. Currently this is approximately the same as CCGT hence its use as the baseline value, however, this factor should only be used as a guide - use of the marginal factor is the correct approach for detailed analysis.

[21] The Green Book: Appraisal and evaluation in central government https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent and supplementary DECC guidance: Valuation of energy use and greenhouse gas

and evaluation. This is currently approximately equivalent to combined cycle gas turbine (CCGT) using natural gas so this has been taken as the baseline value. However, this 'marginal energy' mix is expected to vary over time and is therefore one of the variable parameters in the model. Generating the energy from waste offsets the amount of CO_2 that would have been emitted by a CCGT to generate an equivalent amount of energy.

Fossil CO_2 offset (CCGT) = Energy produced (EfW) x CO_2 emitted per unit energy (CCGT)

69. Estimates of the CO_2 emitted per unit energy from CCGT vary. For the purposes of this model we use the value used by DECC of 373 kg/MWh or 0.373 t/MWh [22].

The Fossil CO_2 Emitted as a Result of Energy Recovery

70. Assuming the waste is fully combusted, all of the carbon in the waste would be converted to CO_2. The fossil CO_2 emitted is therefore directly proportional to the amount of fossil carbon in the waste and similarly for the biogenic CO_2. The factor of 44/12 is used to account for the relative atomic masses of carbon (C=12) and molecular mass of CO_2 (C=12, O=16, 12+(2x16)=44).

Fossil CO_2 (EfW) = mass of waste x proportion fossil C in waste x 44/12

71. The net fossil CO_2 emitted from EfW is therefore CO_2 emitted by the energy from waste plant minus the CO_2 emitted by a CCGT power station in order to produce the same useable energy.

Net fossil CO_2 = Fossil CO_2 (EfW) – Fossil CO_2 offset (CCGT)

The Biogenic CO_2 Emitted as a Result of Energy Recovery

72. Although this is conventionally omitted we wanted to be able to understand the impact of including it. As above,

Biogenic CO_2 (EfW) = mass of waste x proportion biogenic C in waste x 44/12

73. The values used in the model for calorific value and carbon content of different waste streams are summarised in Table 3 below as extracted from the Carbon Balances report.

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emissions for appraisal https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[22] http://www.decc.gov.uk/en/content/cms/about/ec_social_res/iag_guidance/iag_guidance.aspx

Table 3. Waste composition data from the Carbon Balances report

	Total UK arisings (2003/4) kt	Proportion of total arisings	Proportion of waste fraction biogenic C by mass	Proportion of waste fraction fossil C by mass	Gross Calorific value MJ/kg
Paper and card	6462	0.18	0.32		12.6
Plastic film	969	0.03		0.48	23.6
Dense plastic	1313	0.04		0.55	26.7
Textiles	876	0.02	0.2	0.2	16
Absorbent hygiene products	807	0.02	0.15	0.04	8
Wood	1070	0.03	0.44		18.3
Other combustibles	771	0.02	0.19	0.19	15.6
Non-combustible	4262	0.12	0.035	0.035	2.8
Glass	2291	0.06	0.003		1.5
Ferrous metal	719	0.02			0
Non-ferrous metal	186	0.01			0
Kitchen waste	6095	0.17	0.14		5.3
Green waste	6282	0.18	0.17		6.5
Fine material	1395	0.04	0.07	0.07	4.8
WEEE	1394	0.04		0.16	7.6
Hazardous	374	0.01		0.3	12.4
Total	35266	1			

74. The categories used in this paper did not perfectly match those in the MelMod model. To achieve consistency, the following changes were made:

- Plastic film and dense plastic were merged into a single category with the carbon content and calorific values being a weighted average based on the arisings.
- The 'fines' category were split with the value for biogenic fines being assigned to the soils and other organic waste category and the fossil portion to non-organic fines.

75. Finally, a conversion factor of 1000/3600 [23] is applied to the calorific value to give it in megawatt hours per tonne of waste (MWh/t).

76. The final dataset used in the model is shown in Table 4 below.

[23] 1 tonne = 1000kg, 1MWh = 3600MJ

Table 4. Carbon content and calorific value by merged waste stream categories

Merged categories	Previous categories	Proportion biogenic C	Proportion fossil C	Calorific value MJ/kg	Calorific value MWh/t
Mixed Paper and Card	Paper, card	0.32		12.6	3.50
Plastics	Plastic film, Dense plastic		0.52	25.38	7.05
Textiles (and footwear)	Textiles	0.2	0.2	16	4.44
Miscellaneous combustibles	Other combustables	0.19	0.19	15.6	4.33
Miscellaneous non-combustibles	Non-combustable	0.035	0.035	2.8	0.78
Food	Kitchen waste	0.14		5.3	1.47
Garden	Green waste	0.17		6.5	1.81
Soil and other organic waste	Fine material (biogenic portion)	0.07		4.8	1.33
Glass	Glass	0.003		1.5	0.42
Metals, White Goods and Other Non-biodeg Products	Ferrous metal, Non-ferrous metal,				0.00
Non-organic fines	Fine material (fossil portion)		0.07	4.8	1.33
Wood	Wood	0.44		18.3	5.08
Sanitary / disposable nappies	Absorbant hygiene products	0.15	0.04	8	2.22

77. The calculation for the EfW half of the model, based on a theoretical 100% efficient plant, is shown in the table below. By varying the efficiency value in column (3) we can consider the balance for a range of plants

Table 5. Data set and calculations for the energy recovery half of the model

Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Prop. 1t	Calorific value MWh/t	Efficiency	Energy potential MWh =(1)x(2)x(3)	Prop. biogenic C	Mass of biogenic C =(1)x(5)	Mass of biogenic CO_2 released =(6)x44/12	Prop. fossil C	Mass of fossil C =(1)x(8)	Mass of fossil CO_2 released =(9)x44/12	Fossil CO_2 from CCGT offset =(4)x0.373	Net fossil CO_2 from EfW =(10)-(11)
Mixed Paper and Card	0.15	3.50	*1.00	0.54	0.32	0.05	0.18	0.00	0.00	0.00	0.20	-0.20
Plastics	0.13	7.05	*1.00	0.88	0.00	0.00	0.00	0.52	0.07	0.24	0.33	-0.09
Textiles (and footwear)	0.04	4.44	*1.00	0.20	0.20	0.01	0.03	0.20	0.01	0.03	0.07	-0.04
Miscellaneous combustibles	0.06	4.33	*1.00	0.27	0.19	0.01	0.04	0.19	0.01	0.04	0.10	-0.06
Miscellaneous non-combustibles	0.09	0.78	*1.00	0.07	0.04	0.00	0.01	0.04	0.00	0.01	0.03	-0.01
Food	0.31	1.47	*1.00	0.45	0.14	0.04	0.16	0.00	0.00	0.00	0.17	-0.17
Garden	0.03	1.81	*1.00	0.05	0.17	0.01	0.02	0.00	0.00	0.00	0.02	-0.02
Soil and other organic waste	0.03	1.33	*1.00	0.05	0.07	0.00	0.01	0.00	0.00	0.00	0.02	-0.02
Glass	0.05	0.42	*1.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	-0.01
Metals, Other Non-biodeg	0.02	0.00	*1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-organic fines	0.01	1.33	*1.00	0.02	0.00	0.00	0.00	0.07	0.00	0.00	0.01	0.00
Wood	0.03	5.08	*1.00	0.14	0.44	0.01	0.04	0.00	0.00	0.00	0.05	-0.05
Sanitary / disp nappies	0.04	2.22	*1.00	0.10	0.15	0.01	0.02	0.04	0.00	0.01	0.04	-0.03
Total	1.00			2.79		0.14	0.52		0.09	0.34	1.04	-0.70

*efficiency is included to be a potential variable in the calculation. It is set at the hypothetical value of 1 by default for the purpose of setting up the model, however, this is not intended to represent a realistic maximum for the actual value attainable.

78. The figures used for the model give the average calorific value of the mixed residual waste to be 2.79MWh/t, which is equivalent to around 10MJ/kg. The total percentage C in the waste is 23%. 61% of the carbon is biogenic in origin as therefore is the same proportion of the CO_2 emitted. All of these values are within the ranges commonly identified for mixed municipal waste.

79. Notably, if the biogenic proportion by simple mass balance of the waste, assigned by reference to the waste category (i.e. food 100% biogenic, textiles 50% biogenic 50% fossil etc) rather than a measure of the actual carbon content, then the apparent biogenic content of the waste would be much higher at around 67%. Understanding these differences is important when it comes to assessing the renewable energy potential. Calorific value and therefore energy produced is highly correlated to carbon content. A carbon-based measure of biogenic content would give a good indication of renewable energy potential, whereas a category based input measure would overestimate renewable energy potential.

80. The calorific value is slightly higher than some generally used, while the biogenic proportion is lower. This is self consistent as the fossil wastes such as plastics tend to have higher calorific values than the biogenic streams which have higher water content and correspondingly lower calorific values. The actual values determined for the example composition used to set up the model are unimportant, as one of the purposes of the model is to vary that composition and examine the effect.

81. From these figures it can also be concluded that for this composition of waste an overall conversion efficiency of greater than 33% (=100 x 0.34/1.04) would ensure that the EfW plant emitted less fossil CO_2 than CCGT generating the same energy. To emit less CO_2 overall, including biogenic, would require a conversion efficiency of 83% (=100 x ((0.52+0.34)/1.04)). The latter efficiency is probably not obtainable. However, effective use of CHP or ACT could easily reach the former, potentially making EfW with CHP as a power source sustainable compared to other fossil generation, without the need for offsetting landfill emissions (for this composition).

4.4. Landfill model

82. As with the energy recovery model, the landfill model needs to consider a number of factors:

- the proportion of carbon in the waste that actually degrades to give landfill gas
- the relative proportions of CO_2 and methane in landfill gas
- the level of landfill gas capture
- the quantity of energy generated from the methane in landfill gas and how much energy this would offset from an alternative fossil source
- the amount of methane naturally oxidised in the landfill
- the amount of methane released into the atmosphere
- the potency of methane as a greenhouse gas compared to CO_2

83. Conventionally, biogenic CO_2 emissions are disregarded. However, if these are included in the energy recovery part of the model, they should also be included in the landfill part.

84. All of the carbon contained within the fossil portion of waste can be considered to be locked away in landfill, as fossil-based plastics take a very long time to degrade. As a result, it is assumed it does not result in release of greenhouse gases. Biological processes within the landfill will degrade the biogenic portion of the waste. However, not all of the carbon in this biogenic portion will degrade to form CO_2 or methane and some, like the fossil carbon, will become locked away. The proportion of degradable carbon varies by material. This has been assessed for the development of the MelMod model. Values from MelMod have been used in this model and are summarised in Table 6 below.

Table 6. Data set from MelMod

	Proportion of waste that is biogenic C	Proportion of waste that is decomposable C	Proportion of waste in 1t	Mass of biogenic C in 1t	Mass of decomposable C in 1 t
Mixed Paper and Card	0.32	0.158	0.15	0.049	0.024
Plastics		0	0.13	0.000	0.000
Textiles (and footwear)	0.2	0.0667	0.04	0.009	0.003
Miscellaneous combustibles	0.19	0.0889	0.06	0.012	0.006
Miscellaneous non-combustibles	0.035	0	0.09	0.003	0.000
Food	0.14	0.0849	0.31	0.043	0.026
Garden	0.17	0.0872	0.03	0.005	0.003
Soil and other organic waste	0.07	0.0025	0.03	0.002	0.000
Glass		0	0.05	0.000	0.000
Metals, White Goods and Other Non-biodeg Products		0	0.02	0.000	0.000
Non-organic fines		0	0.01	0.000	0.000
Wood	0.44	0.1253	0.03	0.012	0.003
Sanitary / disposable nappies	0.15	0.043	0.04	0.007	0.002
Total			1.00	0.142	0.067

85. As can be seen from the table, under the assumptions in the MelMod model a significant proportion (just over 50%) of the biogenic carbon in the waste is not considered to be decomposable and therefore remains locked in the landfill.

Methane produced

86. Landfill gas produced by decomposition of biogenic waste is a mixture of methane and carbon dioxide. The proportions of each will be dependent upon the exact biological processes being undergone but a reasonable assumption would be that landfill gas is approximate 1:1 mix by volume.

87. In terms of this model this means that the decomposable proportion of the biogenic waste decomposes by a range of processes to give a mixture of CO_2 and methane. The mass balance of the different decomposition routes results in a 1:1 mixture by volume of CO_2 and methane. When differing molecular masses and densities are taken into account this means that the proportion of decomposable biogenic carbon by mass that becomes methane is also around 50%, the remainder is released as biogenic CO_2.

Table 7. Potential contribution to landfill gas by waste stream

	Mass of decomposable C in 1 t	Potential mass of CH_4 from decomposition =Mass of C x 0.5 x 16/12	Potential mass of CO_2 from decomposition =mass of C x 0.5 x 44/12
Mixed Paper and Card	0.024	0.016	0.044
Plastics	0.000	0	0
Textiles (and footwear)	0.003	0.0020	0.0055
Miscellaneous combustibles	0.006	0.0037	0.010
Miscellaneous non-combustibles	0.000	0	0
Food	0.026	0.017	0.048
Garden	0.003	0.0018	0.0048
Soil and other organic waste	0.000	0.000005	0.00016
Glass	0.000	0	0
Metals, White Goods and Other Non-biodeg Products	0.000	0	0
Non-organic fines	0.000	0	0
Wood	0.003	0.0022	0.0061
Sanitary / disposable nappies	0.002	0.0013	0.0035
Total	0.067	0.044	0.12

Methane released

88. It is assumed that all the CO_2 released in this way will find its way into the atmosphere, where it counts as biogenic CO_2 and is generally discounted in calculations. The methane can undergo a number of different fates, standard assumptions are:

- 75%[24] of the landfill gas, and therefore 75% of methane by mass is captured and burned. Of the gas captured around 50% is used to generate energy, the remainder is flared
- of the remaining 25%, 10% will be oxidised to CO_2 before it can be released into the atmosphere - this is equivalent to 2.5% of the overall methane
- the remaining 22.5% of methane is released into the atmosphere

89. For the purposes of the model these are the baseline figures used, however the model is designed in such a way that the proportion of landfill gas captured can be varied with a consequential impact on the amount of methane released into the atmosphere.

Methane released = tot. methane x (1-prop. methane captured) x (1-prop. methane oxidised)

90. For 1 tonne of methane using the baseline figures above

Methane released = 1 x (1-0.75)*(1-0.1)

= 1 x 0.25 x 0.9

=0.225

i.e. 22.5%

91. As with the CO_2 produced as part of the landfill gas, CO_2 produced from combustion of methane captured as landfill gas or natural oxidation is assumed to be released into the atmosphere and counted as biogenic short cycle $CO_{2.}$ Therefore it is not included in calculations unless biogenic emissions are being specifically considered.

Energy from landfill gas

92. The methane captured as landfill gas is assumed to be combusted to produce energy or flared. The amount of energy produced will depend upon the calorific value of the gas and the efficiency of conversion to usable energy.

93. For the purposes of the model the methane in landfill gas is assumed to have calorific value of 50MJ/kg with an electrical conversion efficiency of 41%. Over the lifetime around 50% of this will be flared with the remainder used for energy generation:

Energy (landfill) = mass of methane x proportion used for generation x calorific value x efficiency

[24] This is the estimated lifetime capture rate. The value of 75% is that currently used by Government for Greenhouse Gas Inventory and other purposes. A further discussion on landfill gas capture rate can be found in **0**.The sensitivity of the model to this value is examined later.

94. This gives a generating capacity of 2.8MWh per tonne of methane.

Carbon offset from generation

95. It is assumed that the source of energy being replaced is the same as for the EfW side of the model, i.e. the marginal energy mix. As noted above the baseline value is taken as being approximately equivalent to combined cycle gas turbine (CCGT) using natural gas. Generating the energy from waste offsets the amount CO_2 that would have been emitted by a CCGT to generate an equivalent amount of energy. As with the EfW side of the model this is considered to be a key variable.

$$tCO_2 \text{ offset (CCGT)} = \text{Energy produced (landfill)} \times CO_2 \text{ emitted per unit energy (CCGT)}$$

CO_2 Equivalents released

96. The 22.5% of the methane remaining is assumed to be released into the atmosphere where it acts as a greenhouse gas. The relative potency of methane as a greenhouse gas is a matter of some debate. For some time it has been considered to be 21 times more potent than $CO_{2,}$ however, more recently 25 times has become the more accepted figure based on the IPCC estimates. For the purposes of the model the default is the most recent assessment, 25, although this can be varied to assess the sensitivity. The methane emissions can therefore be converted into equivalent tonnes of CO_2 (CO_2e) by multiplying the tonnes of methane by 25.

$$tCO_2e = \text{t methane} \times 25$$

Net landfill emissions as CO_2e

97. The net CO_2 emissions from landfill can therefore be calculated as:

$$CO_2e \text{ (landfill)} = tCO_2e \text{ (methane)} - tCO_2 \text{ (CCGT)}$$

Or, if all biogenic emissions are counted:

$$CO_2e \text{ (landfill)} = tCO_2e \text{ (methane)} - tCO_2 \text{ (CCGT)} + tCO_2 \text{ (oxidation)} + tCO_2 \text{ (combustion)} + tCO_2 \text{ (decomposition)}$$

98. Based on these calculations the data for this composition of residual waste is shown in Table 8 below.

Table 8. Data and calculations for the baseline landfill component of the model

Column number	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	Prop. 1t	Proportion decomposable C	Mass of decomposable C in 1 t (1) x (2)	Mass of CH_4 (3) x 0.5 x 16/12	Mass of CO_2 (3) x 0.5 x 44/12	Mass of methane captured (4) x 0.75	CO_2 from methane burned (6) x 44/16	Energy from methane burned 2.84 x 0.5 x(6)	CO_2 offset from energy generated 0.382 x (8)	Mass of methane oxidised (4) x (1-0.75) x 0.1	CO_2 from oxidation (10) x 44/16	Methane released (4) x (1 -0.75 -((1-0.75) x 0.1))	CO_2e of methane (12) x 25x	Net CO_2e emitted (13)-(9)
Mixed Paper and Card	0.15	0.158	0.0242	0.0161	0.044	0.0121	0.0332	0.034	0.0132	0.00040	0.00111	0.0036	0.091	0.077
Plastics	0.13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Textiles (and footwear)	0.04	0.067	0.0030	0.0020	0.005	0.0015	0.0041	0.004	0.0016	0.00005	0.00014	0.0004	0.011	0.010
Miscellaneous combustibles	0.06	0.089	0.0056	0.0037	0.010	0.0028	0.0077	0.008	0.0030	0.00009	0.00026	0.0008	0.021	0.018
Miscellaneous non-combustibles	0.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Food	0.31	0.085	0.0262	0.0175	0.048	0.0131	0.0360	0.037	0.0143	0.00044	0.00120	0.0039	0.098	0.084
Garden	0.03	0.087	0.0026	0.0018	0.005	0.0013	0.0036	0.004	0.0014	0.00004	0.00012	0.0004	0.010	0.008

Column number	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	Prop. 1t	Proportion decomposable C	Mass of decomposable C in 1 t (1) x (2)	Mass of CH_4 (3) x 0.5 x 16/12	Mass of CO_2 (3) x 0.5 x 44/12	Mass of methane captured (4) x 0.75	CO_2 from methane burned (6) x 44/16	Energy from methane burned 2.84 x 0.5 x(6)	CO_2 offset from energy generated 0.382 x (8)	Mass of methane oxidised (4) x (1-0.75) x 0.1	CO_2 from oxidation (10) x 44/16	Methane released (4) x (1 -0.75 -((1-0.75) x 0.1))	CO_2e of methane (12) x 25x	Net CO_2e emitted (13)-(9)
Soil and other organic waste	0.03	0.003	0.0001	0.0001	0.0	0.0	0.0001	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Glass	0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Metals, Other Non-biodeg Products	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-organic fines	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wood	0.03	0.125	0.0033	0.0022	0.006	0.0017	0.0046	0.005	0.0018	0.00006	0.00015	0.0005	0.013	0.011
Sanitary / disp. nappies	0.04	0.043	0.0019	0.0013	0.004	0.0010	0.0027	0.003	0.0011	0.00003	0.00009	0.0003	0.007	0.006
Total	1		0.0669	0.0446	0.123	0.0335	0.0920	0.096	0.0365	0.00112	0.00307	0.0100	0.251	0.214

99. The one component missing in the landfill model is time. Whereas all the CO_2 from an energy from waste plant is emitted immediately at the time of combustion the methane released from landfill appears in the atmosphere over an extended period of time. This is particularly challenging to model and beyond the scope of this work. This model therefore compares only the total CO_2e emissions and assumes the same equivalent volume emitted from either source will have the same long term impact. This is a simplification but one that is often necessarily used.

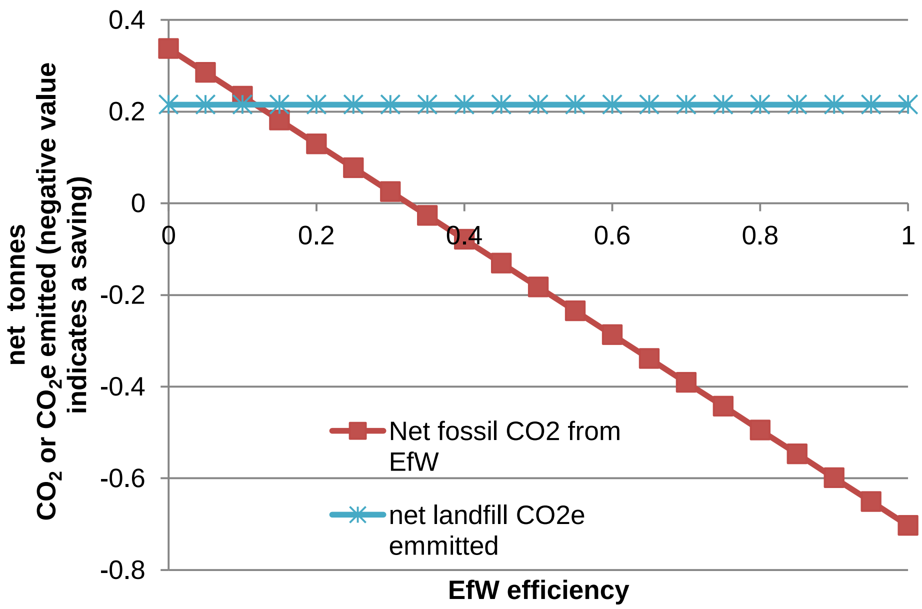
5. The combined model

100. In its simplest form the combined model is the difference between the two components. For the waste composition above the net fossil CO_2 emissions from EfW are -0.73tCO_2 (minus indicates a saving) and those from landfill are 0.215 tCO_2e so for the overall EfW process there is a saving of -0.73-0.215 = -0.945 tCO_2e indicating a significant carbon saving from EfW compared to landfill, as one would expect in the hypothetical case of 100% efficient EfW. In reality EfW efficiencies are much lower than this and thus the balance of carbon savings is more subtle and sensitive to some of the key parameters being modelled here.

101. Of greater interest is the balance point in terms of efficiency at which EfW becomes the same as landfill. This will be dependent on the composition of the waste. At a constant composition it can be determined by applying a linear reduction to the efficiency of energy production. This reduces the CO_2 offset from alternative sources so the overall net impact becomes the same as landfill i.e. in this example at what efficiency is the net impact of EfW equal to the emissions of 0.215tCO_2e from landfill. For this composition and assumption set it turns out this would require a net efficiency of 11.7%, about half that of a typical moving grate incinerator.

102. The next step is to examine the sensitivity of the model to different input parameters and assumptions and the efficiency required to deliver the environmental benefits across a range of different waste compositions.

Chart 1. **Variation in CO_2e emissions from EfW and landfill with EfW plant efficiency for the same tonne of waste**



5.1. Sensitivity analysis

103. There are a number of different assumptions underpinning the model so it is important to understand how varying these affect the model outputs.

104. The impact of different assumptions is also likely to be different depending of on the composition of the waste as factors such as landfill gas capture rate would be expected to be much more important for high biogenic content. To examine this three different theoretical waste compositions were developed for use in the model, set out in Table 9 below. The compositions were developed using simple manipulation of the proportions of the primary biogenic waste streams to give a linear change in biogenic content rather than to exemplify any particular real world composition. The compositions were:

- the baseline composition discussed above with around 60% biogenic content
- a composition containing around 50% biogenic content developed by halving the mass of paper, food, garden waste and wood in the baseline composition and then normalising the new proportions back to 1 tonne
- a composition containing around 40% biogenic content similarly developed by reducing paper, food, garden waste and wood to 25% of the levels in the baseline composition and then normalising the new proportions back to 1 tonne

Table 9. Sample compositions for sensitivity analysis

	Composition approx 60% biogenic	Composition approx 50% biogenic	Composition approx 40% biogenic
Mixed Paper and Card	15.3%	10.6%	6.3%
Plastics	12.5%	17.3%	20.5%
Textiles (and footwear)	4.5%	6.2%	7.4%
Miscellaneous combustibles	6.3%	8.7%	10.3%
Miscellaneous non-combustibles	9.1%	12.6%	14.9%
Food	30.8%	21.3%	12.6%
Garden	3.0%	2.1%	1.2%
Soil and other organic waste	3.4%	2.4%	5.6%
Glass	4.8%	6.6%	7.8%
Metals, White Goods and Other Non-biodeg Products	1.6%	2.3%	2.7%
Non-organic fines	1.5%	2.1%	2.4%
Wood	2.7%	1.8%	1.1%
Sanitary / disposable nappies	4.5%	6.2%	7.3%
Total	100.0%	100.0%	100.0%
Actual % of C of biogenic origin	60.7%	48.5%	39.7%
Total Carbon	23.4%	24.7%	25.0%
CV MWh/t	2.79	3.01	3.11

105. The parameters being examined and key data ranges are set out in Table 10 below. Each parameter is independently varied for each of the three compositions. The output measure is the minimum net efficiency required for EfW to be better than landfill based on EfW fossil only emissions.

106. The ranges were selected to include the likely extremes for each of the variables and also to include an appropriate number of intermediate points. This means that some of the ranges tested are quite large, for example landfill gas capture, where a broad range of figures are quoted in the literature while others are quite small e.g. the potency of methane as a greenhouse gas.

107. The results of the analysis are summarised in Table 11 below in relation to the sensitivity to the changes of the net efficiency of EfW required to be better than landfill.

Table 10. Parameters being independently varied for sensitivity analysis

Parameter being independently varied	Reason for likely variance	Range examined (baseline in bold)	Rationale for range selection
Carbon intensity of displaced energy source	The marginal energy source may change over time	**0.373**, 0.300,0.250, 0.200, 0.150 t/MWh	Background/marginal energy mix expected to reduce in carbon intensity over time
Proportion of decomposable C going to methane	Essentially varying the composition of landfill gas	0.4, **0.5**, 0.6	Values quoted tend to be in the range 40-60% methane
Proportion of methane captured	Landfill gas capture estimates vary significantly depending on the age and type of landfill	0.85, 0.8, **0.75**, 0.7, 0.65, 0.6, 0.55, 0.5, 0.45, 0.40	Baseline estimate of 75% is considered towards likely maximum so range weighted to lower values
Efficiency of landfill gas engine	Range of different engines exist	0.51, **0.41**, 0.31	10% either side of baseline
Proportion of landfill gas used in generation (not flared)	Range of estimates exist for energy use /flaring rate	0.7, **0.5**, 0.3	20% either side of baseline
Proportion of methane oxidised	Range of values exist	0.2, 0.15, **0.1**, 0.05	
Global warming potential of methane	Range of values quoted in literature	**25,** 23, 21	From latest value of 25 to previous estimates of 23 and 21
Calorific value of waste	Different estimates exist	Carbon balances WRATE model	
C content of waste	Different estimates exist	Carbon balances WRATE model	

Table 11. Outcome of sensitivity analysis for each of the parameters varied

Parameter varied	Change applied (% variation cf baseline)	Difference in net EfW efficiency required between extremes (% change cf baseline)			Comments
		At 60%	At 50%	At 40%	
Carbon intensity of displaced energy source	0.373 to 0.15 t/MWh (60%)	0.12 (+105%)	0.35 (+134%)	0.51 (+141%)	**Highly sensitive**. At low biogenic content decreasing the carbon intensity of the energy mix significantly increases the efficiency of EfW required. At high biogenic content decreasing marginal carbon intensity also increases the efficiency required but to a smaller extent.
Proportion of decomposable C going to methane	0.4 to 0.6 (40%)	-0.083 (-22%)	-0.061 (-13%)	-0.044 (-8%)	**Sensitive** at high biogenic. Increasing the proportion of carbon decomposing to methane reduces the EfW efficiency required with the greatest impact with higher biogenic content.
Proportion of methane captured	0.85-0.4 (60%)	-0.45 (-387%)	-0.34 (-129%)	-0.25 (-67%)	**Highly sensitive.** Reducing the proportion of landfill gas captured significantly reduces the efficiency of EfW required. Most sensitive at high biogenic content.
Efficiency of landfill gas engine	0.51-0.31 (50%)	-0.017 (-4%)	-0.012 (-2.5%)	-0.009 (-1.6%)	**Insensitive**. Slight reduction if the landfill gas engine is less efficient. Within the likely range the model is insensitive.
Proportion of landfill gas used in generation	0.7-0.3 (80%)	-0.027 (-6.5%)	-0.020 (-4%)	-0.015 (-2.5%)	**Insensitive**. Slight reduction if less landfill gas is used for generation (more flared). Within the likely range the model is insensitive

Parameter varied	Change applied (% variation cf baseline)	Difference in net EfW efficiency required between extremes (% change cf baseline)			Comments
		At 60%	At 50%	At 40%	
Proportion of methane oxidised	0.2-0.05 (150%)	-0.04 (-10%)	-0.03 (-6%)	-0.022 (-4%)	**Insensitive.** Slight reduction in EfW efficiency required if less of the methane is oxidised
Global warming potential of methane	25-21 (16%)	0.039 (-9%)	0.029 (-6%)	0.021 (-4%)	**More sensitive at high biogenic content.** Increase in EfW efficiency required if the warming potential of methane is assumed to be lower
Calorific value of waste	Carbon balances - WRATE	0.022 (5%)	0.041 (8%)	0.051 (9%)	**More sensitive at low biogenic content**. Slight increase at high biogenic content and greater increase at low biogenic content. This is consistent with WRATE data having slightly higher calorific values for food and garden waste and lower for plastics
C content of waste	Carbon balances - WRATE	-0.01 (-2.5%)	-0.013 (-2.5%)	0.015 (-2.5%)	**Insensitive**. The values only differ marginally between the two data sets

108. The analysis above shows that the key factors in determining the environmental benefits of EfW in terms of the relationship between the efficiency of the EfW plant and the biogenic content of the waste are the background marginal energy mix being offset and the amount of methane being released from landfill (driven by the level of capture and amount produced).

109. Factors such as the exact data set used to represent the calorific value of the waste and carbon make up or efficiency of energy generation from landfill are much more marginal – within the range of variation between the data sets available. Therefore while potentially having an impact on marginal cases it is reasonable to adopt a consistent set of these parameters. For all subsequent analysis we will use the baseline values set out above.

5.2. Varying the composition of waste

110. One of the key aims in developing this model was to understand how varying the composition of the waste input to EfW impacted on the environmental case.

111. As illustrated in the sensitively analysis above the model allows variation in the various components of the waste. This is done by making a change to the mass of a type of waste in the reference composition and then normalising the new composition back to 1 tonne. The example of halving the food waste going to EfW is illustrated in Table 12 below.

Table 12. Example change in relative composition of 1 tonne of waste by altering the absolute amount of a waste stream

	Reference composition	Composition with mass of food waste halved	Revised composition of 1 tonne
Mixed Paper and Card	0.1528	0.1528	0.1807
Plastics	0.1250	0.1250	0.1479
Textiles (and footwear)	0.0449	0.0449	0.0531
Miscellaneous combustibles	0.0627	0.0627	0.0741
Miscellaneous non-combustibles	0.0912	0.0912	0.1078
Food	0.3083	0.1541	0.1822
Garden	0.0302	0.0302	0.0357
Soil and other organic waste	0.0341	0.0341	0.0403
Glass	0.0475	0.0475	0.0561
Metals, White Goods and Other Non-biodeg Products	0.0163	0.0163	0.0193
Non-organic fines	0.0148	0.0148	0.0175
Wood	0.0266	0.0266	0.0315
Sanitary / disposable nappies	0.0449	0.0449	0.0530
Total mass	1	0.8458	1
% C of biogenic origin	60.73		56.75
Calorific value MWh/t	2.79		3.03

112. As can be seen the halving of the total mass of food waste results in less than halving the proportion of food waste in a typical 1 tonne mixture but also an increase

in the proportion of all the other components. The overall number of tonnes of waste available will of course be reduced. This has an impact on the biogenic carbon content and the calorific value of the waste. The former goes down as a purely biogenic source is being removed while the latter goes up as the calorific value of food waste is relatively low due to the high water content.

113. In order to examine the impact of changing composition on the model a range of example compositions were developed. A number of these are somewhat arbitrary, designed to examine how the model performs across the full range of values rather than to reflect possible real world compositions[25], for example a linear reduction in waste with a biogenic component. Others were based on potentially more realistic impacts of policy such as removing food waste, or reduced wood waste, or waste of certain types to EfW increasing due to landfill bans. Also included were the two extremes of no biogenic waste and 100% biogenic waste. These are summarised in Table 13.

Table 13. Example compositions modelled

Composition	Proportion of C in the waste that is biogenic (%)	CV (MWh/t)	EfW net efficiency required to be better than landfill
Baseline	60.73	2.79	0.12
80%* of baseline biogenic waste	56.7	2.90	0.16
60%* of baseline biogenic waste	51.1	3.07	0.22
40%* of baseline biogenic waste	42.7	3.36	0.31
20%* of baseline biogenic waste	28.5	3.94	0.46
No biogenic waste	0	5.77	0.72
No fossil waste	100	2.02	-0.39
No food	51.8	3.38	0.24
No food, no garden waste	50.54	3.44	0.25
No garden, 20% food, 20% wood	50.33	3.22	0.24
No textiles	61.6	2.71	0.10
No inert non combustible material (glass, metal etc)	61.0	3.19	0.11
No plastics	84.1	2.18	-0.16
20% paper/card, 50% plastics, 30% food, 10% garden, textiles, glass and metal (good recycling area)	53.9	2.85	0.22
Plastic and paper with contaminants of food at 10% (RDF from an MBT process)	45.0	4.73	0.28
No wood	58.7	2.73	0.13
Double wood (e.g. if landfill restriction)	62.6	2.85	0.10

[25] It is relatively straightforward to develop new compositions for the purposes of theoretical modelling. The ability to do so in terms of real world interventions is much more limited. The composition of residual waste is dictated by the composition of arisings and the collection, reuse and recycling systems it is subject to. Introduction of new regimes such as separate collection of plastic or the use of MBT type processes could be used to manipulate the composition but they would be unlikely to deliver some of the more extreme example compositions being modelled.

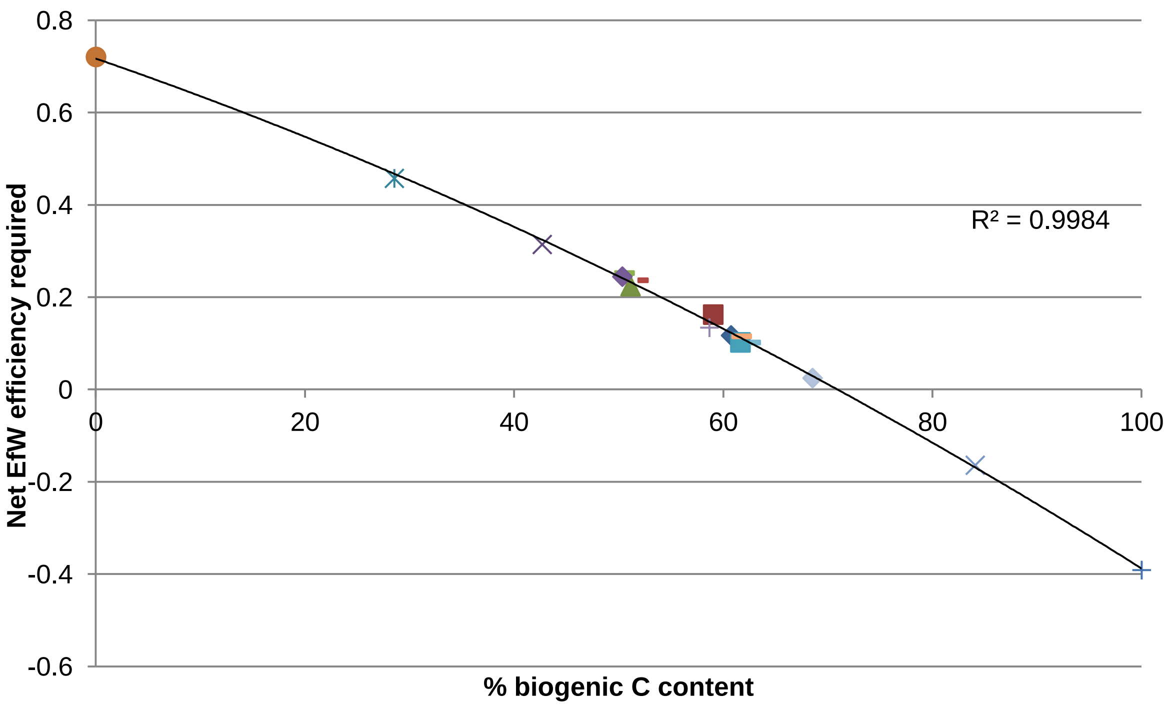
Composition	Proportion of C in the waste that is biogenic (%)	CV (MWh/t)	EfW net efficiency required to be better than landfill
Double wood and double textiles	61.7	2.91	0.12
Reducing each component by a randomly generated percentage	68.5	2.55	0.025

*all wastes with a mix of biogenic and fossil e.g. textiles were included in the reduction

114. The different compositions resulted in a wide range of biogenic content, CV and efficiencies required for EfW to be better than landfill. For a couple of compositions the model produces a negative value for the efficiency of the plant required. This is because for these compositions the mass of fossil carbon emitted from the EfW plant is less than the carbon equivalents emitted by landfill without needing to take into account the energy generated offsetting other sources. In theory combustion of waste with these compositions without energy recovery would be environmentally justifiable on carbon grounds but would clearly be a waste of a valuable energy source and thus highly undesirable.

115. The biogenic composition has been plotted against the minimum net efficiency required for EfW to be better than landfill. Across the range of compositions it is clear that the model produces a highly correlated relationship, albeit slightly non-linear.

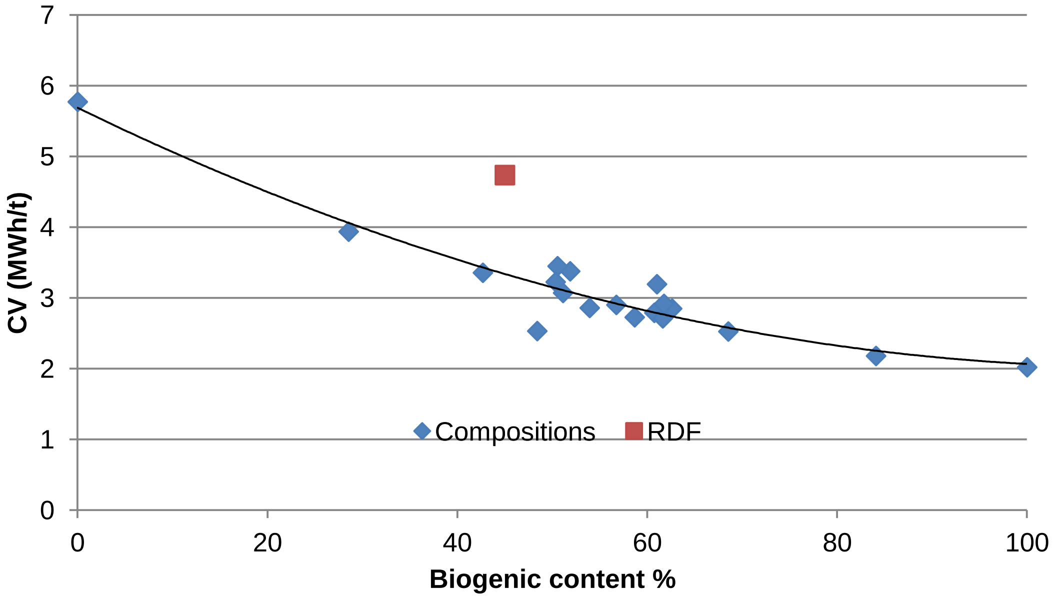
Chart 2. Net efficiency of EfW required as a function of biogenic C content of a range of waste compositions



116. There is some deviation from the trend albeit relatively small for certain compositions of wastes particularly where food is significantly reduced relative to other waste types, tending to give a slightly higher than expected efficiency requirement for the biological content. This is probably due to food having the highest proportion of decomposable carbon of all the waste types and therefore having a proportionally greater impact on methane emissions relative to its calorific value. However, even with these variations the correlation is still very good (R^2 = 0.99). Notably the randomly generated composition also falls on the trend line.

117. A plot of calorific value against biogenic content (Chart 3) also produces a reasonably consistent trend with one notable outlier relating to the composition designed to mimic a paper/plastic RDF. This is due to most biogenic wastes having relatively high moisture content and therefore relatively low calorific value, paper being the exception.

Chart 3. Calorific value of waste as a function of biogenic content of a range of waste compositions



118. The level of consistency in the trends produced by the model means that general conclusions regarding the impact of changes in key variables such as the rate of landfill gas capture can be reliably examined using a relatively small range of example compositions. To this end the first ten compositions in the table above have been used to examine the impact on the trend of changes to key variables in more detail. These compositions were chosen to give a good range of variation in biogenic content as well as a few example compositions that might appear slightly off the trend where food in particular has been reduced.

5.3. Changing the marginal electricity mix

119. One of the variables that showed significant sensitivity across a range of reasonable values was the marginal energy mix in terms of its carbon intensity (tCO_2/MWh). Up to now we have used the comparator of CCGT to estimate the CO_2 offset from

energy generation. More correctly we should use the marginal energy mix which represents the carbon intensity of generating an additional kW of electricity. Currently this is comparable to CCGT as this is the marginal technology, however, as renewable energy and nuclear make a greater contribution to the marginal energy mix this will change and the result will be a significant drop in the carbon intensity of the marginal energy mix.

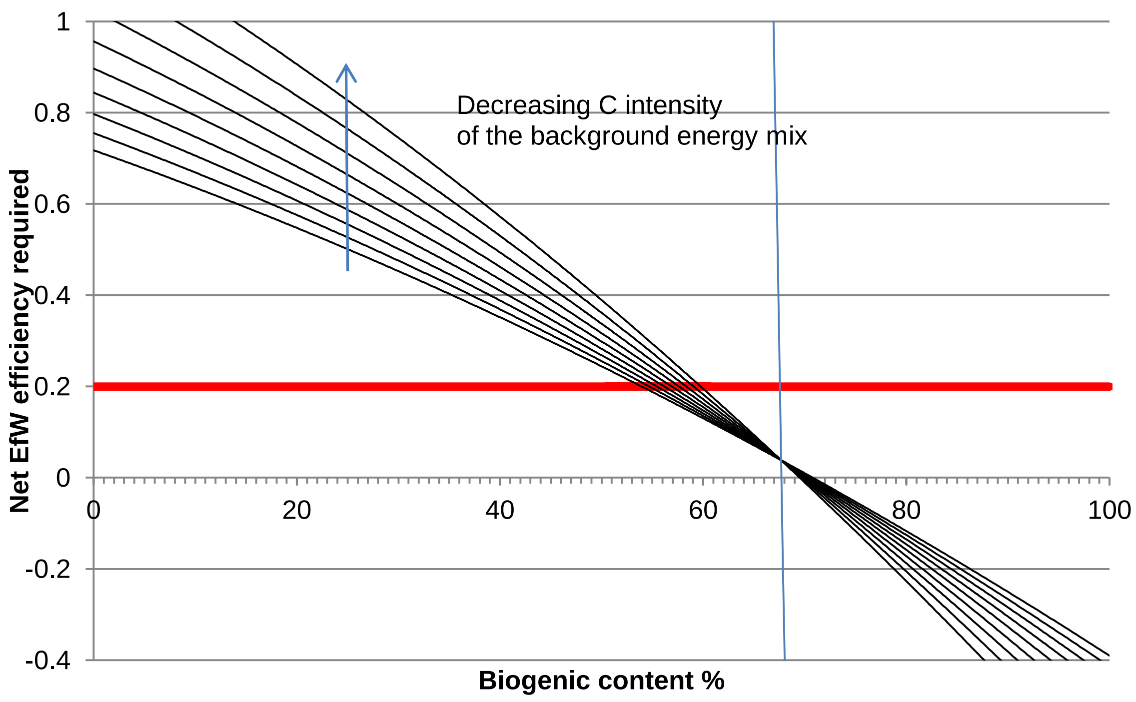
120. The impact of changing this marginal carbon intensity on the efficiency required from EfW was examined using a range of different values set out in Table 14 and the range of compositions outlined above. All other starting parameters were the same as the baseline model.

Table 14. Changing the C intensity of offset energy

Proportion of baseline C intensity	C intensity t/MWh
1	0.373
0.95	0.354
0.9	0.336
0.85	0.317
0.8	0.298
0.75	0.280
0.7	0.261
0.65	0.242
0.6	0.224
0.001 (equivalent to 0 – to avoid Div0 errors, all non-fossil)	0.00037

121. The output from the model for these different values is shown in Chart 4 below.

Chart 4. Impact of changing energy offset on the efficiency of EfW as a function of biogenic C content of a range of waste compositions



122. As expected the efficiency of EfW plant required varies as the marginal electricity carbon intensity changes. As can be seen from Chart 4 there is a static point where the efficiency required is independent of the marginal electricity carbon intensity. This will be the biogenic content at which the energy offset by EfW is the same as the energy offset by generation from landfill gas. Taking the extreme value of zero carbon intensity of the marginal electricity mix the trendline appears vertical at the static point (blue line), which for this set of baseline assumptions occurs at a biogenic content of around 68%.

123. For compositions with a biogenic content to the left of this point (lower than 68%) decreasing the marginal electricity carbon intensity increases the efficiency of energy from waste plant required to outperform landfill whereas for compositions to the right (greater than 68%) the opposite is true.

124. Under this set of assumptions, considering an EfW plant with a net efficiency of 20% (red line) it can be seen that, with the current carbon intensity of CCGT at 0.373t/MWh, waste with a biogenic content of greater than around 54% would be better going to EfW than landfill. But as the marginal electricity carbon intensity reduces, the minimum biogenic content required increases to e.g. 60% at a marginal electricity C intensity of 0.224t/MWh (60% of current). At a zero marginal electricity C intensity this would reach the 68% biogenic content limit.

125. A plant with 60% efficiency would be able to deal with lower biogenic content waste, around 14% with a marginal electricity mix of 0.373t/MWh, but this will be much more sensitive to changes in the marginal electricity mix moving to around 39% biogenic content at a marginal electricity C intensity of 0.224t/MWh (60% of the current value). However, it will be subject to the same limiting value of 68% biogenic content and except at this extreme will always be able to accept lower biogenic content waste than a lower efficiency plant.

126. The static point is above zero efficiency (around 0.025). To the right of this point as the carbon intensity decreases the biogenic content required for EfW to be better than landfill also decreases. The maximum biogenic content required is therefore around 71% at the current marginal electricity C intensity of 0.373t/MWh. Using this baseline set of assumptions EfW will always be better than landfill regardless of marginal electricity mix or EfW plant efficiency for waste compositions of above 71% biogenic content.

127. The slope of the trendline is dependent on the marginal energy mix being offset. As there is inherently a static point for the composition where the energy from EfW matches that from landfill the trendline ‘rotates’ around this point as the background intensity decreases. The lower the background carbon intensity the steeper the line. The lower the biogenic content of the waste then the net EfW efficiency required to favour EfW over landfill will be much more sensitive to changes in the comparative marginal energy mix.

128. This example considered electricity only. There will be a similar marginal energy mix for heat and transport fuels. While the absolute values will be different the expected trend would be the same – as the marginal energy carbon intensity decreases the minimum efficiency required for EfW to outperform landfill will increase.

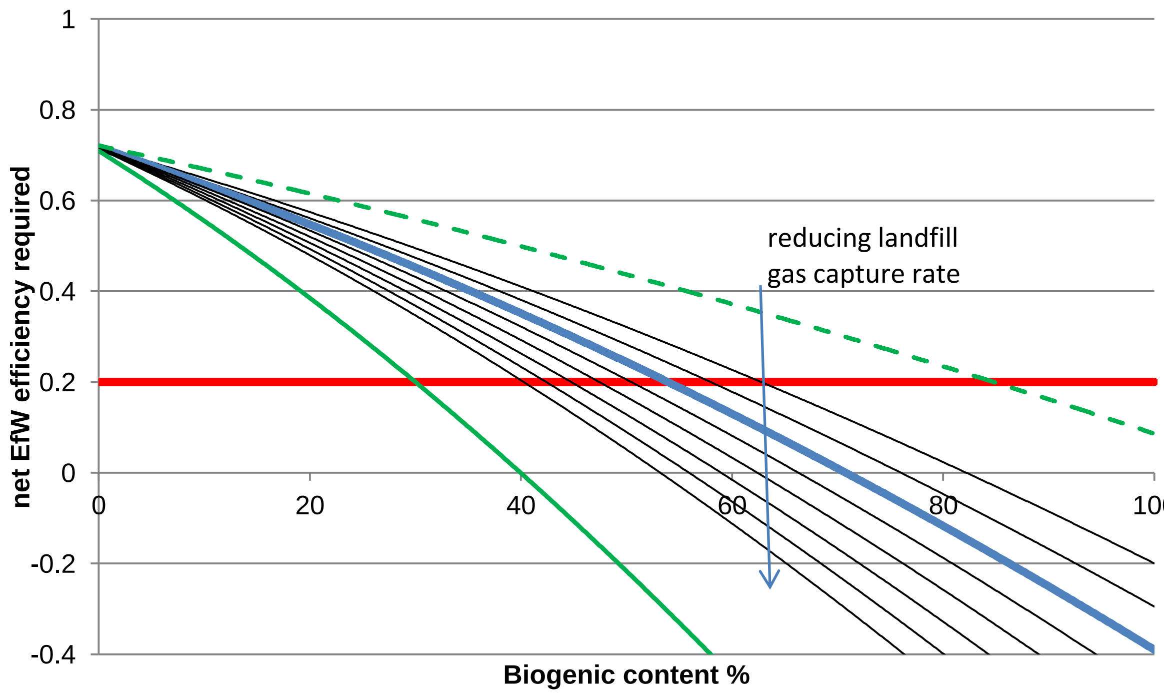
129. The other factor which can affect the slope of the trendline is the position of the static point. This will be a function of methane emissions from landfill.

5.4. Changing methane emissions from landfill

130. There are a number of different factors than can alter the level of emissions from landfill and their impact: the amount of landfill gas captured, oxidation rate and potency of methane as a greenhouse gas are the primary ones. Of these the proportion of methane captured had the greatest impact across the likely range of values in the sensitivity analysis. Estimates of landfill gas capture are discussed in more detail in **Annex 2.** Methane emissions from landfill are very dependent on the technology put in place to prevent them, which in itself will be related to how old the landfill is. Global estimates for emissions from UK landfill will incorporate a whole range of sites, ages and capture technologies many of which will be less efficient than current best practice. For this model we are considering the fate of a tonne of waste being disposed of today. We therefore need to use a capture level consistent with current best practice.

131. The baseline figure for landfill gas capture used in the model is 75% estimated lifetime capture. The percentage of landfill gas captured for flaring or energy generation in the model was varied from 85% down to 50% in 5% steps for the same range of compositions used above. The model output is shown in Chart 5 .

Chart 5. Impact of changing landfill gas capture on the efficiency of EfW as a function of biogenic C content of a range of waste compositions



132. The chart shows that as the proportion of landfill gas captured is reduced the steepness of the curve increases. There is a static point at zero biogenic content as there would be no landfill gas produced. Elsewhere for a given biogenic content a

lower net EfW efficiency is required to outperform landfill as the proportion of landfill gas captured decreases. The baseline value of 75% capture is represented by the thick blue line.

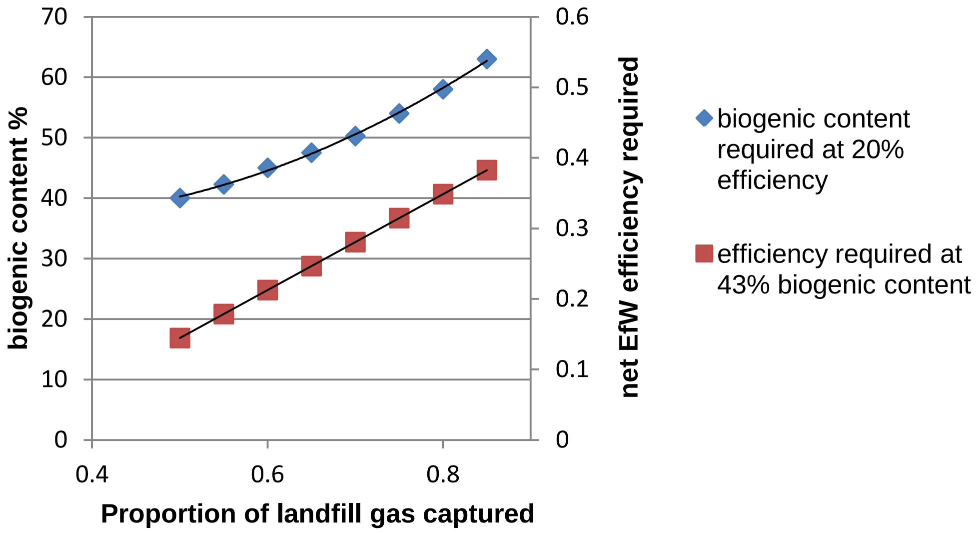
133. Considering an EfW plant with net efficiency of 20% (red line). At 85% landfill gas capture a minimum biogenic content of 63% would be required falling to 54% at the baseline value of 75% capture and 40% biogenic content at a landfill gas capture proportion of 50% (assuming all other background parameters remain constant).

134. At a 100% capture rate, represented by the dashed green line, a biogenic content of greater than 85% would be required. This value will be independent of all other parameters relating to landfill gas production such as warming potential etc. as no methane is released. It will be dependent on factors relating to the EfW plant such as background energy mix and not those which affect generation from landfill.

135. At 0% capture rate, represented by the solid green line, a biogenic content of more than 30% would be required for a 20% efficient plant. This value is highly dependent on other parameters relating to methane release such as warming potential.

136. For a given biogenic content the change in efficiency required with changing landfill gas capture is reasonably linear (Chart 6). Given the static point at zero biogenic content this means that for a given efficiency the rate of change in biogenic content required increases as captured proportion increases. So a change of 5% capture rate from 80 to 85% has a much greater impact on the biogenic content required than a step from 50% to 55%.

Chart 6. Variation in minimum biogenic content required at for a 20% efficient EfW plant and efficiency of plant required at 43% biogenic content with proportion of landfill gas captured

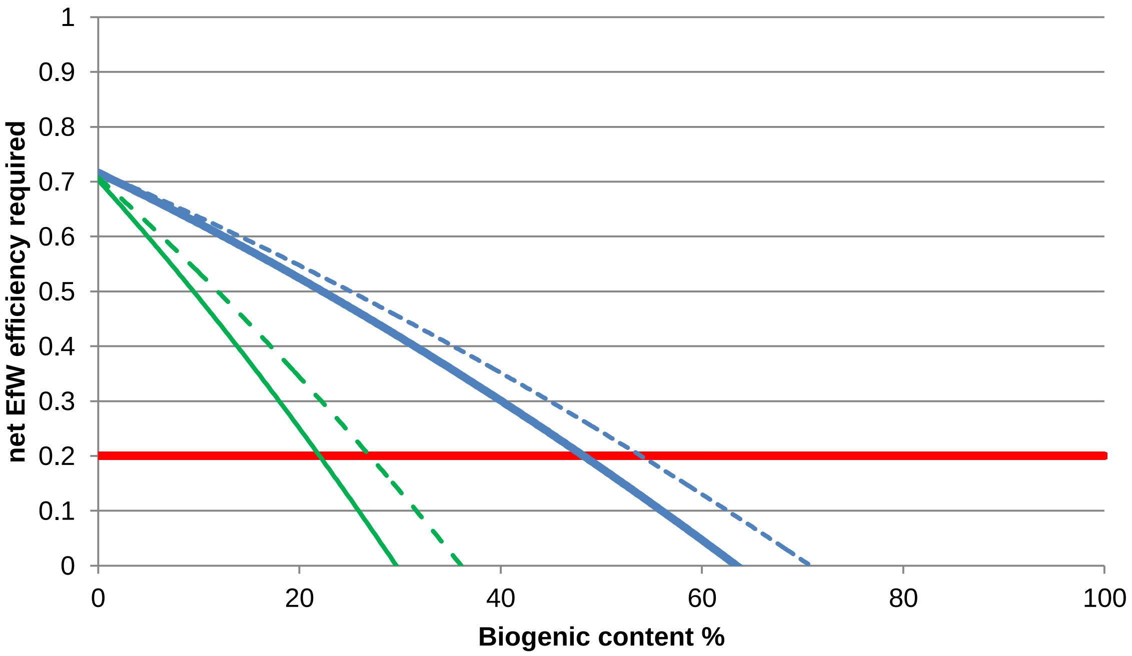


137. Clearly uncertainty in the proportion of landfill gas captured is most important when it is in relation to very high levels of capture.

138. Another key parameter is the potency of methane as a greenhouse gas. The baseline model uses a value of 25. The very latest value recommended by the IPPC for the 100 year warming potential is 34 but this is not yet widely adopted. The impact of this change on the above analysis can be seen in Chart 7 below where solid lines

represent a value of 34 and dotted lines a value of 25 for the baseline and zero capture scenarios. A 100% capture rate has been omitted as the line is the same as before – with no methane emitted it is independent of potency.

Chart 7. Impact of changing global warming potential of methane form 25 (dotted lines) to 34 (solid lines) for the 75% and zero capture scenarios



139. For a given efficiency e.g. 20% the impact of using the higher potency is a reduction of around 5% in the biogenic content required at both the baseline 75% level and the zero capture point. For a given biogenic content the effect is much greater at low capture rates than high, with the greatest impact at the highest biogenic content. This is as expected as these compositions would generate the most methane. As noted in the sensitivity analysis overall the impact of changing the methane potency is not that great compared to other factors.

5.5. Combining key variables – background energy mix and methane capture

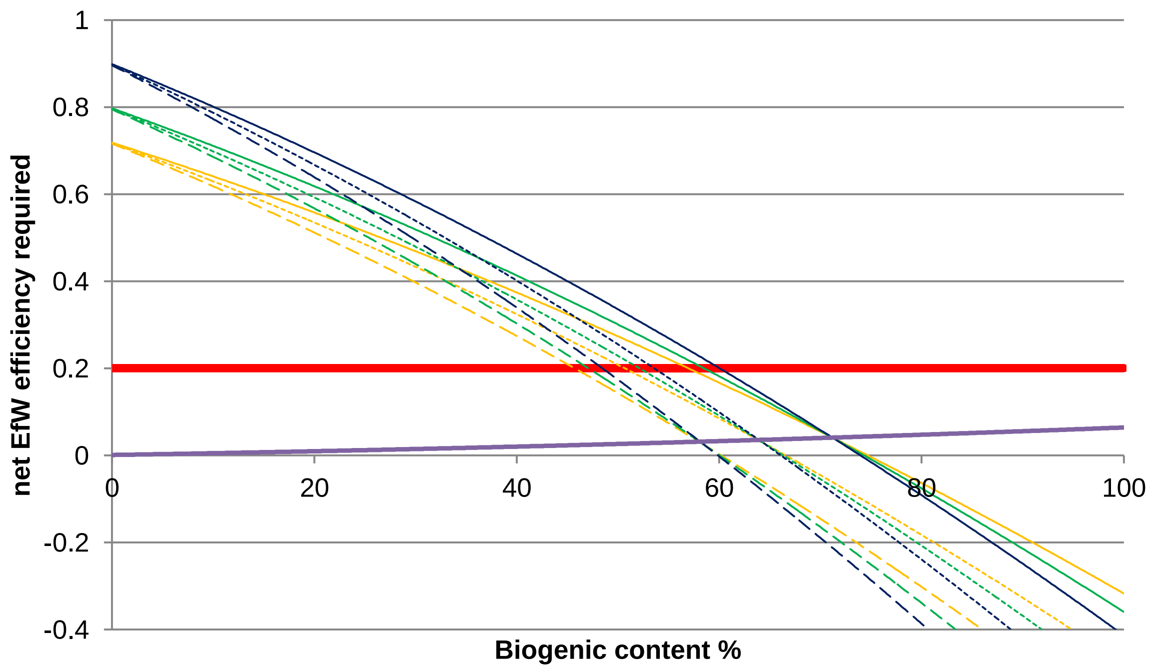
140. Clearly the two factors, energy offset and landfill gas capture, considered above could act in combination so it is important to understand the impact of this covariance. The model was used to examine 3 different levels of landfill gas capture alongside 3 different levels of background energy carbon intensity to give nine different scenarios. These are set out in Table 15 below. The same range of compositions used previously was modelled.

Table 15. Scenarios modelled using different levels of landfill gas capture and carbon intensity

Proportion of landfill gas captured	Background energy carbon intensity
0.75	0.373
0.75	0.336 (90% baseline)
0.75	0.298 (80% baseline)
0.65	0.373
0.65	0.336
0.65	0.298
0.55	0.373
0.55	0.336
0.55	0.298

141. The model output is shown in Chart 8 below.

Chart 8. Model output for the nine scenarios in Table 15



142. As can be seen from Chart 8 for each value of landfill gas capture (indicated by the same line weight) there is a 'set' of trendlines associated with changing the background energy intensity, each with its own unique static point. As the proportion of landfill gas captured increases these static points move to higher biogenic content levels along the line (purple) relating to what would be seen with a very high background energy intensity[26]. Equally for a given background energy intensity

[26] The increase in EfW efficiency required with increasing biogenic content in the very high background energy mix scenario (represented by the purple line in Chart 8) is due to the drop in CV of the waste with increasing biogenic content (Chart 3). With lower energy content in the fuel a higher efficiency of EfW plant is required to match the energy from landfill gas to give the 'energy neutral' static point.

(indicated by colour) there is a static point associated with each set of landfill gas capture values.

143. This analysis indicates that there is no additional complex interaction between the two key sensitivities in the model and that scenarios could be sensibly developed based on choosing specific sets of assumptions without concern that outliers could accidentally be selected.

144. As these key parameters are varied the model output is changing in a consistent and readily explicable manner which gives us confidence in the output and that the model can be used for more detailed analysis.

6. Modelling electricity only EfW

6.1. Scenarios for future impacts on electricity only EfW

145. The above analysis has considered a number of different parameters that could be changed for analysis of the impact of biogenic content on the carbon case for EfW. Some of the factors such as the background energy mix and the level of landfill gas capture may change over time. EfW plants have a long lifetime so it is important that these factors are considered for the end of the plant lifetime as well as the start.

146. The degree to which landfill gas is captured is hotly debated with significant variation depending on the phase of operational life of the landfill. Government has historically used an assumption of 75% capture. This would seem to be an optimistic figure at the upper end of any estimates which can range as low as 20%. 50-60% lifetime capture rate might be a more realistic with an assumption that this will improve with new technology over time to deliver the more optimistic value[27].

147. The marginal energy mix is also predicted to change over time. For electricity only generation DECC have made estimates of how this is expected to change up to 2050. There is a relatively slow decline up to 2025. However, beyond this point the marginal energy mix is expected to drop more significantly, and rapidly, to 2040 as renewable and nuclear energy become a greater proportion of the energy mix. Heat use will have its own separate marginal energy mix. For simplicity in the scenarios below we have considered an electricity only plant.

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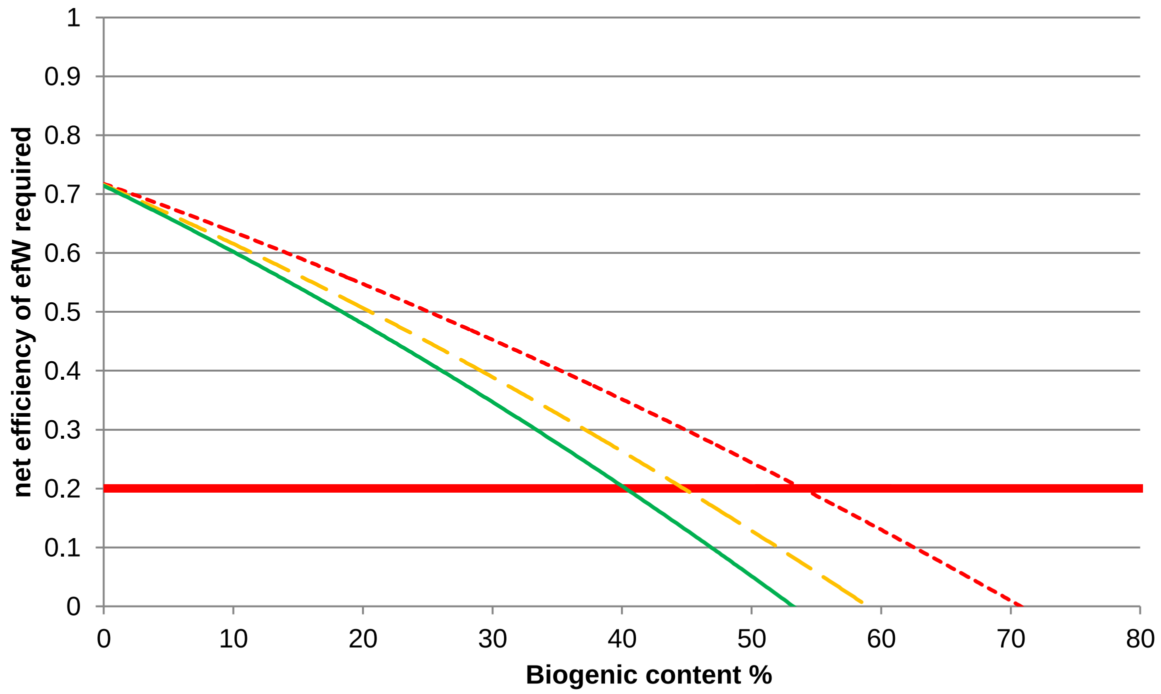
[27] The level of landfill gas capture is one of the most debated issues in this area. The Eunomia report: "A Changing Climate for Energy from Waste? Final report to Friends of the Earth", May 2006; remarks that "there is very little by way of field measurements to substantiate the use of the high gas captures [75%] being posited in Defra" and notes "Dutch field measurements give figures between 10-55% for instantaneous gas capture rates, and average rates of around 25%, whilst default figures for reporting to IPCC are likely to be specified at around 20%". The report itself uses a baseline value of 50%. The source of the biogenic content of waste data used in the model: ERM (2006) Carbon Balances and Energy Impacts of the Management of UK Wastes, Defra R&D project WRT 237 December 2006 uses the value of 75% but their modelling also indicates that adoption of a longer timeframe results in a lifetime capture rate dropping to 59%. Other reports similarly provide a range of values. We have selected the range for the three scenarios based on the above quoted figures (rounding the 59% to 60%).

148. Based on these factors we have modelled three different scenarios.

Low methane case – 75% landfill gas capture
Central case – using the 60% landfill gas capture
High methane case – using 50% landfill capture

149. The three scenarios were input into the model and the variation in minimum EfW efficiency required with biogenic content plotted with a background energy mix of 0.373t/MWh (Chart 9).

Chart 9. Model output for Low (red, small dotted line), Central (yellow, large dashed line) and High Methane (green solid line) scenarios with baseline marginal energy mix



150. All three scenarios give the same efficiency at zero biogenic content as the background energy mix is the same. As expected the rate of landfill gas capture has a significant effect. Under the low landfill emissions scenario a 20% efficient EfW plant should burn waste with a biogenic content of at least 54% for the central scenario this drops to 45% and to 40% for the high methane scenario.

151. These scenarios give a snapshot of the required efficiency/biogenic content balance. Clearly for an EfW plant with a 25+year lifetime we need to consider how this balance changes over time. With improving technology we might expect landfill gas capture rates to move towards the more optimistic emissions figure and we have already demonstrated that changing the marginal energy mix will also have a dramatic effect. Figures for the marginal energy mix are taken from DECC's IAG toolkit[28]. Levels of

[28] https://www.gov.uk/government/policies/using-evidence-and-analysis-to-inform-energy-and-climate-change-policies/supporting-pages/policy-appraisal

landfill gas capture are based on a transition to a long term capture rate of 80% by 2100 with a reducing rate of improvement over time[29].

Table 16. Modelled scenarios changing landfill gas capture rate and marginal energy mix over time

Year	Marginal electrical energy mix C intensity (t/MWh)	Landfill gas capture		
		Scenario 1 (low methane)	Scenario 2 (central)	Scenario 3 (high methane)
2010	0.3564	75%	60%	50%
2015	0.3192	76%	64%	56%
2020	0.2674	77%	67%	61%
2025	0.1950	77%	70%	65%
2030	0.0954	78%	72%	68%
2035	0.0673	78%	73%	70%
2040	0.0482	79%	75%	72%
2045	0.0277	79%	76%	74%
2050	0.0227	79%	77%	75%

152. The outputs from the three models are shown below (Chart 10-0). In all cases in the period up to 2025, while the assumed carbon intensity of the marginal background energy mix drops relatively slowly, the changes are dominated by capture rate with the impact greatest at the lowest efficiencies of EfW plant. As the carbon intensity of the background mix changes, dropping dramatically from 2025 through to 2045 the lines steepen to such a point that the biogenic content required becomes independent of efficiency of EfW plant, dependent essentially on the level of landfill gas capture. By 2050 the difference between scenarios is marginal as they approach the assumed capture limit.

[29] There is insufficient information to give an accurate profile for the rate of landfill gas capture. The modelled profile is based on 80% lifetime capture as a long term limit. The starting capture rate is increased each 5 year step by 20% of the difference between the previous value and this long term limit. This gives a profile where improvements are greatest in the early years and then gradually level off as marginal benefits become harder to achieve. Capture rate in year x = rate in year x-5 + (0.2*(rate in year 2100 -rate in year x-5))

Chart 10. Model output low methane scenario

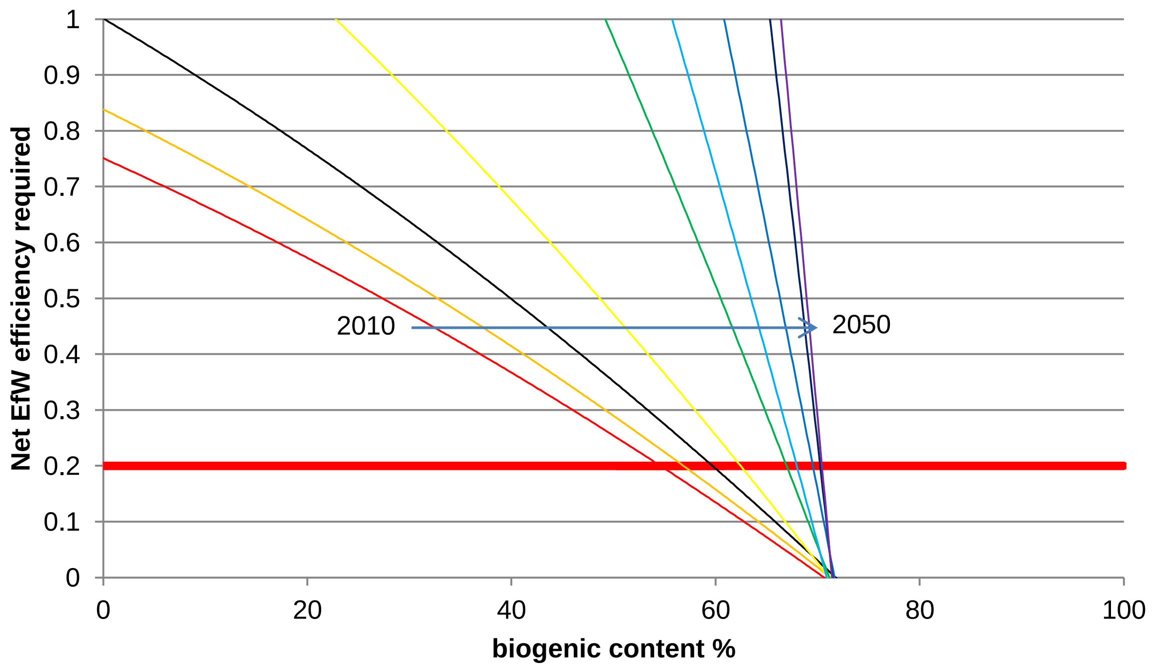


Chart 11. Model output central methane scenario

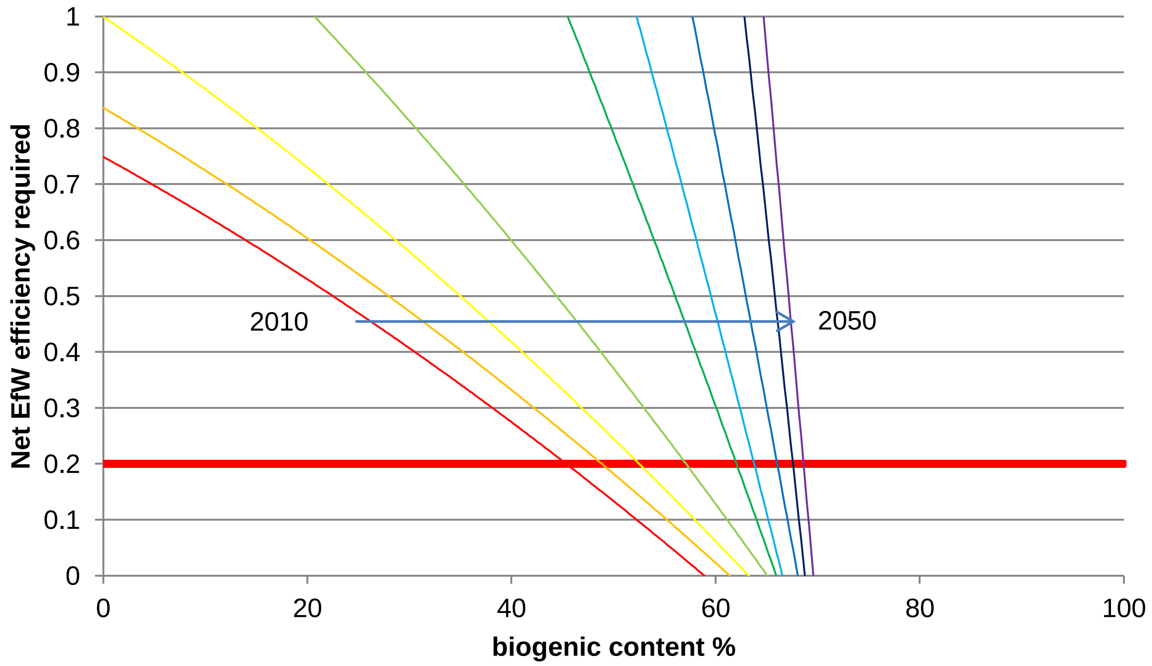
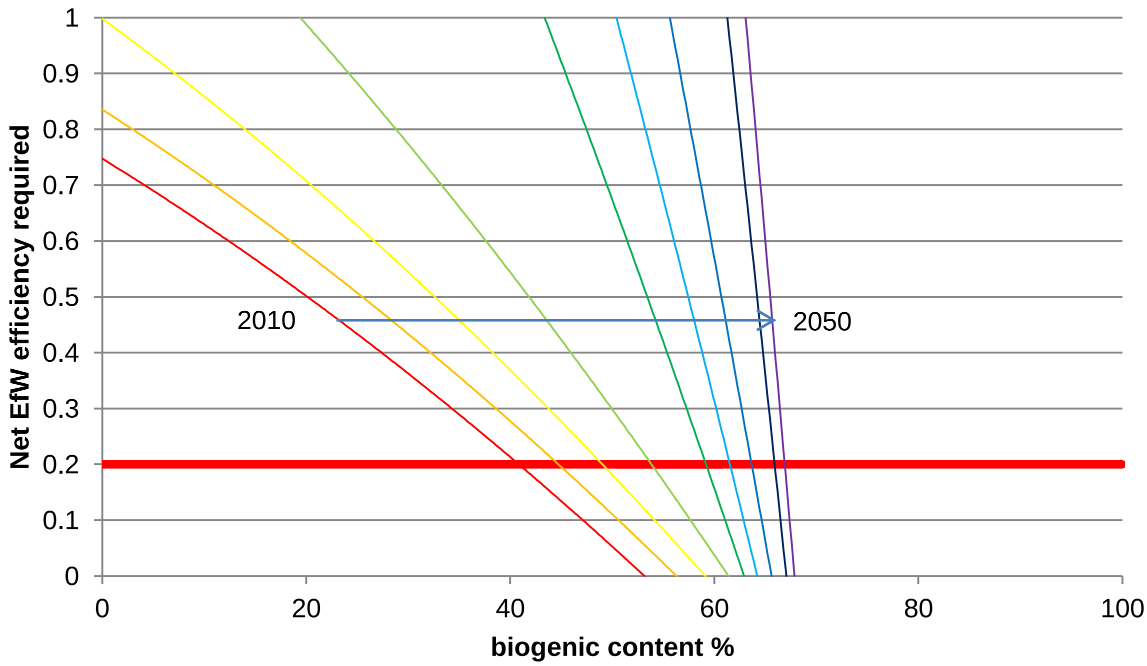


Chart 12. Model output high methane scenario



153. Based on these scenarios, in the very long term electricity only EfW will need to use feedstocks with relatively high biogenic content to be environmentally sustainable from the carbon balance viewpoint. Efficiency of the plant will be irrelevant in terms of determining the biogenic content of the fuel but more efficient plants will of course remain critical in maximising the energy extracted from the waste and the overall economic and environmental case.

154. Based on these scenarios the model indicates that even under the low methane set of assumptions EfW based on waste with a biogenic content of greater than 72% will deliver an environmental benefit throughout the lifetime of the plant. It is important to note that this does not imply that a plant utilising waste with a lower biogenic content for some or indeed all of its life cannot be a more environmentally sound solution than landfill, this is discussed further in the section below.

6.2. Impact over the plant lifetime

155. Energy from waste plants are constructed based upon a return on investment over the lifetime of the plant i.e. in order to make them financially viable they need to operate for a number of years, a 25 year period would be a typical planned lifetime. Landfill is also a long term commitment; in this case the damaging gases are potentially released over tens of years. The year by year balance of emissions will be different depending on the period being considered. Emissions from the energy from waste plant will be essentially constant (with short term fluctuations) for the lifetime of the plant (assuming constant biogenic content) whereas those from landfill will rise to a peak and then tail off, the exact shape of the curve being impacted by the timing and level of any capture.

156. Considering a hypothetical composition of waste such that the same amount of waste being managed in either EfW or landfill over a 25 year period gives the same total CO_2e emissions over a 100 year period. Chart 13 (EfW) and Chart 14 (landfill) below illustrate the 5 yearly and cumulative emissions for the different treatment routes. The cumulative emissions at the end of the period are the same (red line) but the EfW plant would clearly be emitting more in the early years (blue bars) but would be emitting nothing in later years, assuming the plant ceases operation after 25 years.

Chart 13. Illustrative phasing of emissions from an EfW plant

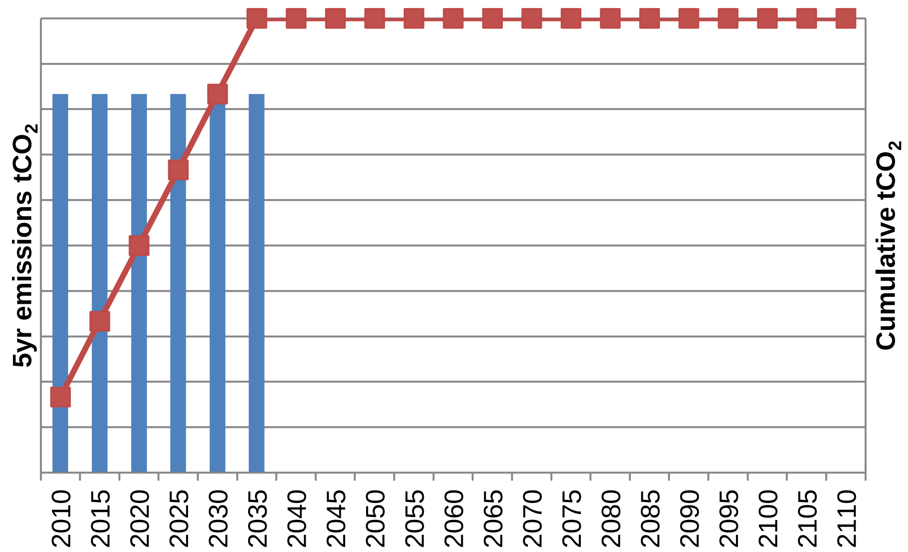
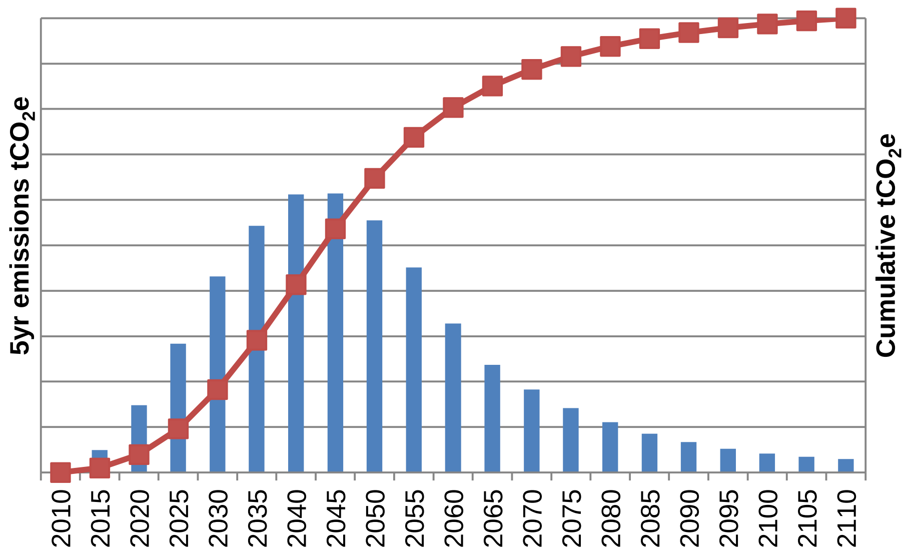


Chart 14. Illustrative phasing for emissions from landfill



157. How to treat this time dependency is one of the key difficulties for analysing the relative impacts of the two approaches. In economic terms there is a well used approach to account for this time dependency, a discount rate is applied with the costs of later emissions being valued less than immediate emissions. However, the discount rate to be applied is a matter of much debate.

158. In environmental terms, which are what this analysis considers, it is even more difficult. There is as yet no ‘discount rate’ for CO_2 or its warming potential. An

alternative approach is therefore to look at the total emissions over an extended period. The assumption here is that providing there is no environmental tipping point during the period then the warming potential and therefore relative environmental impact depends on the cumulative total of gases released over the entire period. In this approach using the examples shown in the graphs above EfW and landfill have been modelled with assumptions to give the same overall impact in CO_2eq terms, whereas, by comparison on a year by year basis they differ markedly.

159. This long timescale approach can be applied to the scenarios outlined above for a number of compositions with different biogenic contents. We will consider total emissions over a 100 year period, based on the following assumptions:

- All of the methane that will be released from landfill will have been released by the end of this period – 100 years is a standard assumption for this in many climate models
- The biogenic content of the waste will remain broadly the same over time – while it is expected that waste composition will change plants will often only be able to operate within a given range of calorific value, this in turn may lead to the requirement for a relatively constant composition developed from mixing different waste sources.
- The Energy from waste plant will be operated for the lifetime required to give the planned return on capital investment, this 'planned lifetime[30]' is assumed to be 25 years – if a plant cannot operate for the full time to recoup the investment then it will not be built .

160. There is the possibility that a plant will continue to be utilised beyond the planned lifetime if EfW was considered to be the best option at that point. However, if EfW was no longer sustainable then it is assumed it will cease to run. It is important to recognise that the plant needs to run for this period in order to be built, so even if EfW becomes the less desirable option during the plant's life we should assume it will continue to be operated until this return on investment point is reached. Whether this is desirable will depend on the overall environmental balance over the plant's lifetime. Hence it is important for both the landfill and EfW sides of the model to consider the total impact over the lifetime of the infrastructure.

161. There is the additional issue of which comparators are fixed over the lifetime of the plant and which are varied. Clearly there will always be the option to send the waste to landfill rather than EfW so landfill effects, such as capture rate, should vary over the course of the plant's lifetime. The issue of comparative energy mix is more difficult. There are two options, either the marginal energy mix is varied throughout the plants lifetime or it is set at the level at which the plant started operation. The former is more consistent with it being a waste management tool that happens to produce energy, the latter with considering it as an energy generation plant, i.e. if you need the energy you will have to build some form of power plant at that point in time be it the EfW plant or the marginal energy plant, therefore the marginal plant at the time of initiation is what you are offsetting for the lifetime of the plant. In the analysis below we have assumed the former which will make it more challenging for EfW to maintain primacy over landfill.

[30] For municipal waste plants this planned lifetime will be linked to the duration of the local authority waste contract – often 20-25 years.

Modelled net carbon benefits over 25 year plant lifetime

162. From the charts above for a biogenic content of around 75% or greater EfW would always seem to be the better solution, across all three scenarios. We have therefore considered the impact of a lower biogenic content on a range of different efficiencies and plant construction dates. The net CO_2 emissions were calculated every five years from 2010 to 2050 against a background of varying marginal emissions factors for electricity. Values for intermediate years were estimated assuming linear change between data points. Using this data the average net tCO_2eq per tonne of waste for a plant operating over a given period was calculated. For plants that were operating before 2010 it is assumed net emissions were the same as 2010 for previous operating years. The results are summarised below in Table 17 (low methane), Table 18 (central) and Table 19 (high methane).

163. The red shaded cells indicate combinations of efficiency and plant where over the lifetime of the plant the average net CO_2eq emissions would be greater than those from landfill (positive value).

164. Under all of the scenarios there is a threshold beyond which a new plant would have carbon disbenefits versus landfill. This is understandably closely linked to the decarbonisation of the marginal energy mix. The efficiency and year at which this threshold appears is dependent on the level of landfill gas capture, with higher capture rates reducing the primacy of EfW over landfill earlier for a given efficiency of plant.

165. The orange shading indicates plants that over their lifetime produce a positive benefit (negative value in the table) but at the end of their planned life would be giving net emissions relative to landfill for a tonne of waste. For such plants extending operation beyond the planned lifetime may not be the best environmental outcome. Unshaded plants on the other hand still have net benefits at the end of their planned life and therefore it may be beneficial to have their lifetime extended.

Table 17. High capture Low methane scenario (75% initial capture)

	Average net t CO_2eq emissions from 1t of waste with 61% biogenic content over the period						
Plant efficiency	Existing plant 1995-2020	Existing plant 2000-2025	Existing plant 2005-2030	Existing plant 2010-2035	New plant 2015-2040	New plant 2020-2045	New plant 2025-2050
30%	-0.167	-0.141	-0.102	-0.055	-0.009	0.034	0.068
25%	-0.118	-0.097	-0.064	-0.025	0.014	0.050	0.078
20%	-0.070	-0.053	-0.026	0.005	0.037	0.065	0.088
15%	-0.021	-0.008	0.012	0.036	0.060	0.081	0.098

Table 18. Central methane scenario (60% initial capture)

	Average net t CO_2eq emissions from 1t of waste with 61% biogenic content over the period						
Plant efficiency	Existing plant 1995-2020	Existing plant 2000-2025	Existing plant 2005-2030	Existing plant 2010-2035	New plant 2015-2040	New plant 2020-2045	New plant 2025-2050
30%	-0.312	-0.273	-0.216	-0.149	-0.083	-0.025	0.022
25%	-0.263	-0.228	-0.178	-0.119	-0.060	-0.009	0.032
20%	-0.215	-0.184	-0.140	-0.088	-0.038	0.007	0.042
15%	-0.166	-0.139	-0.102	-0.058	-0.015	0.022	0.052

Table 19. Low capture High methane scenario (50% initial capture)

	Average net t CO_2eq emissions from 1t of waste with 61% biogenic content over the period						
Plant efficiency	Existing plant 1995-2020	Existing plant 2000-2025	Existing plant 2005-2030	Existing plant 2010-2035	New plant 2015-2040	New plant 2020-2045	New plant 2025-2050
30%	-0.408	-0.359	-0.291	-0.210	-0.132	-0.064	-0.009
25%	-0.359	-0.315	-0.253	-0.180	-0.109	-0.048	0.001
20%	-0.311	-0.270	-0.215	-0.150	-0.086	-0.032	0.011
15%	-0.262	-0.226	-0.176	-0.119	-0.063	-0.017	0.021

166. Under all scenarios existing plants with a higher efficiency have a potentially longer operational lifetime, and based on this set of assumptions and biogenic content any plant commissioned after 2015 by the end of its planned life may have reached a point where it would not be environmentally beneficial to extend its life.

167. These assessments are very dependent on the underlying assumptions. Increasing the biogenic content of the waste being used will essentially extend the beneficial lifetime of the plant as will any use of heat, which would both increase the efficiency and change the marginal energy mix being offset. Metal recycling from bottom ash and ash recycling would similarly benefit EfW over landfill and shift the balance point.

Composition required to sustain benefits over plant lifetime

168. The above approach looks at the environmental benefits of a plant based upon a specific biogenic content. An alternative approach is to examine the minimum biogenic content over a plant's lifetime required to be a zero net emitter when compared to the alternative of the waste going to landfill.

169. To achieve this a function was introduced to alter the proportion of all fossil containing wastes in the composition and this was optimised using a 'what if' tool to give a zero net CO_2 benefit over a 25 year plant lifetime. The corresponding biogenic content was noted. The results are summarised for the central scenario in the table below.

Table 20. Central methane scenario (60% initial capture) minimum lifetime biogenic content required

	Minimum lifetime biogenic content required %						
Plant efficiency	Existing plant 1995-2020	Existing plant 2000-2025	Existing plant 2005-2030	Existing plant 2010-2035	New plant 2015-2040	New plant 2020-2045	New plant 2025-2050
30%	40.19	42.46	45.98	50.31	54.8	58.93	62.39
25%	43.47	45.51	48.63	52.46	56.44	60.08	63.12
20%	46.71	48.54	51.26	54.59	58.06	61.22	63.85
15%	49.93	51.53	53.87	56.71	59.68	62.35	64.57

170. Cells shaded green indicate where the lifetime biogenic content required is less than the 50% currently used for deeming of Renewables Obligation Certificates (ROCs). Orange indicates where the content falls in the 60-68% range currently considered likely for mixed municipal waste. This indicates that for the central set of assumptions all plants are viable for municipal waste with a biogenic content at the top end of the commonly used range. As might be expected the low methane scenario required higher biogenic content than the central scenario for a given plant while conversely the high methane scenario required lower biogenic content.

171. Once the plant reaches the end of its 25 year life it needs to still be providing a carbon benefit for that life to be extended. The minimum biogenic content to extend a plant's lifetime to a given year is shown in the table below. Higher biogenic content is required to justify extending a plant's lifetime beyond the initial 25 years under this set of assumptions.

Table 21. Central methane scenario (60% initial capture) Minimum biogenic content required to extend plant life beyond initial 25yr lifetime

	Minimum biogenic content required to extend plant lifetime beyond initial 25 year period %						
Plant efficiency	Existing plant 1995-2020	Existing plant 2000-2025	Existing plant 2005-2030	Existing plant 2010-2035	New plant 2015-2040	New plant 2020-2045	New plant 2025-2050
30%	47.12	52.86	59.67	61.93	64.53	66.48	67.61
25%	49.77	54.84	60.63	62.61	65.03	66.77	67.85
20%	52.4	56.8	61.59	63.29	65.53	67.06	68.09
15%	55.01	58.75	62.55	63.97	66.02	67.34	68.33

6.3. Treatment of biogenic CO_2

172. So far this analysis has ignored biogenic CO_2 emissions based on the assumption that it is short cycle and therefore has no net global warming impact. Impacts from factors such as changes in land use to grow the original plants are accounted for in overall carbon inventories elsewhere and are conventionally not considered as part of waste management or energy generation.

173. However, the model assumes that not all of the biogenic material decomposes in landfill but it is all converted to CO_2 in energy from waste. Landfill therefore acts as a partial carbon sink for the biogenic carbon. This is a potential additional benefit for landfill over energy from waste.

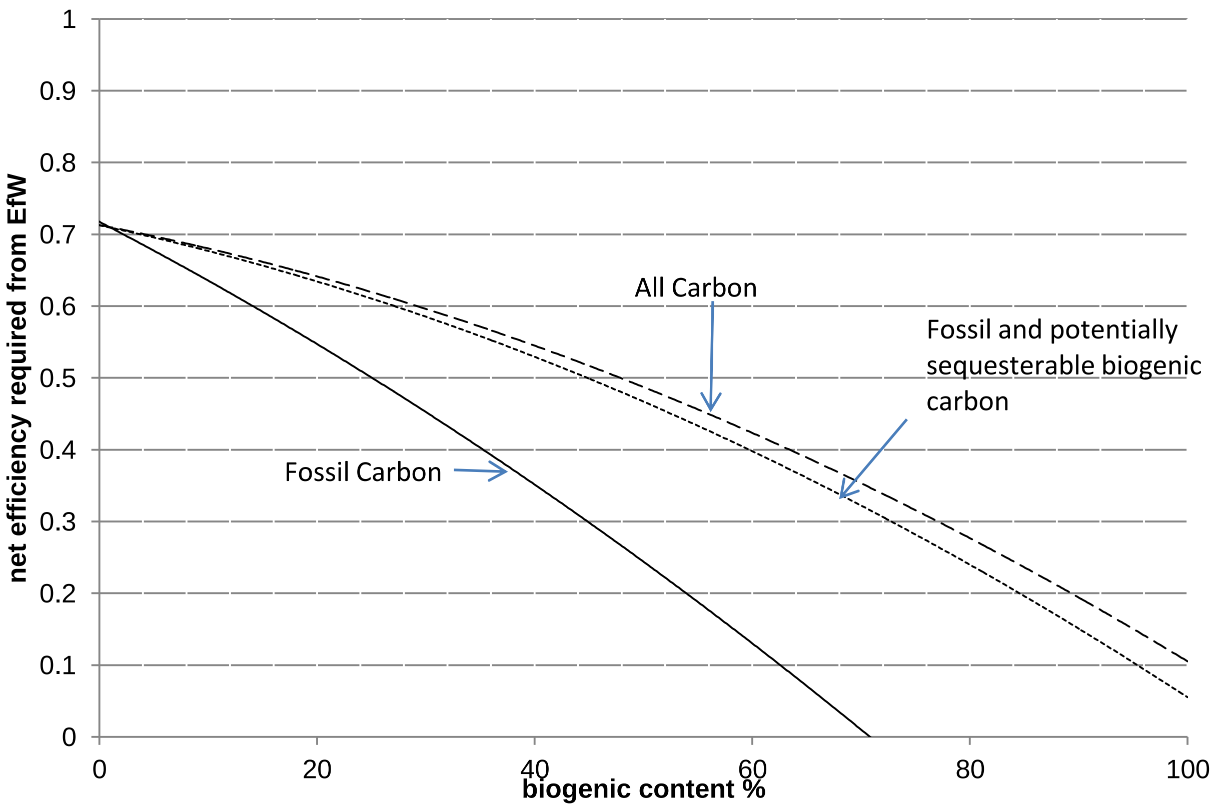
174. There are two ways to account for this additional effect:

- Estimate the amount of biogenic carbon sequestered and include the CO_2 produced from the same amount of carbon in the EfW side of the model (or subtract it from the landfill side)
- Include all carbon emissions, both biogenic and fossil on both sides of the model

175. While both approaches would address the issue of sequestered biogenic carbon the first would potentially be the better solution as it would avoid double counting carbon with other inventories.

176. Both approaches were examined in the model using the baseline set of assumptions (equivalent to the high capture low methane scenario) and the results are shown in Chart 15 below.

Chart 15. Net efficiency of EfW plant required with different biogenic content of waste considering EfW emissions of: only fossil carbon (solid line), fossil and potentially sequesterable biogenic carbon (dotted line) and all carbon (dashed line)



177. It can be seen from Chart 15 that both approaches deliver a very similar change with, as expected, EfW becoming more disfavoured relative to landfill with the greatest change at high biogenic content of the waste. Taking into account sequestered biogenic carbon in landfill will require greater EfW efficiency and/or biogenic content.

178. The similarity between the two approaches is unsurprising as biogenic carbon which is not sequestered in landfill or converted to methane becomes CO_2, as it would in EfW, so for that aspect the two sides of the model cancel out. The slight difference is due to the need for EfW to compensate for the CO_2 offset by electricity generation

from landfill gas when all emissions are considered. The small difference indicates how relatively small a contribution this energy makes to the overall balance. Given this similarity it may be better to consider only the sequestered biogenic C to avoid double counting with other inventories.

179. A range of different values exist in the literature for the amount of biogenic carbon that is sequestered in landfill. The baseline assumptions used in this model result in a very high level of sequestration, around 53% for the baseline composition. The outcome will be sensitive to the level of sequestration in two ways. Reducing the level of sequestration will require less biogenic carbon to be included in the EfW side of the model and will also result in more methane being emitted from the landfill side. Both factors will favour EfW over landfill. To examine the sensitivity of the model to changes in sequestration the baseline proportion of decomposable carbon in each waste type was increased by 50%. This changed the overall proportion of sequestered biogenic carbon from 53% to 29.5%. The values used are summarised in Table 22 below.

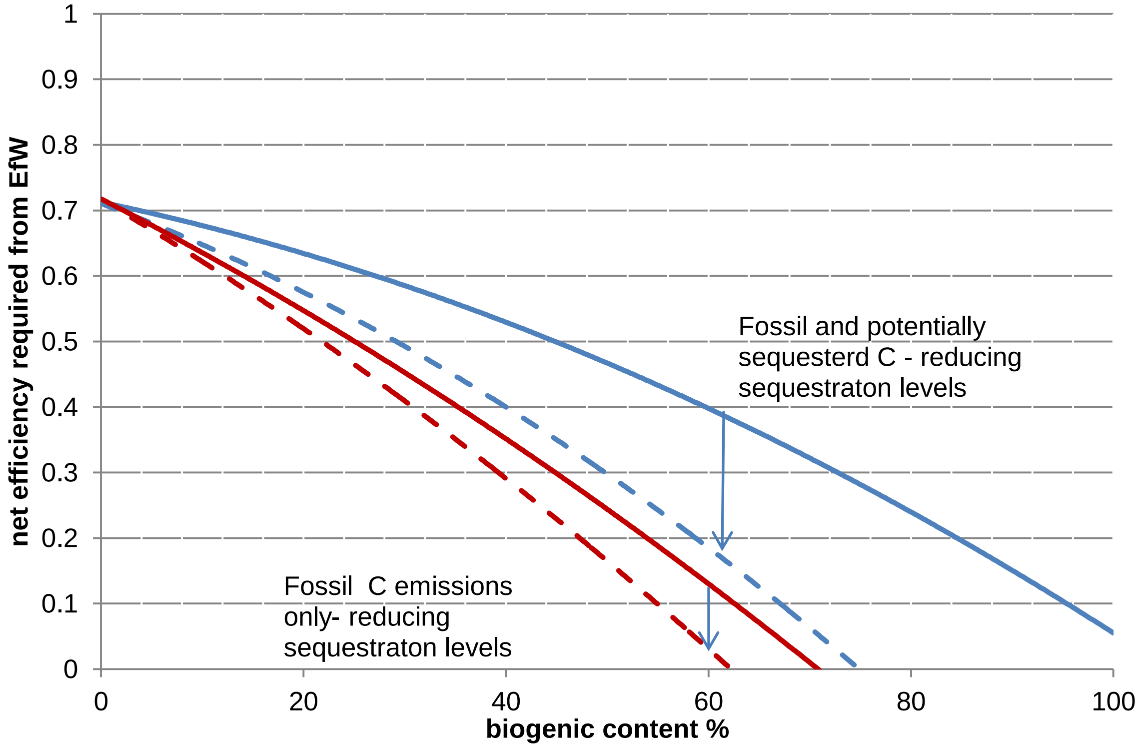
Table 22. Changes in modelled sequestration levels for each component by increasing the proportion of biogenic C considered sequesterable

Material	High sequestration % (model baseline)	Reduced sequestration %
Mixed Paper and Card	50.63	25.94
Plastics		
Textiles (and footwear)	66.65	49.98
Miscellaneous combustibles	53.21	29.82
Miscellaneous non-combustibles	100	100
Food	39.36	9.04
Garden	48.71	23.06
Soil and other organic waste	96.43	94.64
Glass	100	100
Metals, White Goods and Other Non-biodeg Products		
Non-organic fines		
Wood	71.52	57.28
Sanitary / disposable nappies	71.33	57
Total	53.00	29.50

180. By taking this approach materials which already have a high proportion of decomposable carbon are most greatly affected, i.e. Food, Paper and garden waste.

181. The impact of these changes on the model outputs is shown in Chart 16 below.

Chart 16. Impact of reducing the assumed level of carbon that decomposes on model outputs for fossil emissions (red) and fossil and potentially sequestered biogenic C (blue). Baseline model (solid line) and reduced sequestration (dashed line)



182. As noted above, changing the level of sequestration impacts on both the amount of biogenic carbon that needs to be counted on the EfW side of the model and the amount of methane emitted on the landfill side. As a consequence changing the sequestration level impacts not only when considering both fossil and sequestered carbon but also when considering fossil carbon alone.

183. In the example above for the baseline composition (61% biogenic) reducing the amount of sequestration of biogenic carbon from 50% to 30% results in a drop of 10% in the efficicncy required if just considering fossil carbon and 20% if considering both fossil and sequestered biogenic carbon.

184. There is an additional complicating factor regarding the assumptions around sequestration levels. The proportion of landfill gas captured is difficult to measure directly so assumed levels have previously been derived from a combination of measurement of the amount of landfill gas captured as a proportion of the amount modelled as being produced. However, the modelling for this also contains assumptions on sequestration, Therefore any lowering in the sequestration assumptions will also inherently reduce the assumed level of landfill gas capture. This interaction has not been captured in the above analysis. As a result the scenarios outlined above will be particularly sensitive to sequestration levels with any drop in assumed sequestration significantly favouring EfW over landfill. Given all of these interactions there is a high degree of uncertainty and further work is required.

7. The impact of utilising heat

185. All of the above analysis considers an EfW plant operating in electricity only mode. However, most plants have the potential to operate in combined heat and power (CHP) mode.

186. Use of heat has two important impacts on the above analysis

- It significantly increases the net efficiency of the EfW plant
- It changes the marginal energy mix being offset

187. Heat is expected to decarbonise more slowly than electricity therefore in the long term it will have a higher marginal energy mix than electricity. For example a recent technical report for the Committee on Climate Change assumes a carbon intensity of 246gCO_2/kWh for oil heating and 183gCO_2/kWh for gas[31] up to 2050

188. As the marginal energy mix for heat is predicted to be maintained over the period up to 2050 only changes in the landfill gas capture rate impact on the minimum biogenic content/efficiency required from an EfW plant. This was modelled for the central scenario offsetting gas (Chart 17) or oil (Chart 18) heating.

189. If the heat source being offset is a gas fired boiler then in 2050 for the baseline composition a heat efficiency of 30% is required. If the heat source being offset is an oil fired boiler then an efficiency of only 20% is required. Both of these are easily achievable.

190. In reality it is much more likely that a plant will operate in CHP mode producing both power and electricity. Based on the baseline composition and central scenario in 2050 a plant generating electricity with 20% efficiency in 2050 will have net CO_2 emissions of 0.325tCO_2 per tonne of waste relative to landfill emissions of 0.229tCO_2 giving a net disbenefit of 0.096tCO_2 per tonne of waste. However, all of the carbon emissions from the plant have been counted against the electricity generation, this assumes the heat is just wasted. Using this heat in addition to electricity doesn't produce any additional CO_2 (the same waste is being burned) therefore any additional heat produced can be counted as 'carbon free' energy. This energy can offset fossil sources generating elsewhere.

191. With a marginal carbon intensity for gas heating of 0.183tCO_2/MWh this means the plant would need to generate an additional 0.52MWh of heat energy per tonne of waste to offset the electricity emissions. This is equivalent to producing heat at less than 20% efficiency which is easily achievable.

[31] Decarbonising Heat in buildings:2030-2050 Technical annex p143 http://archive.theccc.org.uk/aws/IA&S/Element%20Energy%20-%20Decarbonising%20heat%20to%202050%20-%20Annex.pdf

Chart 17. Model output for central scenario offsetting gas fired heating 2010-2050

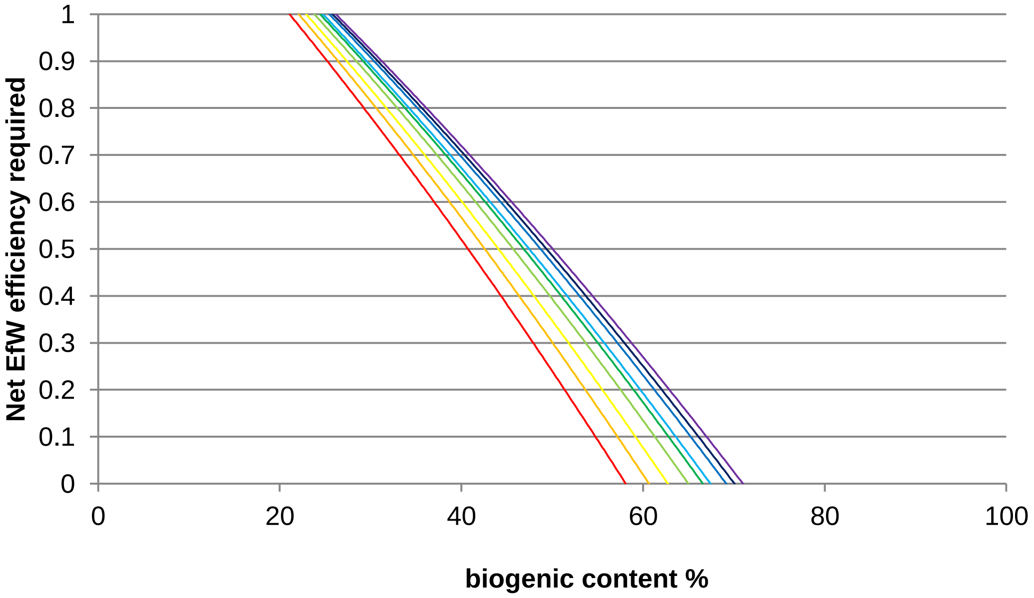
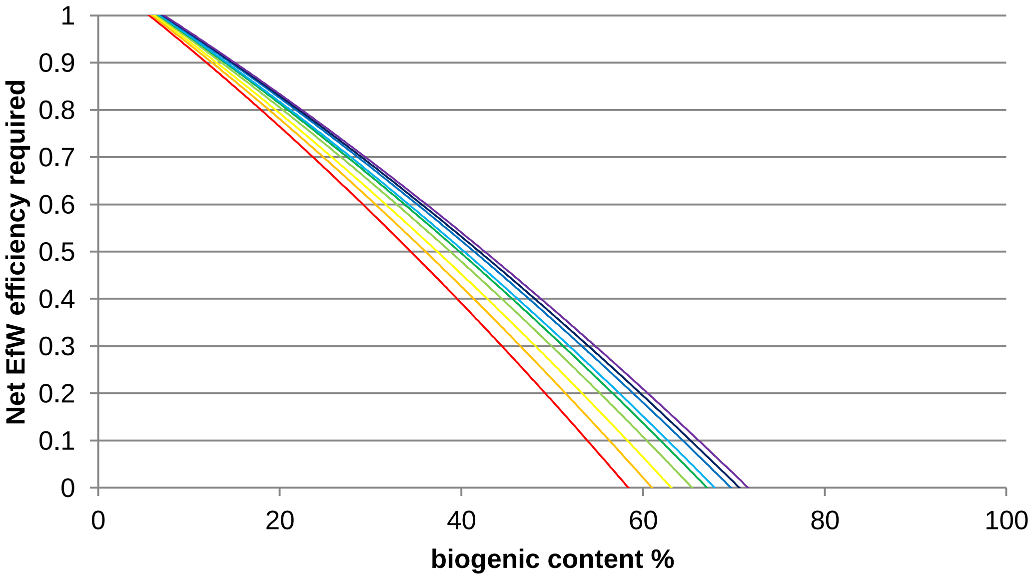


Chart 18. Model output for central scenario offsetting oil fired heating 2010-2050



192. There is a trade off between electricity and heat. The z ratio, additional heat energy supplied per unit electrical energy foregone, for Energy from Waste CHP should be in the range 4-5 i.e. for every additional 4MWh of heat 1MWh of electricity is lost. So in the above example the plant operating at 20% electrical efficiency in CHP mode might actually operate closer to 25% efficiency in electricity only mode (where it would still be a net CO_2 emitter).

193. Alternatively, considering the lifetime emissions as above, a plant constructed in 2025 delivering 20% electrical efficiency would need to produce an average additional 0.18MWh to offset the 0.032tCO_2 average net emissions per tonne of waste, equivalent to using heat at less than 7% additional heat efficiency. Alternatively the plant could use the heat for some of its lifetime at a higher level.

194. If circumstances permitted, the most beneficial approach would be to operate in CHP mode optimised for power while the marginal electricity carbon intensity was high, and switch to optimising for heat output once the marginal electricity intensity dropped below that of heat. In reality the availability of heat customers will constrain the availability of this approach.

195. If the plant is a gasifier producing a syngas, which is used to drive a gas engine or gas turbine, electrical efficiencies may be higher, enabling such plants to operate in electricity only mode for their whole lifetime. However, there would still be significantly greater benefits from operating in CHP mode and also using the waste heat. Unlike with steam based generation there is no trade off between heat and electricity and very high total efficiencies may be attainable.

196. However, gasifiers producing syngas generally require a prepared fuel such as RDF/SRF. Manufacturing this fuel has a disbenefit in terms of the energy consumed during the processing and the generation of a residue that has to be landfilled. There will be additional benefits from any recyclates recovered during the fuel manufacture process and fuel could potentially be manipulated to ensure sufficient biogenic content in line with the arguments above. Further work is necessary to determine the overall CO_2 balance of a full scale commercially operating gasifier. Experience in the UK of full scale gasifiers treating wastes is limited and their potential has yet to be fully demonstrated.

8. Other energy outputs

197. In the case of gasification technology producing syngas there is the potential to deliver other energy outputs such as gas to grid or transport fuels. Although as noted above this potential has yet to be fully demonstrated on a commercial scale in the UK.

198. In these processes it becomes more difficult to calculate the overall net efficiency of the process as this needs to consider the energy losses in production, transportation and use of the fuel.

199. However, domestic boilers or internal combustion engines in cars are highly efficient in terms of turning their fuel into heat or useful work. Therefore even with production losses the overall process could be highly efficient.

200. Taking the example of transport fuels. The EU average lifecycle emissions value for fossil fuels is 88.3 grams CO_2e/MJ, equivalent to 0.318tCO_2/MWh. However, this is likely to rise over time as oil (at the margin) will increasingly be sourced from higher GHG intensity pathways (e.g. tar sands, oil shale).

201. Assuming the emissions value remains static under the central scenario, baseline composition, in 2050 an overall process efficiency of less than 20% will be sufficient to be better than landfill. Even under the most challenging scenario for EfW, high capture (low methane) and an assumption of high sequestration an overall process efficiency of 50% would be sufficient.

9. Discussion

202. As with all modelling the results should be used with a suitable degree of caution. The scenarios have been developed to understand likely trends and should not be considered predictions. There are uncertainties in many of the assumptions and while the model's sensitivity to these has been examined one should avoid placing too much weight on exact figures but rather focus on the general trends they exemplify.

203. Using conventional analysis (disregarding biogenic carbon) the model indicates a good carbon case for continuing to include EfW as a key part of the hierarchy. However, as time goes on this case will get progressively worse for electricity only generation as the carbon intensity of the marginal energy mix decreases and if technology for landfill gas capture improves.

204. The model supports the conclusion that existing plants can and should continue to operate as a better solution than landfill. However, once that plant reaches the end of its planned life (assumed to be 25 years) then a detailed analysis should be conducted to determine whether extending its life is the best environmental option as the model indicates there is a significant likelihood that, from a carbon perspective at least, this will not be the case. Modifying processes to use fuel with a higher proportion biogenic material and with increased efficiency throughout the lifetime of a plant, for example through greater use of heat, will improve its overall environmental performance and may help extend its environmentally beneficial operational lifetime. In particular even relatively little use of heat can significantly improve the lifetime benefits of a plant.

205. New plants commencing operation will minimise the risks of becoming environmentally unsound by adopting higher efficiency processes, not just producing electricity but also heat and/or using high biogenic content fuels.

206. This will potentially require a degree of pre-processing of black bag waste to raise the biogenic content of the fuel through removal of fossil based plastics. However, the energy cost of any such processes will need to be included in the calculation of the net efficiency.

207. An alternative approach would be to adopt collection and recycling regimes that remove more of the fossil plastic from the residual waste which will both decrease the overall volume of residual waste and increase the relative biogenic content of that which remains. Where separate collections of organic waste for AD or composting have been shown to have lifecycle benefits over EfW these should not be abandoned in order to feed the need for biogenic waste of an EfW solution.

208. How high a biogenic content is required is very dependent on the level of landfill gas capture and more research is required to estimate this in a manner which decouples estimates from modelled values of carbon sequestration. This work is ongoing.

209. Including an element of sequestered biogenic carbon in the analysis has a significant impact on the conclusions, dramatically reducing the benefit of EfW over landfill, or alternatively significantly increasing the biogenic content required in the waste for a given plant. However, it also significantly increases the uncertainty in the model as it becomes highly sensitive to the assumed sequestration levels. The baseline assumptions used in the model assume a very high level of sequestration (around

50%) which could be considered to be an upper limit. On this basis all new plants would need to operate with some degree of refined fuel, where significant fossil plastic recycling occurs resulting in high biogenic content residual waste and/or with significant use of heat.

210. Much more work is required to understand the levels of sequestration present in landfill to remove the uncertainty and develop policy decisions on this basis.

211. However, based on the modelling presented above, a new plant operating on fuels with greater than 90% biogenic carbon would maintain overall environmental benefits even under the low emissions scenario and modelling including biogenic carbon sequestration. This is the threshold above which energy from waste already qualifies to be considered as biomass under incentive schemes.

212. The uncertainty in the modelling does not preclude the development of energy from waste facilities, there are significant energy security and other drivers for developing these, in the short term they will almost certainly provide carbon benefits. Longer term dis-benefits could be addressed by modifying processes, fuels or appropriately pricing the carbon they produce.

213. While we have used the term 'balance point' to indicate where the modelled carbon case switches between favouring EfW and landfill in reality there is a large zone of uncertainty either side of this point where impacts may be only marginal in either direction. In this zone it could be said that the carbon case is equivocal and other considerations should dominate. The carbon case being set out here is just one of the factors that needs to be considered in determining the best treatment route for waste.

214. To move to a position where the carbon case for EfW is less equivocal and minimise risk of dibenefits the modelling indicates that:

- High efficiency solutions should be preferred, beyond that obtainable with mass burn incineration electricity only, for plants commissioned beyond 2015.
- Use of heat provides the simplest route to ensuring continued primacy of EfW over landfill.
- The biogenic content of the waste should be maintained as high as possible through the removal of fossil plastics for recycling.
- The biogenic content of the waste needs to be understood and monitored in relation to the technology being used.
- Increasing the biogenic content of the waste fuel and the process efficiency of a plant during its lifetime will help ensure it continues to provide a carbon benefit.
- Mixed residual waste may need pre-processing to achieve the biogenic content required. The parasitic load required to do this should be included in efficiency calculations.
- It should not be assumed that extending the operational life of existing infrastructure is the best environmental option.

215. The modelling does not directly address the question of whether AD or composting of source segregated food waste is superior in environmental performance to EfW, this

is beyond the scope. However, in line with the hierarchy, high biogenic content in residual waste fuels needs to be driven by greater removal of fossil plastics rather than additional biogenic material.

Annex 1. Comparison of thermal efficiencies using gross and net calorific values

216. The thermal efficiency of a power-only EfW is defined as

$$\text{power exported to grid/energy content of the waste} \times 100\%$$

217. The energy content of the waste is given by the calorific value of the waste. Most European sources (including WRATE) use the net calorific value (or lower heating value) here. However, due to the data sources available we have used the gross calorific value (or higher heating value). To compare our results with values given in the literature there is a need to make a correction.

218. The standard formula for converting gross to net CV is

$$\text{Net CV} = \text{Gross CV} - 0.212H - 0.0245M - 0.008O$$

219. Where CVs are in MJ kg^{-1} and H, M and O represent the percentage hydrogen, moisture and oxygen in the waste respectively.

220. So, a plant efficiency quoted in net CV terms needs to be corrected as follows to be directly comparable with our figures.

$$\text{Gross CV efficiency} = \text{net CV efficiency} \times \text{net CV/gross CV}$$

221. Clearly, this correction factor will be a function of the waste composition, but if we take the NHWAP CV and chemical composition data and the category composition data from Table 2, we can determine an approximate value as shown below.

Table 23. Composition and calorific values (Composition adjusted to remove minor fractions not included in NHWAP)

Material	Composition (%)	Gross CV (MJ kg-1)	Net CV (MJ kg-1)
Paper and card	16.21	12.58	10.75
Dense plastics	6.67	27.90	26.74
Film plastics	6.67	23.56	21.24
Textiles	4.77	15.94	14.34
Misc combustibles	6.67	15.57	13.93
Misc non-combustibles	9.64	2.63	2.53
Food	32.84	5.35	3.39
Garden	3.18	6.50	4.58
Glass	5.30	0	0
Metals	1.69	0	0
Nappies/sanpro	4.77	7.95	5.39
Fines	1.59	5.02	3.46
Overall CV	100	9.95	8.37

222. Therefore the conversion factor is

$$\text{Gross CV efficiency} = \text{net CV efficiency} \times 8.37/9.95$$

$$\text{Gross CV efficiency} = \text{net CV efficiency} \times 0.84$$

Annex 2. Landfill gas capture

223. The assumed rate of landfill gas recovery or rather the methane emissions that result from a particular assumed rate is crucial to the impact of landfills on global climate change.

224. Environment Agency recommended models[32] predict more than 99.5% of landfill gas will have been produced over 150 years, using probabilistic modelling and the 50th percentile. The Environment Agency best practice requirements for landfill gas collection are '*An active gas extraction system to achieve the maximum practicable collection efficiency. The annual collection efficiency for methane should be compared against a value of 85 per cent. The operator or regulator may use this simple assessment to trigger further investigation. This collection efficiency should be achieved in that part of the landfill where gas collection must be taking place (i.e. the capped areas of the site)*'.

225. In 2006, ERM reported to Defra[33] that modelling the active collection phase at 85% recovery gives an overall (150 year) recovery figure of 75%.

226. 'Gas collection efficiency is set at 75% over a 100 year period in Scenarios A-B to replicate the approach of the spreadsheet modelling performed elsewhere in this study. In Scenarios C-D, gas collection efficiency is set at 85% when gas can be actively managed at the landfill. This excludes the stage of filling a landfill cell, and the period post closure when gas cannot be collected and combusted. The 85% value is the Environment Agency's expectation of a landfill operator in a current design of landfill. The gas collection efficiency during the active gas management period in earlier decades for previous landfill designs are (sic) significantly less than this. Scenarios A-B are compared with Scenarios C-D to demonstrate that the 75% overall collection efficiency is justified in a model representing the effect seen in the population of all current UK landfills (as modelled in the study core scenarios)'.

227. The modelling for the Defra report was carried out using GasSim, the same model used for the landfill emissions modelling in WRATE.

228. According to the Environment Agency[34] gaseous emissions from landfills can arise from a wide range of sources including:

- freshly deposited wastes;
- uncapped wastes;
- caps or temporary cover materials;
- intrusive engineering work and excavation;
- leachate and the infrastructure for leachate collection and treatment;
- cracks, gaps, fissures and along the edges of the site capping;
- lateral migration through surrounding geology;

[32] A computerised model developed for the Environment Agency by Golder Associates.
[33] Carbon Balances and Energy Impacts of the Management of UK Wastes, Defra R&D Project WRT 237, Final Report, December 2006, Environmental Resources Management Limited
[34] Landfill Guidance Note 3, Environment Agency Guidance on the management of landfill gas.

- landfill gas flares and engines (utilisation plant);
- emissions through leakages in gas collection and distribution pipework, e.g. poorly sealed; and
- balanced collection wells in which gas pressure exceeds the available suction.

229. The problem is that there are too many unknowns. First, the percentage of methane in the gas will change with time. More importantly, even on the best run sites, some methane will be emitted before an effective collection and recovery system is installed. The problem is compounded when considering lifetime emissions, as overall recovery rates as high as 75% depend on continuing maintenance of the extraction system for decades after the economic incentive has ceased.

230. In 2007, Lefebvre et al reported at the Landfill Symposium in Sardinia that they had sampled different closed landfills and that the closed landfills studied lost 90% of their degradable carbon in ten years, suggesting almost total decomposition in 15 years[35].

231. Barlaz et al[36] reviewed the available literature and then calculated temporally adjusted recovery rates based on the likely rate of gas production at the time.

232. The temporally adjusted rates varied according to the decay rate but were between 55% and 91%.

233. More recently, Defra has funded research looking at surface emissions from different landfill sites[37]. This work was led by the National Physical Laboratory (NPL) and used various techniques, including a long-path laser to estimate surface methane emissions. Unfortunately, the report does not give any figures on the proportion of gas collected. However, the methane flows estimated from concentrations detected above the site show that there are significant flows from areas with active gas management.

234. Spokas, Bogner, Chanton et al looked at the overall methane balance on several sites[38]. The researchers studied four landfill sites in France, recorded recovery rates and calculated emissions to produce an overall methane mass balance. The results showed relatively low surface fluxes and oxidation rates up to 50%. The authors report that '*The results of these studies were used as the basis for guidelines by the French environment agency (ADEME) for default values for percent recovery: 35% for an operating cell with an active landfill gas (LFG) recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geomembrane final cover and active LFG recovery.'*

[35] X. Lefebvre, S. Pommier, A. Åkerman, G. Barina and A. Budka (2007), Analysis of the Waste Mass Degradation Degree in the Context of Functional Stability of Closed Landfills, Eleventh International Waste Management and Landfill Symposium, Sardinia.
[36] Barlaz MA, Chanton JP, Green B, Controls on landfill gas collection efficiency: instantaneous and lifetime performance. Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27695- 7908.
[37] F Innocenti, R A Robinson, T D Gardiner, J Tompkins, S Smith (2011), WR1125 - Measurements of Methane Emissions and Surface Methane Oxidation at Landfills. NPL, Analytical Science Division. D Lowry and R Fisher, Royal Holloway, University of London. Defra.
[38] K. Spokas, J. Bogner, J.P. Chanton, M. Morcet, C. Aran, C. Graff, Y. Moreau-Le Golvan, I. Hebe (2006), Waste Management, Volume 26, Issue 5, 2006, Pages 516-525

235. Thus, these figures show reasonable agreement with the Environment Agency best practice guide for 85% recovery from covered cells with full gas extraction and therefore potentially with an overall best practice recovery rate of 75%.

236. The most authoritative study comparing the recovery rates used by individual European countries was published in 2010[39]. This examined in detail the greenhouse gas emissions returns on landfills for nine European countries submitted to the European Environment Agency.

237. The study shows that the reported landfill gas capture rates vary widely between countries. The authors report that recovery rates of 70% are possible in individual cells but are unlikely to be replicated across the entire landfill population in a country. The UK recovery rates reported were the highest in the nine countries examined. Achieving them depends on achieving best practice and not encountering any of the problems that can decrease the amount collected, increase surface leakage etc., the overall effect of which is to make the 75% lifetime recovery rate the likely maximum under current best practice.

[39] Sustainable Landfill Foundation and Solagro (2010), Waste landfilling in Europe, European Environment Agency.