Greenhouse Gas Balances of Waste Management Scenarios

Report for the Greater London Authority

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Executive Summary

Measuring greenhouse gas (GHG) emissions from waste management is an extremely complex subject area. Written in appreciation of the time constraints of the readership, it is therefore intended that this Executive Summary can also function as a standalone summary report. It is thus somewhat more comprehensive than might normally be expected.

The essential goal of this study was to measure and rank a range of scenarios for the management of residual waste[1] with regard to their performance on GHG emissions. Only emissions of carbon dioxide (CO_2) and methane (CH_4) are included within the scope of this study. Where reported in this document, these are expressed in CO_2 equivalents, whereby methane is assumed to have 23 times the potency of CO_2 as a GHG.

It should be noted that we do not at any point in the study aim to assess:

- Whether some of the more complex scenarios will perform effectively in practice;
- Costs or gate fees associated with any of the scenarios; and
- Alternative environmental impacts.

A fundamental consideration when conducting this type of analysis is the scope of system modelling, i.e. where does GHG accounting start and finish. 'Whole system' modelling is a term familiar to proponents of lifecycle assessment (LCA) approaches, and although this is often considered the ultimate goal for such studies, it is not fully appropriate here. It is important to note in this context that we have omitted consideration of emissions from *collection* of residual waste. This is both the result of their relative insignificance[2], and the fact that we are assessing scenarios for the treatment of residual waste and thus (other things being equal) emissions from collection will be the same for all scenarios.[3] For each scenario, we have also omitted the energy demand associated with materials required to construct waste treatment facilities, which in many analyses are typically small compared to operational elements.

Methodology

It should first be noted that our methodology for undertaking this study has received formal peer review.[4] Using our Atropos© model, which has been developed internally over several years, we have adopted what might be regarded as a state-of-the-art approach. This largely echoes that undertaken in the recent Stern Review[5], but with some important distinctions. There are three distinctive features to Atropos©, which differentiate it from typical LCA methodologies:

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[1] Residual waste is the fraction of the waste stream which remains following removal of materials for recycling at the kerbside and at 'bring' sites

[2] They typically represent less than 1% of greenhouse gas emissions (as discussed in Section 5.3)

[3] We are, however, aware that different types of facilities are likely to be implemented at different scales, and therefore have modelled transport costs between treatment stages

[4] Holland, M (2007) Peer review of a study by Eunomia for the GLA into the greenhouse gas balances of waste recovery technologies, EMRC on behalf of the Greater London Authority, October 2007

[5] Stern Review: The Economics of Climate Change, HM Treasury, October 2006

- Monetization, through estimation of marginal damage costs;
- The addition of a 'time-profile' to GHG emissions through discounting;
- Inclusion of all non-fossil emissions of CO_2; and

The marginal damage costs of GHG emissions are also generally expressed as the social costs of carbon (SCC). The SCC represents the economic cost to society from climate change actually occurring. As demonstrated in the Stern Review, there is a recent convention of projecting increasing marginal social costs of carbon over time. Stern has been criticised, however, for the use of excessive values for the SCC.[6] Thus, following the approach of previous work undertaken by Eunomia,[7] we have used what we consider to be more acceptable, lower values based on the available literature - although it should be acknowledged that this kind of estimation will always be somewhat controversial.

Discounting represents a counter-weight to the rising SCC and enables comparison of costs and benefits that occur at different points in time by converting all costs and benefits to present monetary values. It is based upon the premise that costs and benefits occurring at some future date are worth less to current society i.e. we would rather have benefits now, and defer costs to future generations.

There is considerable debate regarding the choice of discount rate, and the Stern Review has received similar criticism, this time for the low rates employed. For the purposes of the present study we have applied the declining discount rate proposed in the HM Treasury Green Book. Again, we have used this approach previously and feel it is more acceptable, but once more, we are aware of alternative views.

The monetisation and discounting elements within Atropos© facilitate the inclusion of all non-fossil CO_2 in our analysis.[8] Traditional LCA methods exclude all emissions from non-fossil CO_2 on the basis that they are simply balancing the CO_2 which has already been removed from the atmosphere during plant or animal growth. In the GHG balances compiled through LCAs, only methane emissions from landfill are counted within what might be considered a fairly arbitrary 100 year period. The climate, however, responds no differently to fossil or non-fossil CO_2, and thus it is important to include all emissions on a like-for-like basis where comparative analysis is concerned.[9]

It should be emphasised that the argument for consideration of GHG emissions from non-fossil carbon is made within the context of a comparative study of residual waste treatment technologies only. This argument should not be taken out of context and is not intended to refer to any other areas, such as comparison of renewable energy sources with those from fossil fuels or the compilation of a GHG emissions inventory, which is usually undertaken according to IPCC conventions.

In this study, all CO_2 and CH_4 emissions are modelled with no time limit imposed. Waste composition data, the carbon characterisation of each waste material type, and the mineralization profiles of the main carbon fractions (i.e. lignin, cellulose, and

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[6] Nordhaus, W (2006) The Stern Review on the Economics of Climate Change, November 2006; Dasgupta, P (2006) Comments on the Stern Review's Economics of Climate Change, November 2006

[7] Eunomia (2007) Managing Biowastes from Households in the UK: Applying Life-cycle Thinking in the Framework of Cost-benefit Analysis: A Final Report for WRAP, May 2007

[8] Non-fossil CO_2 is often referred to as 'biogenic' CO_2 and represents emissions from sources which are not derived from fossil fuels, i.e. which are from biomass, for example, food and green wastes

[9] Albeit taking into account the far greater impact per tonne of methane emissions

hemicellulose fractions of paper, food waste, etc) are all considered in Atropos©. Therefore, the model accounts for slow, medium, and fast degradation of carbon, and the emissions from these fractions (which are discounted over time) within landfill.

Many additional key functions within Atropos© are detailed within Appendix 7, which also provides an example schematic to illustrate the scenario modelling process, as followed by the user.

‘Generic’ and Technology Specific Assumptions

As stated above, the core objective of the study is to provide a ranking of waste technology scenarios. We are fully aware that there will never be complete consensus upon all the assumptions we have used within Atropos©. Towards establishing this ranking, however, it is necessary to form clear judgements upon a set of fundamental, underlying parameters which underpin our analysis.

We have focused on modelling consistent elements of the lifecycle according to a range of ‘generic’ assumptions which relate to all technology scenarios. The most important of these relates to the ‘carbon intensity’[10] attributed to ‘avoided’ electricity generation.[11] Other ‘generic’ assumptions include the emissions reductions offered by materials recycling / reprocessing, the emissions from transportation and the input waste composition for each scenario.

Assumptions relating to specific technologies are also fundamental to this study and underpin the results derived from Atropos©. All assumptions are based not only upon a sound review of existing information, but also upon primary data and personal communications with a range of technology providers. For each technology, we have been careful to undertake our modeling using assumptions which are based upon ‘best-of-breed’ processes operating today, i.e. technology ‘brands’ which are proven at commercial - or in the case of some of the novel processes – at demonstration scale.

It was agreed with the Project Steering Group (PSG)[12] at an early stage that the scenarios included for analysis within the scope of this study ought to reflect those most likely to be implemented in London. As a result, a number of alternative configurations have been omitted, as detailed in Appendix 2, and in Section 8.3 with regard to the specific policy context within London.

Results under Central Assumptions

As can be seen from the results presented in Table A under our central approach and assumptions, Atropos© was used to model 24 technology scenarios. Table A reflects marginal SCC (or net externalities), thus taking into consideration the emissions from different technology elements within each scenario, along with the emissions avoided from both energy generation and materials recovery/reprocessing. The results reflect the cost of carbon (equivalents) to society and are based upon treating one tonne of input waste.

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[10] The term ‘carbon intensity’ refers to the level of CO_2 emitted by an energy source, i.e. those which emit high levels of CO_2 per unit output, are considered ‘carbon intense’

[11] ‘Avoided’ electricity generation refers to electricity from other sources for which there is no longer demand due to generation at waste management facilities

[12] The Project Steering Group consisted of members from the Greater London Authority, London Development Agency, and the London Climate Change Agency

Table A: Ranking of Scenarios under Central Assumptions

Rank	Scenario Number	Scenario Description	Net Externality (£s)
1	11	MBT (AD and maturation) with output to landfill and export of biogas for conversion to H_2 for use in vehicles	4.48
2	21	Plasma gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	4.83
3	13	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (CHP)	5.25
4	12	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (electricity only)	5.45
5	5	Gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	5.75
6	9	MBT (AD with maturation) with CHP, output sent to landfill and plastics to reprocessing	6.01
7	14	MBT (AD with maturation) with output to landfill and compression of biogas for use in vehicles	6.21
8	10	MBT (AD with maturation) with CHP, output to landfill and plastics sent for pyrolysis to synthetic diesel	6.47
9	20	Plasma gasification (following autoclaving) with export of syngas to H_2 fuel cell for power generation (CHP) and plastics to reprocessing	6.50
10	6	Gasification (following autoclaving) export of syngas to H_2 fuel cell for stationery power generation (CHP) and plastics to reprocessing	6.90
11	15(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.35
12	16b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for pyrolysis to synthetic diesel	7.53
13	17	'Biomass' boiler (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	7.67
14	19	Plasma gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.98
15	15(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	8.38
16	16(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for pyrolysis to synthetic diesel	8.57
17	8(b)	Gasification (following MBT biodrying and maturation of rejects) using a gas engine (CHP)	9.01
18	7	MBT (biostabilisation) with output sent to landfill	9.55
19	3	Incineration (with CHP)	10.21
20	8(a)	Gasification (following MBT biodrying and maturation of rejects) using a steam turbine (CHP)	10.71
21	18	Incineration (following MBT biodrying and maturation of rejects) using a steam turbine (electricity only)	10.97
22	2	Incineration (with electricity only)	11.45
23	4	Incineration (with heat only)	11.66
24	1	Landfill (with electricity only)	31.90

As can be seen from Table A, the best performing scenarios are those either based upon MBT (AD with maturation) or upon gasification (or plasma gasification), coupled with hydrogen (H_2) fuel cell technologies. This is the result of the far greater conversion efficiencies of fuel cells when compared to other energy generation technologies. Consequently, a greater amount of alternative energy generation is avoided, which delivers significant GHG reductions. The use of H_2 fuel cell vehicles delivers the best performance due to the avoidance of burning diesel, rather than the avoidance of electricity generation, as is the case with stationery fuel cells.

It should be acknowledged that there has been limited investment and research into the use of waste-derived syngas in hydrogen applications. In addition to the inclusion of an autoclave, a gasifier and a fuel cell within such scenarios, the syngas generated by a gasification facility treating municipal solid waste (MSW) would require processing with a number of intermediate technologies.[13] Today, this would represent a technical risk that is likely to be beyond that which might attract commercial finance. This suggests that our results for Scenarios 5, 6, 20 and 21 should be treated with caution. One of the key goals of this analysis, however, is to report upon ‘leading edge’ configurations which have the potential to deliver both GHG benefits and which fit with wider policy goals at national and city level. The PSG for this study were therefore keen that such scenarios be included within the project scope.

In contrast to the conversion of waste-derived syngas into hydrogen, the use of biogas in fuel cells is proven at commercial scale for stationary power generation, albeit this is a process still in its infancy.[14] This report does not seek to analyse financial viability, but it should be noted in this context that scenarios coupling MBT (AD with maturation) with gas engines (in CHP mode), or with biogas-fuelled vehicles, are the highest ranked configurations which might currently be affordable to local authorities.

When coupled with H_2 fuel cells, plasma gasification (Scenarios 20 and 21) performs better than more ‘conventional’ gasification (Scenarios 5 and 6). This is because vendors of such plasma technologies are tending to promote oxygen (rather than air) blown gasifiers, which produce significantly more hydrogen.[15] The subsequent additional energy generated by the fuel cell offsets the greater energy use of the plasma gasifier. When coupled with a gas engine, however, the ‘conventional’ gasifier performs better than plasma gasification. Whilst the energy generated by the two systems is similar, the greater energy use of the plasma gasifier results in greater overall externalities, as demonstrated by the rankings for Scenarios 15(b) and 19.

Similarly, coupling gasification technologies using a gas engine (whether this is following MBT or autoclaving) demonstrates the greater efficiencies, and thus lower GHG emissions, when compared to using a steam turbine for energy generation. The positioning of Scenario 17 above Scenarios 15(a) and 16(a) also shows that combustion technologies can deliver GHG benefits over gasification if this is coupled with a steam turbine.

Perhaps surprisingly, when compared to many LCA studies, MBT (‘biostabilisation’) process performs better than many of the configurations generating energy due to both

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[13] These technologies would include steam reforming (gas shift), pressure swing adsorption (PSA) and gas filtration

[14] A stationary 250kW Molten Carbon Fuel Cell (MCFC) designed by MTU CFC Solutions is operating at 47% electrical efficiency (in CHP mode) at an anaerobic digestion facility in Leonberg, Germany

[15] It should be noted, however, that ‘conventional’ gasifiers could also be oxygen blown, and could thus perform better than plasma gasification if configured as such

the lack of any release of GHGs associated with fossil carbon from energy generation and reduced emissions of methane in landfill.[16]

Whether preceded or not by MBT ('biodrying'), scenarios incorporating traditional incineration technologies perform poorly. This is the result of significant emissions from wholesale combustion of plastics at relatively low efficiencies, which negates the benefits derived from avoided emissions associated with energy generation. Only Scenario 1 (landfill with electricity only) performs at a lower level than all these scenarios, and is the only approach for which it has been assumed that no metals are recovered, which would offset emissions from manufacturing processes using raw materials.

To demonstrate and compare the performance of core technology types which can be used to generate energy, in Table A, we have highlighted the performance of all key scenarios incorporating AD, gasification and incineration. This demonstrates the better performance not only of AD over gasification and incineration, but also of fuel cells over gas engines and steam turbines. With regard to GHG balances, a key advantage of AD and gasification over incineration, therefore, is that these two technologies can be coupled with more efficient generation technologies, whilst incineration remains locked to the use of a steam turbine.

Table A: Performance of Core Technology Types under Central Assumptions

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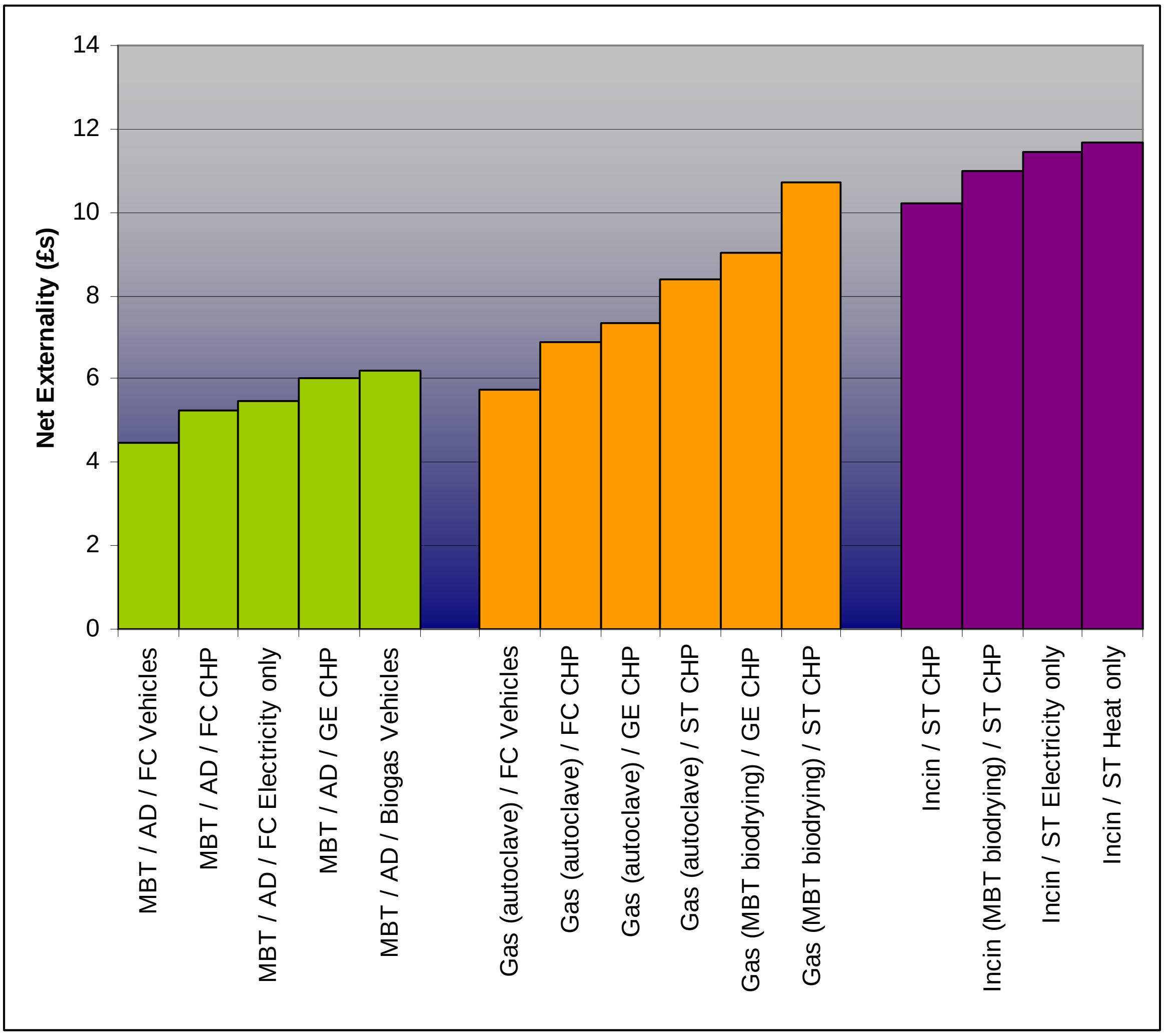
[16] It should be noted for this scenario that a designated 'stable' landfill cell is assumed, with an active oxidation layer reducing fugitive methane emissions to a minimal level.



Note: FC = Fuel Cell, GE = Gas Engine, ST = Steam Turbine

Sensitivity Analysis

As mentioned above, due to the nature of this study, some of our assumptions are likely to be controversial. It should be emphasised, however, that in no way is this study intended as an academic paper, which might seek to explore every possible form of sensitivity analysis using wide ranges of potential variation in assumptions. To deliver a relevant ranking of technology scenarios and thus to function as a useful policy tool, we have therefore chosen to focus upon a limited number of sensitivities within Atropos©:[17]

1. Using a greater ‘carbon intensity’ for avoided electricity generation;
2. Assuming a higher degree of heat utilization from processes to displace heat from alternative sources;
3. A ‘non-monetised, non-discounted’ approach (but with all non-fossil CO_2 equivalents still included within the balance); and

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[17] See Sections 7.2.1 to 7.2.5 for full tables of results

4. A ‘traditional LCA approach’, with exclusion of all non-fossil emissions aside from methane from landfill.
5. Using a likely ‘future’ waste composition, designed to reflect higher levels of recycling.

As outlined above, there was some debate over the carbon intensity to ‘ascribe’ to avoided electricity generation. This was within a very limited range, however, and we have therefore restricted our sensitivity analysis for this parameter from 447g CO_2/kWh under our central assumptions, to 0.522kg CO_2/kWh, which is the value proposed in the Mayor’s Climate Change Action Plan (CCAP). Perhaps unsurprisingly, the outcome of this analysis is by no means dramatic - and far less so than might occur, for example, if one was to assume the marginal avoided source of electricity generation was switching from gas to coal. As one would expect, some scenarios generating relatively higher levels of electricity move upwards as a result of the greater amount of CO_2 being avoided from alternative generation capacity. There is, however, very little noteworthy change in the rankings in that no scenario moves more than one place in either direction.

As a result of fluctuations in day/night and seasonal demand, from both residential and commercial off-takes, our central assumption is such that only 55% of heat generated by any waste management facility is used to displace alternative sources. In situations where more embedded generation might be possible, however, there is likely to be greater potential for heat use, as smaller facilities might be more easily switched on and off to accommodate local heat demand. Consequently, to provide limited sensitivity analysis on this parameter, we have raised the rate of heat utilisation to 80%. Compared to our central results, most scenarios which produce relatively large amounts of heat perform better; most notably, Scenario 4 (incineration with heat only), whilst scenarios without any heat generation fare worse. Again, however, perhaps unsurprisingly, across all scenarios the order of magnitude of change is insignificant.

The adoption of this ‘non-discounted, non-monetized’ approach results in little material change to the rankings when compared to those under our central assumptions. ‘Slow’ degrading, non-fossil carbon (i.e. lignin) sent to landfill has a greater impact when not discounted and thus all scenarios incorporating gasification (following autoclaving) move upwards at the expense of scenarios incorporating MBT (AD with maturation), which send stabilised wastes to landfill. In the bottom half of the table, however, there is no change to the rankings.

Perhaps the most interesting and important comparison for this study (and one which in many senses represents an entirely different methodology rather than a form of sensitivity analysis) is the adoption of a typical LCA approach, the results for which have also been generated by Atropos©. The results show, however, that this has little impact on the rankings compared to our central results. Some scenarios which generate significant non-fossil CO_2 emissions through energy generation move upwards but this is usually by no more than one place in the rankings.

Changes in ranking under an LCA approach also occur partly because we have assumed – as many LCA studies do – a 100 year cut-off for the emissions. In doing so, we have attributed – which many LCAs do not do (when logically they should) – a credit in respect of non-fossil carbon still sequestered in landfill after 100 years. Also, in accounting for methane emissions from landfilled residues, we have credited back to the process those emissions which would otherwise have been associated with the carbon in the landfilled material if it had been released as CO_2 (which is consistent with the assumption that emissions of non-fossil derived CO_2 should be given zero weighting in the analysis).

Another point worth making is that effectively, to ignore most of the non-fossil carbon emissions (and how they occur over time) implies shifting the baseline. Some technologies now appear to reduce net emissions of GHGs, whilst others make net contributions to GHG emissions. It seems to us to be counter-intuitive to speak in terms of processes 'contributing to reductions in GHG emissions' when in the round, they do not.[18] To the extent that they do relies upon a particular accounting convention which is only appropriate in a limited context.

The final sensitivity tested relates to likely future changes in waste composition. In response to policy and regulatory drivers, this is likely the change significantly during the next 25 years, and thus we have modelled the impact of changing the current composition to that representative of a 45% recycling rate, as per the target set by the Mayor for 2015.[19] This impact is minimal, with only one scenario moving more than one place in the rankings compared to under our central assumptions. What should be noted, however, is that in terms of overall externalities, the Scenarios focusing on generating energy through thermal treatment processes such as incineration and gasification perform worse than under our central assumptions, whilst those scenarios employing biological treatment deliver an improved score.

Conclusions and Recommendations

As mentioned above, the goal of this study is to measure and rank a range of waste technology scenarios with regard to their performance on greenhouse gas (GHG) emissions. We do not attempt to pass judgement upon issues such as cost, planning or a host of environmental issues other than GHG emissions from waste management. Climate change, however, is recognised as a core problem facing society and therefore our conclusions and recommendations, although remaining in context, are intended to contribute to guiding waste policy development in London and beyond.

- Scenarios incorporating MBT (AD with maturation) perform most consistently well both under our central assumptions and in each form of sensitivity analysis. Currently an under-exploited approach across the UK, the GLA could bring together and integrate related research into specific planning and cost analysis, to build upon the results of this study and promote development of best-of-breed MBT (AD with maturation) facilities across the city;
- MBT (AD with maturation) delivers the greatest GHG benefit when coupled with highly efficient hydrogen fuel cell technologies. Stationary power generation using molten carbonate fuel cells (MCFCs) fueled by biogas is proven at commercial scale[20], but is currently significantly more capital-intensive than generation with more conventional steam turbines or gas engines. The case for

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[18] To suggest that waste management can reduce overall CO_2 emissions would imply that producing more waste is good for climate change, when in reality it clearly is not

[19] Greater London Authority (2006) The London Plan: Spatial Development Strategy for Greater London – Housing Provision Targets, Waste and Minerals Alterations

[20] One such facility is operating in Leonberg, Germany

commercial roll-out would therefore benefit significantly from the first installation of the technology within a building in London;[21]

- There has been too little research to make clear judgment as regards the potential use of fuel cells to generate energy from hydrogen converted from syngas from gasification (or plasma gasification) processes. The results of our analysis demonstrate that there is clear potential for such approaches, but we again urge caution as to the context in which they should be used. To reduce uncertainty and promote development such scenarios, the GLA should consider funding additional research of this specific area;
- The results generated by our Atropos© model have clearly shown that CHP generation delivers far greater GHG benefits than generation based upon electricity or heat only solutions. Again, there may be potential for the GLA to intervene in future planning applications to promote heat off-take in addition to electricity generation, or encourage developers to select sites which offer clear potential for embedded generation, either in communities or in industrial applications;
- Under our central assumptions and the five forms of sensitivity analysis, however, incineration with CHP reaches a high of only 18th place in the scenario rankings. The other two incineration scenarios fare worse still, and do not emerge from the bottom six positions, whilst Scenario 18, involving MBT (biodrying) prior to incineration does not fare much better. This poor performance is largely the result of wholesale combustion of plastics, which results in significant CO_2 emissions. On this basis, unless coupled with both significant kerbside recycling programmes and clear provision for good quality CHP (GQCHP), the GLA position regarding mass-burn incineration within London receives some qualified support (in that the analysis undertaken here does not cover all relevant factors and issues);
- The results from our analysis have shown that materials recycling / reprocessing, particularly of plastics, makes a considerable difference to GHG balances by avoiding emissions from virgin manufacturing processes. Compared to emissions avoided by energy generation using waste technologies, these benefits are not insignificant and are far higher than those delivered by conversion of plastics to synthetic diesel.[22] The GLA should thus ensure that they are not overlooked as a result of related stakeholders' desire to meet targets for installed 'renewable' energy capacity;
- This study has shown that autoclave technologies, if implemented and operated as planned by technology suppliers, have potential to be part of relatively well performing scenarios. As stated above, this study is not concerned with assessing the technical viability of particular technologies. Until autoclaving has been commercially proven in the UK, however, only limited conclusions should be drawn from this particular aspect of our analysis;
- It should be acknowledged that the maturation time of reject streams from 'pre-treatment' technologies such as MBT and autoclaving has a key impact on scenario performance. As outlined for each technology in Section 6.0, we have

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[21] Toward this end, the GLA and London Climate Change Agency are considering potential installation of a MCFC at a regional government office building in London

[22] As can be seen from the detailed breakdown of results provided in Appendix 5

set these maturation times according to how they are being presented by bidders for local authority procurement contracts. In reality, however, all scenarios can be tweaked to incorporate greater or lesser maturation times according to the Landfill Allowance Trading Scheme (LATS) requirements of a particular authority.

- A key point ot note is that under our central assumptions, the difference in GHG-related externalities between the first 10 scenarios is, in monetary terms, only £3.05 per tonne of input waste. This would indicate that based upon the assumptions used within this study, should any of these scenarios incur significant capital or operating expenditure above the others, it is unlikely to be justifiable through reference to GHG-related externalities alone. It should be highlighted, however, that there are wide-ranging estimates of the SCC, as discussed in Section 3.3.[23] Thus, if higher values had been employed within Atropos©, this difference in externalities between the first 10 scenarios might have been significantly greater; although similarly if a lower SCC had been modelled, far smaller differences would have been recorded; and
- Finally, although there is still further research to be undertaken, this study has shown that new technologies can deliver far lower GHG emissions than using conventional incineration or landfill. As the potential to utilise hydrogen fuel cell technology develops, and becomes more affordable, such benefits are likely to increase further.

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[23] Also, discussed in more detail in Appendix 3

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1.0 Introduction and Background

The concept of climate change, induced by increased emissions of so-called greenhouse gases (GHGs), has now become a widely accepted scientific fact,[24] recently put into an economic context by the government-sponsored Stern Review.[25] Waste management is estimated to contribute around 2.5% to total GHG emissions (including 41% of methane emissions) in the UK,[26] which is a considerable volume when compared to most other sectors of the economy.

London is a significant contributor to GHG emissions in the UK and has an ecological footprint far greater than its geographical area.[27] Currently, a large percentage of London's waste is sent, in un-treated form, to landfills outside of the city, an approach which is not consistent with the Mayor's goal of reducing associated GHG emissions as part of more sustainable waste management practice.[28]

The political emphasis upon climate change and drive towards alternative technologies for waste treatment and recycling is principally derived from the EU Landfill Directive. Additional mechanisms such as the Kyoto Protocol and EU Emissions Trading Scheme are also propelling change in waste and resource markets in the UK and further afield, and their influence is only likely to become more widespread as they become more integrated into how we manage wastes from all sectors of the economy.

The GLA has recently published a Climate Change Action Plan (CCAP) which seeks to deliver a strategic, integrated approach to tackling GHG emissions from within London.[29] Alongside or within the GLA, there are a range of strategic bodies which are indirectly working towards sustainable waste management. An important element of this project has been the feedback and insight received from a range of stakeholders including the London Climate Change Agency, the London Energy Partnership, the London Hydrogen Partnership and the London Development Agency. The sections below, therefore, are based upon a genuine attempt to develop a joined-up approach to waste, energy, environment and planning which is seen as essential for London to maintain its position as a first class capital city.

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[24] Most recently, see IPCC (2007) *Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability – Summary for Policymakers*, Working Group II Contribution to the IPCC Fourth Assessment Report, April 6th 2007.

[25] Stern Review: The Economics of Climate Change, HM Treasury, October 2006

[26] AEAT Technology (2006) *UK Greenhouse Gas Inventory 1990 to 2004*, October 2006. It should be noted that this estimated contribution depends on the accounting conventions used, this figure referring to the UK emissions as reported to the IPCC

[27] WSP Environmental (2003) *Making London a Sustainable City: Reducing London's Ecological Footprint*, September 2003, Biffaward

[28] Greater London Authority (2003) *Rethinking Rubbish in London; The Mayor's Municipal Waste Management Strategy*, September 2003

[29] Greater London Authority (2007) *Action Today to Protect Tomorrow: The Mayor's Climate Change Action Plan*, February 2007

As is repeated throughout the sections below, however, this report does not attempt to pass judgement upon issues such as cost, planning or a host of environmental issues other than GHG emissions from waste management. Climate change, however, is recognised as a core problem facing society and therefore our conclusions and recommendations, whilst they need to be placed in this context, are intended to contribute to guiding the development of waste and energy policy in London (and beyond) in the years ahead.

2.0 Scope and Objectives

The essential goal of this study is to measure and rank a range of residual waste technology scenarios with regard to their performance on greenhouse gas emissions.[30] It is hoped that this will contribute to a wider evidence-base to support GLA policy-making for waste management.

A fundamental consideration when conducting this type of analysis is the scope of system modelling, i.e. where does carbon accounting start and finish? 'Whole system' modelling is a term familiar to proponents of lifecycle approaches, and although this is often considered the ultimate goal for such studies, it is not fully appropriate here. We have thus focused on modelling consistent elements of the lifecycle as detailed throughout Section 5.0.

It is important to note in this context that we have omitted consideration of emissions from *collection* of residual waste.[31] This is both the result of their relative lack of significance,[32] and the fact that we are assessing scenarios for the treatment of residual waste. This means that (other things being equal) emissions from collection will be the same for each scenario. For each scenario, we have also omitted the emissions from energy demand associated with materials required to construct waste treatment facilities. Again, in many analyses, these emissions are typically small compared to operational elements, although it should be acknowledged that the approach taken to discounting the future, as explored in Section 3.2, has the potential to make them somewhat more significant than has been the case in other studies.

The analysis seeks to be as inclusive as possible in terms of the potential different technology scenarios. Within the time and budget allocation, however, some potential options are omitted from the study, as detailed in Appendix 2. Most scenarios have a range of configurations and might include a number of different waste technologies. It was therefore agreed with the Project Management Group[33] at an early stage that the scenarios included for analysis within the scope of this study ought to reflect those most likely to be implemented in London.

In light of London's high profile position, consideration of exemplar configurations is also applicable. There would seem to be no point in choosing 'obviously poor examples' of specific technologies, and thus we have omitted consideration of options which existing data shows will not compare favourably with regard to greenhouse gas (GHG) emissions. Furthermore, insofar as there is reliable information available, it was agreed that we would provide analysis of technologies which are very much 'leading edge'.

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[30] Carbon dioxide and methane only

[31] Residual waste is the fraction of the waste stream which remains following removal of materials for recycling at the kerbside and at 'bring' sites

[32] As discussed in Section 5.3

[33] GLA Policy group consisting of members from the Greater London Authority, London Development Agency, and the London Climate Change Agency

It should be re-iterated that we do not, at any point in the study, aim to assess:

- Whether some of the more complex, ‘leading edge’ technology scenarios will perform effectively in practice; or
- Likely costs, or gate fees, associated with any of the scenarios.

Following establishment of a performance hierarchy with regard to GHG emissions, consideration of such parameters would present a logical extension of the present work to assess the practical strengths and weaknesses of the most highly rated scenarios.

It is also useful to acknowledge that this assessment is of greenhouse gas (GHG) impacts only and does not aim to provide analysis of other types of environmental impact, such as eutrophication or ground-level pollution – and, as such, does not attempt to present the complete story.

3.0 Approach and Methodology

It should first be noted that this study, and thus our methodology for undertaking the analysis, has received formal peer review.[34] Following reading of this review and subsequent dialogue with its author, we have made amendments to limited elements of our final report.

As stated in Section 2.0, the core objective of this study is to provide a ranking of waste technology scenarios with regard to their performance on GHG emissions. We are fully aware that there will never be complete consensus upon all the assumptions we have used. Towards establishing a clear ranking of scenarios, however, it is necessary to form clear judgements upon a set of fundamental, underlying parameters which underpin our analysis, as detailed in Sections 5.0 and 6.0.

These core assumptions were determined during an extensive review process undertaken in partnership with the Project Steering Group (PSG) for this study.[35] This process was initiated by a full review of both published information and primary data supplied by technology suppliers, which was submitted and subsequently presented by Eunomia to the PSG.[36]

During this presentation, Eunomia proposed values for each key assumption, whilst highlighting those parameters which would most materially affect the analysis, and thus for which sensitivity analysis would be most appropriate. All assumptions and sensitivities were then agreed with the PSG during several subsequent project meetings.

It should be emphasised here that in no way is this study intended as an academic paper, which might seek to explore every possible form of sensitivity analysis using wide ranges of potential variation in assumptions. To deliver a relevant ranking of technology scenarios and thus to function as a useful policy tool, we have therefore chosen to focus upon a limited number of sensitivities as detailed in Section 7.2.

All our analysis has been undertaken using our in-house model, Atropos©, which has been developed over a 5-6 year period and is based both upon peer-reviewed information in published journals and upon data provided by technology providers. It is an iterative model, which is continually updated as new information comes to light, so that it presents the most current picture as possible.

For the purpose of this study, we have used Atropos© to model the GHG emissions from one tonne of waste input to a technology scenario in year one. Thus, it is only in scenarios which include sending biodegradable wastes to landfill that impacts will occur in future years. These impacts are either positive, in the form of methane

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[34] Holland, M (2007) Peer review of a study by Eunomia for the GLA into the greenhouse gas balances of waste recovery technologies, EMRC on behalf of the Greater London Authority, October 2007

[35] This PSG included a range of stakeholders from the Greater London Authority, the London Climate Change Agency, the London Energy Partnership, the London Hydrogen Partnership and the London Development Agency

[36] See Literature Review in Appendix 3

emissions through the landfill cap, or negative, through the displacement of other energy sources via power generation from landfill gas.[37]

Atropos© is based upon 'first principles', and thus a proximate analysis of each element of the input composition is generated at the beginning of each project. Both the fossil and non-fossil carbon content of each constituent is then tracked through each phase of the technology scenario to determine the extent of GHG emissions. Within the model, non-fossil carbon is broken down into lignin, cellulose, sugars, fats, and proteins so that the rapidity of degradation can be determined when waste is resident either within biological treatment processes or in landfill.[38]

The model is therefore both 'bottom-up' and transparent, and enables Eunomia to trace the path not only of forms of carbon, but of moisture content and other elements relevant to wider environmental impacts, should these be applicable. This differs significantly from WRATE, the life-cycle assessment (LCA) tool developed and promoted on behalf of the Environment Agency (EA) to model the environmental impacts of waste management. WRATE provides a helpful 'user interface' that enables scenarios to be created with 'drag and drop' functionality. This 'top-down' approach, however, results in an opaque view for the user, who is usually unable to follow the flow of carbon or other elements through the chain of different technologies which might make up a particular scenario.

There are two other important differences between the approach we have taken using Atropos© and typical LCA methodology:

- We have included all GHG emissions derived from non-fossil carbon (CO_2 and CH_4) within our analysis, whilst LCA studies typically exclude all non-fossil CO_2 emissions. This approach is discussed in more detail in Section 3.1;
- We used a Cost-benefit Analysis (CBA) approach to monetise (and discount) all GHG emissions to present them in terms upon which decision-making might be based, whilst LCA studies present these in CO_2 equivalent terms only.[39] This is discussed in more detail in Sections 3.2 and 3.3.

Many additional key functions within Atropos© are detailed within Appendix 7, which also provides an example schematic to illustrate the scenario modelling process, as followed by the user.

3.1 Inclusion of Non-fossil Emissions

As mentioned above, under our central assumptions, GHG emissions associated with non-fossil carbon are counted alongside those from fossil sources. The climate responds no differently to fossil or non-fossil CO_2, and thus we feel it is important to

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[37] Assumptions relating to landfill are discussed in Section 6.1, whilst assumptions relating to the displacement of other energy sources are detailed in Section 5.1

[38] Please see Appendix 7 for more detailed discussion

[39] Although part of our core sensitivity analysis also models the outcomes in both 'non-discounted, non-monetised' and LCA terms. See Section 7.2

include all emissions on a like-for-like basis.[40] Many forms of non-fossil carbon present in the waste stream are not part of short carbon cycles and thus should not be excluded on the basis of being ‘carbon neutral’ or ‘renewable’. Put in context, application of life-cycle assessment (LCA) methodologies usually results in waste management scenarios appearing to reduce overall GHG emissions, which is somewhat counter-intuitive.

Although this is not the current convention used when compiling GHG inventories, in this instance we are undertaking a comparative study of residual waste treatment technologies rather than an inventory. If this analysis were part of an Intergovernmental Panel on Climate Change (IPCC) GHG emissions inventory, or a macro (i.e. global) scale study of climate change, then non-fossil carbon might be excluded from calculations. For the current purpose of micro-scale comparison of residual waste treatment technologies, however, all GHG emissions, whether fossil or non-fossil in origin, associated with each technology will be considered. The rationale supporting this decision is presented in detail in Appendix 3, but fundamentally, it is the safest assumption to make in a comparative analysis of the effects of the processes on climate change.

It should be emphasised that the argument for consideration of GHG emissions from non-fossil carbon is made within the context of waste treatment. The argument, as presented in the present work, should not be taken out of context and is not intended to refer to any other areas, such as renewable energy from non-fossil carbon sources. Within the sensitivity analysis presented in Section 7.2.4, however, we have modelled each scenario according to a traditional LCA approach, which excludes all non-fossil carbon aside from that emitted as methane from landfills. In LCA, some approaches take account of carbon sequestered in landfills / soils etc., but typically, this sequestration ‘credit’ is applied at the – usually arbitrary - cut-off point which is taken as the period for the study (typically 100 years). Our reporting of LCA-style results includes a sequestration credit estimated for the 100 year period.

In the main approach taken in the current study, carbon emissions are modelled as per estimated actual emissions over time, with no time limit imposed (i.e. the model effectively extends to infinity). Actual carbon emissions from residual waste depend on waste composition, with the different carbon components of each waste material (i.e. lignin, cellulose, and hemicellulose fractions of paper, food waste, etc) degrading at different rates. For example, the emissions of CO_2 from wood waste will vary with time according to the percentages of lignin, cellulose, and hemicellulose attributed to wood, and their respective rates of degradation (conversion of carbon to CO_2 via decomposition processes). Waste composition data, the carbon characterisation of each waste material type, and the mineralization profiles of the main carbon fractions are considered in Atropos©.

It should be clarified that inclusion of non-fossil carbon in the model does not represent an attempt to favour one treatment process over another, but rather an attempt to show all emissions associated with each technology as realistically as possible. However, the model does place importance on ‘time-limited sequestration’ of carbon as well as highlighting any shift in material composition. For instance, the

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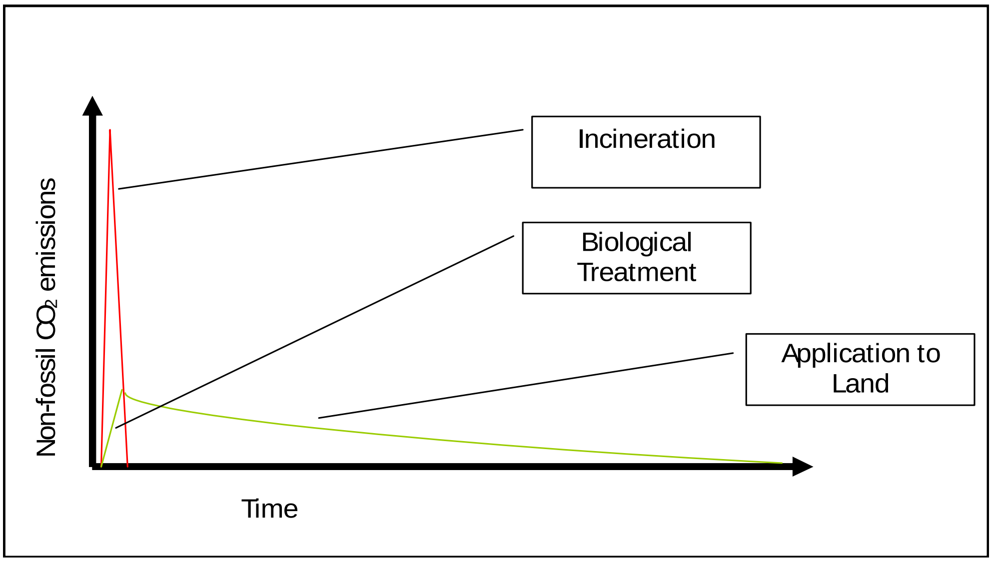
[40] Albeit taking into account the far greater impact per tonne of methane emissions

carbon emission profile for incinerated biowaste can be compared to the profile for biowaste treated via an aerobic stabilisation process and then applied to land, as shown in Figure 3-1.

In the former case, virtually all carbon is emitted instantaneously, whereas in the latter case a large proportion of carbon is emitted within a period of weeks (i.e. degradation of the faster degrading pools of carbon), with the remaining carbon being degraded more slowly over time. The actual significance of the time profile is mediated through the assumptions regarding the discount rate to be used in the model, and the way in which the social costs of carbon are deemed to change over time (see Sections 3.2 and 3.3, respectively).

We are fully aware that our approach in this respect is controversial, and therefore as part of our sensitivity analysis in Section 7.2.4, we have also modelled and ranked each scenario according to an LCA approach, under which emissions from non-fossil CO2 are given zero weighting.

Figure 3-1: Time-related CO2 emissions of the non-fossil carbon component of waste



3.2 Monetisation and Discounting

Monetisation and discounting enables comparison of costs and benefits that occur at different points in time by converting all costs and benefits to present monetary values. This is achieved by applying the premise that costs and benefits occurring at some future date are worth less to current society – we would rather have benefits now, and defer costs to future generations.

Discounting is a technique common to cost-benefit analysis (CBA), but not considered in LCA. Essentially, LCA is insensitive to time (e.g. emissions are aggregated over an arbitrarily selected time-scale) whereas discounting enables CBA to consider the varying value of impacts over a potentially infinite time-scale. Such an approach becomes particularly relevant when considering the potential of different waste management technologies to sequester non-fossil carbon, and thereby delay GHG emissions to a future date. Discounting is implicitly related to the inclusion of GHG emissions from non-fossil carbon. Simply put, the question becomes one of how much do we value a delay in emissions in the context of climate change?

These issues have been addressed to some extent by applying time-discounting rates (i.e. hyperbolic discounting – see Figure 3-2) based on observations of how people actually do discount the future (e.g. through financial investment profiles).[41] Essentially, since it is debatable whether either the present or future generations should dictate outcomes that may affect both, the method of hyperbolic discounting provides something of an ethical middle ground.

Within the version of Atropos© used to model scenarios for this study we have applied the declining discount rate proposed by the HM Treasury Green Book, as presented in Table 3-1. The Green Book recommends using a discount rate of 3.5%. However, for projects with impacts exceeding thirty years, i.e. in this case, those scenarios which include the landfill of biodegradable wastes, it recommends that a declining schedule of discount rates should be used rather a single, constant discount rate.

It should be acknowledged, however, that there is considerable debate regarding the choice of discount rate,[42] with the approach employed in the recent Stern Review receiving criticism for using relatively low rates.[43] As we consider this to be an assumption which could materially affect the results of our analysis, as part of our sensitivity analyses, we have run each scenario within Atropos© not only using a zero discount rate, but also with no monetisation, as discussed further in Section 3.

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[41] Pearce, D., Atkinson, G. and Mourato, S. (2005) *Cost Benefit Analysis and the Environment: Recent Developments.* OECD / Edward Elgar, Cheltenham

[42] Discussed in detail in Appendix 3

[43] Nordhaus, W (2006) *The Stern Review on the Economics of Climate Change*, November 2006; Dasgupta, P (2006) *Comments on the Stern Review's Economics of Climate Change*, November 2006

Figure 3-2: Comparison of constant (4%) discount rate and the time-declining discount rate recommended in the Green Book

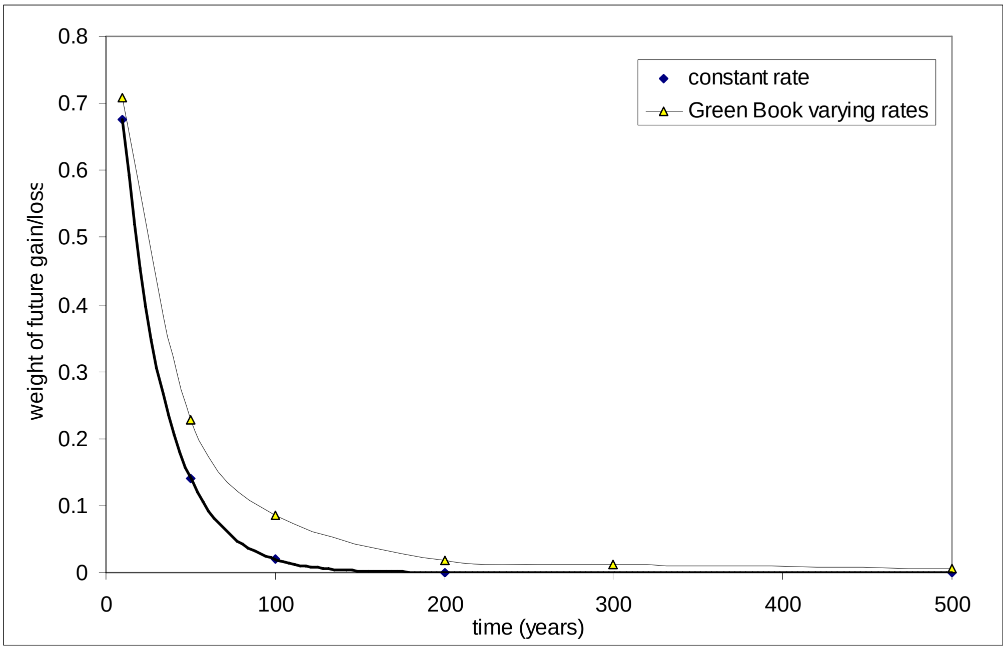

Table 3-1: The declining long-term discount rate, as recommended in the Treasury Green Book.

Period of years	0-30	31-75	76-125	126-200	201-300	301+
Discount rate	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%

3.3 Marginal Damage (Social) Costs of Carbon

In Section 3.2 we have outlined our approach to monetisation and discounting, whilst here we discuss the values we have chosen to use for each tonne of CO_2 equivalent emitted in any given year.

Marginal damage costs of GHGs are increasingly being expressed in terms of the Social Costs of Carbon (SCC). The SCC are the economic costs to society from climate change actually occurring, and are estimated as ‘the net present value of climate change impacts over the next 100 years (or longer) of one additional tonne of carbon emitted to the atmosphere today’.[44] There is a recent tendency towards projecting increasing marginal social costs of carbon emissions (i.e. the damages

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[44] Watkiss, P., D. Anthoff, T. Downing, C. Hepburn, C. Hope, A. Hunt, and R. Tol (2005). *The Social Costs of Carbon (SCC) Review – Methodological Approaches for Using SCC Estimates in Policy Assessment, Final Report*. AEA Technology on behalf of Defra

associated with emitting carbon are predicted to increase with time) due to the predicted escalating impact of climate change.

Marginal damage costs, or social costs[45], should be distinguished from abatement costs; the former estimates the value of impacts caused by marginal increases (in carbon emissions), whereas the latter estimates the costs associated with measures to reduce or halt those impacts. In the present study we are not interested in abating GHG emissions, but rather in comparing the potential costs of emissions from a variety of waste treatment scenarios.

All measures of marginal damage costs are controversial to some degree. As explored in greater detail in Appendix 3, the wide range of estimates of social costs is predominantly due to:

- Each study's approach to identifying and valuing the impacts of carbon emissions and climate change;
- Rate of discount applied with respect to value of future impacts; and
- Equity weighting when aggregating global damage costs.

In this study we use the escalating social costs of carbon recommended by Watkiss et al (2005) for policy-related decision-making, as presented in Table 3-2. The Table combines values for the SCC as estimated by various studies. Only the 'Central Guidance' figures which appear in the Table have been used within our central assumptions. This is appropriate for project-type appraisals such as this where a basis for a decision is sought.

The variation shown in Table 3-2 reflects the inclusion or exclusion of some risks, major climatic system events, and socially contingent effects (e.g. poverty and regional conflict) in the various models used to generate values.

Table 3-2: SCC Values from the Review by Watkiss et al (2005) (£/tonne carbon)

Year of emission	Central guidance	Lower central estimate	Upper central estimate	Lower bound	Upper bound
2000	55	35	130	10	220
2010	65	40	160	12	260
2020	80	50	205	15	310
2030	100	65	260	20	370
2040	140	90	330	25	450
2050	210	130	420	30	550

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[45] Social costs may also be referred to as shadow costs. The shadow cost is the cost that would prevail if a market price could be determined. Shadow pricing is used when placing a monetary value on program outcomes that cannot be bought or sold, such as social value. These prices may be different for different time periods

We believe this assumption to be the most accurate, although it should be acknowledged that all such measures are controversial to some degree. The core goal of this study, however, is to score technology scenarios according to their GHG performance, rather than offer any definitive measure of their external costs.[46] Irrespective of the SCC value used, therefore, assuming that this is consistent across technology scenarios, there will be no impact upon rankings.

As discussed in Section 3.2, for the purposes of sensitivity analysis, in Section 7.2.3 we have modelled and presented the results according to a non-discounted, non-monetised approach, to remove any perceived influence of rising SCCs.

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[46] Although this may be useful in wider decision-making over the financial costs and impacts of certain technologies

4.0 Waste Technology Scenarios

There are a range of technologies which might be used to manage or treat residual wastes. The scenarios shown in Table 4-1 involve either one or a number of these technologies in a logical sequence. As mentioned in Section 2.0, those included reflect configurations most likely to be implemented in London both now and in the medium term. As can be seen from the Table, there are 24 potential combinations, which we, together with the PSG, believe are applicable to this study.

Table 4-1 is supplemented by a more detailed schematic for each scenario in Appendix 1, along with a clear rationale outlining why we have omitted certain alternative scenarios from our analysis, in Appendix 2. These schematics show the positive and negative contributions to the total GHG balances for each scenario element, whilst arrows indicate movement of materials, or residues, between processes, which will also result in GHGs.

For the majority of technology scenarios, the key GHG impacts relate to:

- Energy use in the treatment process (from electricity, or primary fuel use);
- Emissions associated with the operation of the process itself (for example, combustion or biological degradation of the waste material);
- Offsetting emissions associated with:
  - Materials recycling;
  - Energy generation.
- The disposal of residues to landfill (which may incur further emissions or / and energy offsets).

All assumptions regarding the above parameters are outlined in Sections 5.0 and 6.0.

Table 4-1: Technology Scenarios

Scenario	Mechanical separation of dry recyclables followed by..							Incineration		Gasification			Biomass Boiler (CHP)	Plastics Pyrolysis	Gas Shift (to H2)	Fuel Cell Vehicles	Stationery Fuel Cell		CBG Upgrading	CBG Vehicles	Synthetic Diesel Vehicle	Landfill (+ elec)
	Anaerobic Digestion			Aerobic (Bio-stabilisation)	Aerobic (Biodrying)	Autoclaving	Aerobic Maturation															
	Elec	Heat	Export					Elec	Heat	Elec	Heat	Export					Elec	Heat				
1																						x
2								x														x
3								x	x													x
4									x													x
5						x						x			x	x						x
6						x						x			x		x	x				x
7				x																		x
8(a)					x		x			x	x											x
8(b)					x		x			x	x											x
9	x	x					x															x
10	x	x					x							x							x	x
11			x				x								x	x						x
12			x				x										x					x
13			x				x										x	x				x
14			x				x												x	x		x
15(a)						x	x			x	x											x
15(b)						x	x			x	x											x
16(a)						x	x			x	x			x							x	x
16b)						x	x			x	x			x							x	x
17						x	x						x									x
18					x		x	x														x
19						x				x	x											x
20						x						x			x		x	x				x
21						x						x			x	x						x

Notes:

1. Option 8(a) involves the use of a steam turbine for energy generation, whilst Option 8(b) involves the use of a gas engine for energy generation
2. Option 15(a) involves the use of a steam turbine for energy generation, whilst Option 15(b) involves the use of a gas engine for energy generation
3. Option 16(a) involves the use of a steam turbine for energy generation, whilst Option 16(b) involves the use of a gas engine for energy generation
4. Options 19, 20 and 21 are based upon a plasma gasification technology
5. Option 19 involves the use of a gas engine for energy generation

5.0 Overview of Generic Assumptions

As mentioned in Section 3.0, the assumptions used within our Atropos© model are critical to the results of this study. Our discussion within this section focuses upon a range of assumptions which are generic to all technologies. These include:

- Carbon intensity of avoided and used energy;
- Emissions reductions offered by recycling / reprocessing;
- Emissions from transportation (of residues between scenario elements); and
- Composition of waste to be treated.

Assumptions which relate to specific technologies are discussed in Section 6.0, whilst more detailed literature reviews corresponding to the following Sections can be found in Appendix 3.

5.1 Carbon Intensity of Avoided and Used Energy

All waste management processes consume, and in many cases, generate energy. It is therefore often necessary to calculate a net energy balance. In lifecycle assessment (LCA) and cost-benefit analysis (CBA), the carbon intensity of imported energy is often considered differently from that exported. Thus, to estimate the overall carbon emissions from a process, both imports and exports require analysis, potentially on a separate basis.

It is important here to define the system “limits” or “boundaries” for these parameters, i.e. where the carbon accounting starts and finishes. For the purposes of this study, displaced energy sources include those used in extraction and transfer of fossil fuels through to their combustion and onward management. As noted in Section 2.0 with regard to the system limits for waste management processes, however, we have omitted consideration of emissions from *collection* of residual waste. This is both the result of their relative insignificance,[47] and the fact that we are assessing scenarios for the treatment of residual waste and thus (other things being equal) emissions from collection will be the same for each scenario. We have also omitted the energy demand associated with construction materials. In many analyses, this is deemed to be relatively insignificant as a proportion of the total, although there are circumstances (and assumptions) which might so increase their significance in the overall analysis, for example, the approach taken to discounting the future, as explored in Section 3.2.

Sections 5.1.2 and 5.1.3 therefore provide analysis of the displacement of CO_2 by energy *generation from* waste, whilst Section 5.1.4 explores what is often known as the ‘parasitic load’, or *energy used by*, processes. It should be noted that assumptions relating to emissions avoided from generation of power in vehicles with waste-derived fuels are detailed in Sections 6.7 (hydrogen) and 6.11 (compressed biogas and synthetic diesel).

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[47] As discussed in Section 5.3

5.1.1 Avoided CO_2 Emissions from Energy Generation

In virtually all analyses, energy generated, either as heat or electricity, during waste management processes, can be considered to replace a requirement for equivalent amounts of heat or power from other sources – here described as the avoided marginal source of generation. There is some debate, however, regarding exactly what source should be considered as avoided.

The choice of avoided generation has a major impact on the carbon balance of different waste management scenarios, as previous studies have shown. [48] If it is assumed that energy sources with a very high carbon intensity, for example, coal-fired power stations, are being substituted, scenarios which are net generators of significant amounts of energy will appear more favourable. Alternatively, if the assumption made is that less carbon-intense sources – for example, nuclear or renewable energy sources – are substituted, then the credit associated with energy generation is reduced, and the net performance of systems generating relatively small amounts of energy is improved.

5.1.2 Marginal Source of Electricity

As explored in Appendix 3, there are several different approaches taken within the literature, but we feel that these do not give adequate weight to the key question of whether demand for electricity rising or falling? If it is the former – and historical DTI (now BERR) energy statistics appear (sadly, one might say) to back this up - then the marginal avoided source of generation ought to be the alternative 'new-build' capacity, rather than any mix of existing capacity.[49] Many authors do indeed adopt a similar view[50], but this limited consensus does not extend to the actual profile of likely new generation capacity for electricity.

Our analysis indicates that the mix of new generation capacity is likely to be affected by a range of factors:

- Cost effectiveness of new build - under which Combined-cycle gas turbines (CCGT) remain a relatively favourable option (though this is dependent on gas prices);
- Base load operation – most waste management facilities operate continuously, and so are most likely displace other base load capacity, i.e. nuclear, coal and gas;
- The need for the UK to meet the targets set by the Kyoto Protocol and related guidance for planning authorities to help determine permissions for new renewable power generation facilities;[51]

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[48] AEA Technology (2001) *Waste Management Options and Climate Change*: Final Report, European Commission: DG Environment, July 2001; Profu (2004) *Evaluating waste incineration as treatment and energy recovery method from an environmental point of view*, CEWEP, May 2004

[49] Indeed, the latest DTI Energy Review forecasted growth in electricity use from 350TWh in 2005 to around 400TWh in 2020

[50] See Appendix 3 for details

[51] DCLG (2006) Planning Policy Statement: Planning and Climate Change (Consultation) – Supplement to PPS1, December 2006

- The Renewables Obligation (RO), which includes targets, and provides incentives, for power suppliers to source energy from renewable sources;
- Energy security and increasing reliance on politically volatile or unstable states for fossil fuels, especially natural gas;
- Age of existing coal-fired power stations and their ability to meet the forthcoming regulatory requirements of the EU Large Combustion Plants Directive (LCPD); and
- Technological advances, both in terms of renewable energies and 'clean coal' power generation.[52]

As a result of the factors outlined above, determining the likely marginal source of electricity in the UK is extremely complex. Applications for new power generation facilities above 50MWe output – or for gas-fired applications, above 10MWe - must be submitted to BERR, and are listed on the Department's website,[53] as summarised in Table 5-1.

Table 5-1: Summary of planning applications under consideration by DTI (Feb 2007)

Technology	Number of Applications	Potential New Capacity
CCGT	8	8,670
Off-shore Wind	10	4128
On-shore Wind	7	483
Wave	1	20[1]
Biomass (non-waste)	1	350
Waste	2	269
Gas CHP	1	140
Coal	1	N/A[2]

Notes:

1. Although this facility is under the 50MW threshold, it has been referred to the DTI
2. The plans are for retrofit of existing capacity, which will actually result in a net fall in total power output, albeit generation will be at higher efficiencies

As discussed in Appendix 3, both the DTI (now DBERR) and Defra focus on CCGT as the marginal source of electricity, but we believe that issues surrounding energy security and new political will for nuclear power indicate a broader mix of technologies.[54] Based upon the data in Table 5-1, it would seem logical that new

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[52] Usually involving some kind of carbon capture and sequestration (CCS)

[53] http://www.dti.gov.uk/energy/markets/consents/applications/page23224.html

[54] Defra (2006) Greenhouse Gas Policy Evaluation and Appraisal in Government Departments, April 2006; DTI (2006) *The Energy Challenge*: Energy Review, July 2006

build capacity will be predominantly CCGT and renewables. In the context of the driver provided by the RO, however, electricity generated from waste is only likely to displace renewable generation under quite specific market conditions. Table 5-1 also shows that not all coal-fired power stations are likely to be decommissioned due to the requirements of the EU LCPD, and new “clean” coal technology is also spawning limited plans for new facilities.[55]

As discussed in Sections 3.0 and 7.0, Atropos© models the GHG emissions from each scenario treating one tonne of waste in year one. For scenarios which include sending biodegradable wastes to landfill, however, impacts will also occur in future years, either through methane emissions through the cap or the displacement of other energy sources via power generation from landfill gas.[56] It is therefore necessary to model the likely mix of marginal generation technologies, and thus carbon intensity of displaced energy, into the future.

Much debate seems to relate to whether new coal or nuclear capacity will be developed alongside CCGT, and thus Table 5-2 presents three potential scenarios for the market share of new-build capacity for these three sources.[57] It should be acknowledged here that it is possible that market shares for both nuclear and coal-fired power will be significantly higher than those presented in Table 5-2. As discussed in Section 3.0, however, the objective of this study is to provide a ranking of waste technology scenarios, and thus it has been necessary to take a clear view upon assumptions such as this, which will materially affect the results of the study. As outlined below and in Section 7.2.1, this is reflected in the limited nature of our sensitivity analysis undertaken for this parameter.

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[55] E.On has submitted a planning application for a new coal-fired power station to replace the current facility at Kingsnorth, Kent. BERR is also funding the commercial scale demonstration of a full chain of carbon capture and storage (CCS) technologies from coal-fired generation

[56] Assumptions relating to landfill are discussed in Section 6.1

[57] It should be pointed out that use of these assumptions is not in any way intended to support the ‘case’ for any of the mixes suggested here. Rather, the principle rationale is to generate plausible ranges for the carbon intensity of the avoided marginal source of electricity.

Table 5-2: Avoided marginal sources of electricity

Technology	Estimated Market Share of New-build Capacity (%)		
	Central Scenario	High Coal Scenario	High Nuclear Scenario
CCGT	100	70	70
Coal	0	20	10
Nuclear	0	10	20

As explored in Appendix 3, there is also much debate over the values which should be used for the carbon intensity of the above technologies. To account for technological development and improvements in the efficiency of power generation technologies and supply chains over the lifetime of some of the new waste management facilities, we have modeled reductions in carbon intensity over time for each core technology, as presented in Table 5-3. These are based upon values presented in the Literature Review in Appendix 3 and include emissions from the extraction and transfer of primary fuels, but do not take into consideration energy lost in the process of transmission and distribution.

Table 5-3: Carbon intensity of power generation technologies

Technology	GHG Emissions (g CO_2 / kWh)		
	2007	2020	2032[1]
CCGT	413	382	351
Coal	798	739	605[2]
Nuclear	10	9	8

Notes:

1. We have used the figures in this column for 2032 and all subsequent years
2. This considerably lower value is the result of retrofit of existing facilities with more efficient, super-critical boilers and limited roll-out of new "clean" coal power stations

In the context of transmission and distribution losses, it is important here to note the possibility of the development of private wire electricity networks, potentially as part of CHP development within buildings and communities.[58] As outlined in the GLA Climate Change Action Plan (CCAP), the development of such networks would be more likely to result in a higher rate of energy displacement.[59] Such networks would also avoid transmission and distribution losses and thus could deliver greater overall system efficiencies and lower GHG emissions. Therefore to take this possibility into

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[58] Which are more likely to be able to accommodate smaller scale facilities

[59] Greater London Authority (2007) *Action Today to Protect Tomorrow: The Mayors Climate Change Action Plan*, February 2007

consideration, Table 5-4 presents the figures from the CCAP alongside the central, high coal and high nuclear options from Table 5-2, which have been modelled according to the carbon intensities presented in Table 5-3.

Figure 5-1 shows both the linear fall in carbon intensity over time and the median value for carbon intensity of 447g CO2/kWh, which forms our central assumption for the carbon intensity of displaced electricity within this study. In Section 7.2.1, to provide sensitivity analysis on this parameter, we have also modelled each scenario within Atropos© using the CCAP values. We acknowledge that this sensitivity range is very limited, but as discussed in Section 3.0, this is due to the nature of this study with the core objective of delivering a ranking of technology scenarios for the GLA to function as a useful policy tool.

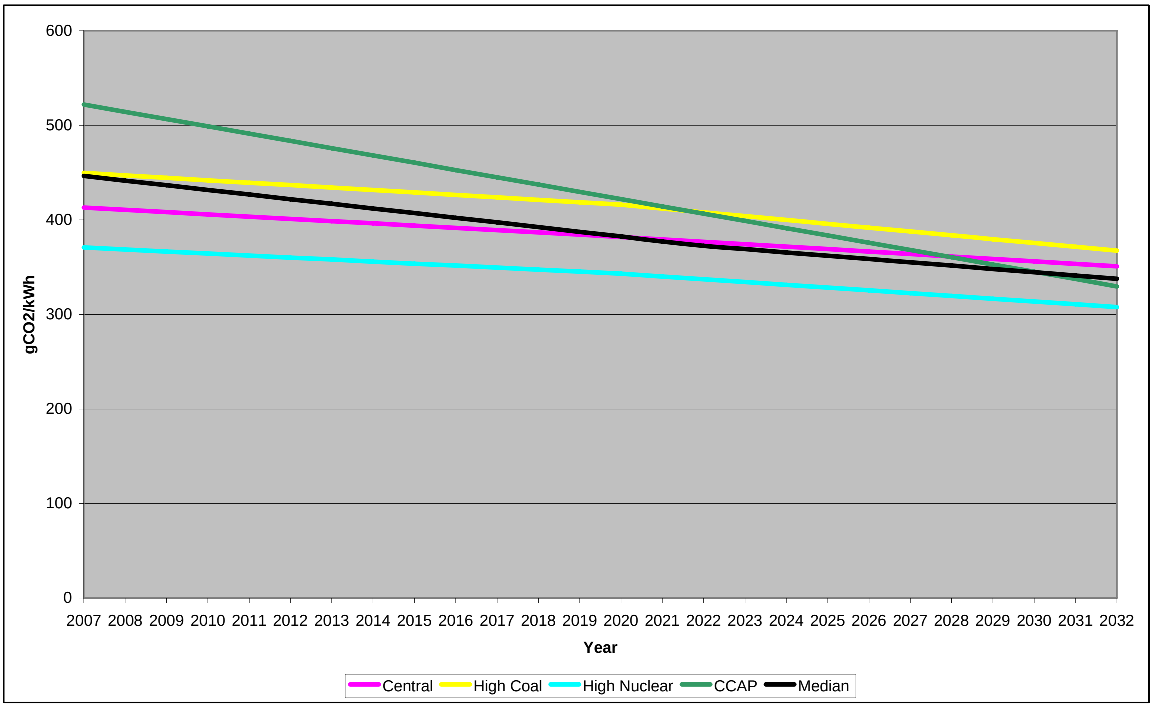
Table 5-4: Carbon intensity of avoided energy sources

Scenario	Carbon Intensity (g CO_2/kWh)		
	2007	2020	2032
Central (100% CCGT)	413	382	351
High Coal (avoided new capacity)	450	416	368
High Nuclear (avoided new capacity)	371	343	308
GLA Climate Change Action Plan	522	422	330[1]
Baseline (Median) Value	447	383	338

Notes:

1. This data point is not listed within the GLA CCAP, but represents the same linear fall in value as between the years 2007-20

Figure 5-1: Carbon Intensity of avoided energy sources



5.1.3 Marginal Sources of Heat

Choosing the marginal source of heat, i.e. determining the GHG emissions which would be avoided as a result of provision of useful heat from waste management facilities, might be considered a simpler proposition than for electricity. It is true that this parameter has attracted less attention and controversy than the calculation of marginal electricity, but has been no shortage of considerations in reaching agreement with the PSG for the value to be used as a central assumptions within Atropos©.

Unlike electricity, future demand for heat in the UK is uncertain. A rising population in the South East of England indicates increasing demand from domestic sources, but falling industrial output in the area would suggest lower requirements from industry. Furthermore, BERR data relating to energy demand does not separate this into heat and power, and thus is not useful in the analysis of historical trends for heat demand.

For heat, more so than electricity, Profu emphasizes the importance of local conditions in determining what should be modeled as the marginal source.[60] For the purposes of this report, therefore, rather than levels of demand determining the choice of marginal heat source, we believe this should be made with reference to specific local drivers and constraints.

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[60] Profu (2004) *Evaluating waste incineration as treatment and energy recovery method from an environmental point of view*, CEWEP, May 2004

As discussed in Appendix 3, there is limited published information relating to avoided emissions from heat production. The majority of the literature relates to average EU mixes of heat provision,[61] or focuses upon demand in other countries,[62] and thus is not relevant to this study.

Many other EU Member States have significant underground district heating networks, which could readily be switched from fossil fuels to heat from waste management processes. The vast majority of households in the UK, however, do not have similar connections to accept and monitor heat from a wider network.[63] Retrofit of such networks is very expensive, and is thus more likely where there is new build of houses. In London and surrounding areas, there are significant plans for new housing both within the Thames Valley[64] and Milton Keynes South Midlands (MKSM)[65] growth areas. It is uncertain to what extent these will be fully realized – and indeed if they are, whether waste management facilities could be built nearby - but it might be assumed that in some cases, off-take of useful heat would be possible. Heat can also be used in district cooling systems, which may become important, ironically, as a consequence of the very phenomenon which drives our study (climate change).

Use of heat in this way would usually result in the avoidance of emissions from domestic gas boilers, but in some cases electrical energy would be displaced. This latter source has highest penetration in densely populated apartment-style dwellings which do not often facilitate provision of space for dedicated boilers.

Demand for non-domestic heat comes not only from industry, but also from such organizations as schools, hospitals, shopping centres and entertainment venues. All such organizations have a requirement for far fewer heat connections than would be needed for district heating. Thus we might assume that a large part of avoided emissions would be from the displacement of incumbent sources within these venues, i.e. industrial scale gas boilers.

Based upon the above assumptions, in Table 5-5 we have estimated the likely sources of heat generation, which would be most likely to be displaced by off-take from waste management facilities.

Table 5-5: Marginal sources of heat

Technology	Estimated Share (%)
Domestic Gas Boiler	30

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[61] AEA Technology, *Waste Management Options and Climate Change*: Final Report, European Commission: DG Environment, July 2001

[62] Dehoust et al, *Status Report on the Waste Sector's Contribution to Climate Protection and Possible Potentials*, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, August 2005

[63] Although it should be noted that such networks do exist in parts of Sheffield, Nottingham, Glasgow and Southampton – the former two cities taking heat from waste incinerators

[64] www.communities.gov.uk/thamesgateway

[65] www.communities.gov.uk/index.asp?id=1162645

Domestic Electrical Energy	20
Industrial-scale Gas Boiler	50

For displacement of heat by gas boilers, BERR uses a generic estimate for emissions of CO_2 equivalent of 205 g/kWh, which is based upon an assumption of 90% efficiency.[66] Based upon the average efficiencies of both new domestic and new industrial boilers, we believe this to be a reasonable estimate.[67] With regard to domestic electric heat, we have used the same assumption as for our central assumption for marginal electricity, i.e. 447 g/kWh.

Heat generation from waste management facilities is generated continuously and would not always be capable of being utilised. To take into account the effect of load factors, we have therefore incorporated into our model assumptions for falls in heat demand during night-time and non-winter seasons. These assumptions are summarised in Table 5-6, and also take into consideration the possibility of using heat exchange technologies to provide cooling during summer months.

Table 5-6: Heat load scenarios

Technology Displaced[1]	Load Factor under Central Assumptions (%)
Domestic Gas Boiler	50
Domestic Electric Heat	50
Industrial / Commercial Gas Boiler	60

Notes:

1. Assumes useful cooling can be supplied through heat exchangers in addition to displacement of heat

Application of the load factors in Table 5-6 to the estimated system efficiencies described above results in an overall central value for avoided emissions of CO_2 of 134 g/kWh. As for the carbon intensity of displaced electricity generation, this is an assumption which could have a material impact upon the results of our analysis. Again, however, it should be stressed that although we have undertaken associated sensitivity analysis, its scope has been limited by the core goal of this study; to deliver a ranking of technology scenarios, as discussed in Section 3.0.

5.1.4 Emissions from Parasitic Loads

All waste management processes require energy to operate, which is often described as having a “parasitic load”. Whilst many can use heat and power that has been generated by, and recycled within, the process itself, others do not generate

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[66] DTI, Energy Trends (2003) *Special Feature CHP: Savings in carbon emissions resulting from the use of Combined Heat and Power*, April 2003

[67] It has been argued that a lower value should be used as many existing boilers are significantly old, and operate at far lower efficiency. However, as one might assume the likely replacement of these with new, efficient boilers, it is these that would be displaced by heat provided by waste management facilities

energy and thus will draw this from the electricity and gas networks. Furthermore, until recently, to take advantage of additional revenues through the generation and onward sale of Renewable Obligation Certificates (ROCs), some facilities in the UK have been configured to draw all their power from external sources, thus exporting as much higher value "green" energy as possible. [68]

In line with our approach for avoided electricity emissions, discussed in Section 5.1.2, we believe that additional demand for electricity should be represented in the same way as additional supply, i.e. in terms of the value of new-build capacity at the margin. As a result, our central assumption within Atropos© for parasitic electricity load is based upon the same carbon intensity as that for avoided emissions from electricity generation, i.e. 447g/kWh.

Parasitic heat load is somewhat different in that our assumptions in Section 5.1.3 were not based upon a scenario of increasing demand over time. In our experience, waste technology providers base their assumptions regarding external heat requirement predominantly upon on-site use of primary fuels, usually gas or diesel generation. As a result, our modelling of each technology scenario is based upon the fuels actually used by the different processes, rather than on any generic assumptions.

5.1.5 Summary of Central Assumptions

The table below provides a list of the core assumptions related to energy balance, which we have used in modelling the scenarios included within the scope of this study. Within our sensitivity analysis, however, we have modelled each scenario according to alternative carbon intensities, as presented in Section 7.2.

Table 5-7: Summary of central assumptions

Parameter	Assumption
Carbon intensity of avoided emissions / parasitic load from electricity generation (2007)	447 gCO_2/kWh (Median)
Carbon intensity of avoided emissions from heat generation	134 gCO_2/kWh
Carbon intensity of heat demand from parasitic loads	N/A[1]
Notes: 1. Modelling of each technology scenario is based upon the primary fuels actually used by the different processes	

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[68] Amendments to the Renewables Obligation Orders, introduced from 1 April 2007, however, mean that generators which use their power on-site can now receive ROCs directly for this activity. The relationship of technologies to policy mechanisms is discussed in detail in Section 8.0

5.2 Emissions Reductions Offered by Recycling / Reprocessing

The climate change benefits of recovering materials from waste for reprocessing compared to manufacture with virgin materials are now widely appreciated. Of course, there are limits to the argument. If more energy is used to recycle the material than is embodied in the material, then it may be the case that it makes more sense to treat the material in other ways and to continue production from primary resources.

Most LCA studies provide estimates of GHG reductions delivered by 'front-end' collection and recovery systems i.e. kerbside or bring recycling, followed if necessary by sorting within a Materials Recovery Facility (MRF) (if collected in co-mingled form). Materials recovered from residual wastes, however, have far higher levels of contamination as a result of contact with the residual waste stream. Depending upon the material, this contamination may have three potential impacts:

- Materials are not of sufficient quality for recycling (for example, paper and textiles);
- Rather than a 'closed-loop' process (i.e. container glass being recycled back into container glass), materials might be recycled into lower value applications (for example, mixed glass to aggregates or plastics to "plaswood", which deliver reduced, or no, carbon benefits); and
- Prior to reprocessing, contaminated materials will require energy for cleaning processes - for example, hot-washing of plastics - and thus will deliver lower carbon benefits than clean streams.

For metals, there is no available data to assess the scale of these impacts, as the three key studies relevant to this report provide estimates of GHG reductions delivered by 'front-end' collection and recovery systems only.[69] However, as summarised in Table 5-8 for plastics and glass, recovery from the residual stream has been taken into consideration in some studies. We have therefore derived the mean for each material from this data to be used in our Atropos© model with the acknowledgement here that the actual benefits might be slightly reduced due to the factors listed above.

As can be seen from the table, recycling of plastics delivers significant benefits if undertaken on single-stream polymers on a 'closed-loop' basis. If recycled, however, into what is often know as 'plaswood' or plastic 'lumber', the carbon balance appears to be comprehensively negative. Unfortunately, there has been very limited research on this approach, and there appears to be only one published data point by which to assess the carbon balance. This seems unlikely to have taken into account

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[69] H. Wenzel (2006) *Environmental Benefits of Recycling. an International Review of Life Cycle Comparisons for Key Materials in the UK Recycling Sector*, Report to Waste and Resource Action Programme (WRAP), Banbury: Oxon, May 2006; ERM (2006) *Carbon Balances and Energy Impacts of the Management of UK Wastes*, Final Report for Defra, December 2006; AEA Technology. (2001) *Waste Management Options and Climate Change*, Final report to DG Environment, European Commission.

any effects of time, or of the impacts of recycling such material on forest stocks.[70] We therefore have concerns as to the robustness of the data and as a result, have assumed that all plastics which are unlikely to be reprocessed as a single polymer stream, i.e. all but PET and HDPE (plastic bottles and containers) will be sent to landfill.[71]

Table 5-8: Assumptions for GHG benefits of materials recycling / reprocessing

Material Type	GHG Benefits (kg CO2 equ/t)[1]			
	ERM	AEAT	WRAP	Mean
Steel	700	1500	1300	1133
Aluminium	11200	9100	7000	9100
Plastics (PET)	1400	1800	1000	1400
Plastics (HDPE)	1400	500	1000	967
	ERM	Enviros	WRAP	Mean
Plastics (to “plaswood”)	- 850[2]	-	-	-850
Glass (to aggregate)	2	-2	0	0

Notes:

1. System boundary is for the substitution within the production process of recovered material for virgin raw materials only
2. It is assumed that the energy requirements of washing, sorting, granulating and reforming are greater than the offset burdens of wood production

Source: Wenzel (2006), ERM (2006), AEA Technology (2001), Enviros Consulting (2003) *Glass Recycling: Life Cycle Carbon Dioxide Emissions*, Report to British Glass

It should be noted that our previous analysis of similar GHG balances indicates that the tonnages of materials that are assumed to be sent for recycling / reprocessing have a material impact upon results of scenario performance modeling.[72] Logically this also suggests that assumptions for associated GHG ‘reductions’ also play a key role in determining the performance of some scenarios.

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[70] Only one LCA study – carried out by the USEPA – appears to have done this. As a result, reported savings of GHG emissions associated with paper and card recycling are far higher in that study than in similar European studies, even though the USEPA study highlights the likely transferability of the results associated with the modelling of the dynamics of the forest sector (see U.S. Environment Protection Agency (1997). *Greenhouse gas emissions from municipal waste management*. Draft working paper. Prepared by: ICF Incorporated, EPA Contract No. 68-W6-0029)

[71] Unless they are sent for pyrolysis for conversion into synthetic diesel, as is the case in some technology scenarios (discussed in Section 6.10)

[72] Eunomia (2006) *A Changing Climate for Energy from Waste?* Final report to Friends of the Earth, May 2006

The relatively significant variation between the different estimates for the GHG reductions presented in Table 5-8 suggests, therefore, that it may be relevant to perform sensitivity analysis on the mean value we have used for each material. In the context of this study, however, where a clear ranking of scenarios is required, it has been necessary to make a judgement upon this parameter following discussions with the PSG. In this respect we therefore feel that our use of mean values is appropriate, without undertaking sensitivity analysis.

5.3 Emissions from Transportation

As mentioned in Section 2.0, the collection of waste is outside the agreed system boundaries of our model. Each of the technology scenarios appraised are based upon the input and onward management of residual waste. The GHG emissions from collection will therefore be consistent for each scenario, and thus not relevant in the context of a comparative study.[73]

Emissions from transport of materials between different elements of a process chain are a different proposition. Although potentially equally negligible, these are not consistent across different scenarios, and thus are included within our analysis.[74] It should be noted, however, that consideration of this parameter is distinct from appraisal of GHG emissions from the use of alternative fuels in transportation. Assumptions for technology chains incorporating both hydrogen fuel cells and compressed biogas in transportation are included in Section 6.0.

For each technology scenario, we have assumed all transportation to take place by road, although in certain instances it may be possible to use navigable waterways to move material around the city.[75]

5.3.1 Potential distances travelled within and around London

The purpose of our approach is to make estimated distances specific to the way the technology scenarios would function in and around London. To allow for the full range of possibilities in this context, we have provided low and high estimates for each scenario. For example, steel from an incinerator would need to travel to the nearest steel reprocessing facility, which would be in Scunthorpe or Port Talbot, whilst fly ash would require transport to the nearest hazardous landfill cell, currently on the Isle of Sheppey or otherwise Swindon. Many, other materials, however, would be likely to require less mileage, for example, syngas might be converted to

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[73] Some discussion took place within the PSG to consider the potential scalability of technologies, and the likelihood or otherwise of some technologies being operable in a more decentralised network. A view was expressed that this could influence transport movements. However, in principle, all technologies *could* operate in this way, and since this study was assessing specifically GHG performance, to overlay what might be subjective assumptions regarding scalability was deemed inappropriate.

[74] See Appendix 3 for further discussion

[75] For example, the current transport of residual waste in purpose-built barges along the River Thames from West London to Mucking Landfill site as part of a contract between Western Riverside Waste Authority (WRWA) and Cory Environmental

hydrogen through steam reforming on the same site as a gasification facility, or alternatively might be transferred to another site within London.

The assumptions in Table 5-9 are based upon round-trips for delivery of materials. It should be acknowledged, however, that waste management companies or logistics organizations will often back-haul other materials to the original destination, thus potentially offsetting emissions from alternative practices. There is, however, no way of estimating opportunities for back-hauling and it has thus been omitted from our analysis.

Table 5-9: Estimated distances for transportation of different waste types

Journey Description	**Average Distance (km)[1]**	
	Low[2]	**High**
Fly ash from incinerator/gasifier to hazardous landfill	50	280
Bottom ash from incinerator/char from gasifier to landfill	86	186
Steel from incinerator to reprocessing	530	600
Bio-stabilised output from MBT / autoclave to landfill	86	186
Steel from MBT / autoclave to reprocessing	530	600
Aluminium from MBT / autoclave to reprocessing	613	681
Rejects from MBT / autoclave to landfill	86	186
RDF from MBT (Biodrying) / autoclave to gasifier	0	100
Syngas (from gasifier) / biogas (from MBT) to steam reforming	0	40
Syngas (from gasifier) / biogas (from MBT) to stationary fuel cell	0	40
Hydrogen from steam reforming to vehicle refuelling points	0	40
Plastics from MBT (AD) / autoclave to pyrolysis	0	40
Plastics from MBT (AD) / autoclave to reprocessing	0	40
Synthetic diesel from pyrolysis to vehicle refuelling points	0	40
Biogas from MBT (AD) to gas compression facility	0	0
Compressed biogas to vehicle refuelling points	0	40

Notes:

1. Based upon round-trip
2. Zero values assume processes are undertaken on same site

5.3.2 Vehicle Types and Payload

The use of different vehicles usually depends upon the distance that a particular material must travel. HGVs are generally used for longer distances, whilst hazardous residues might be safer to transport in LGVs. We have based our assumptions for emissions from these vehicle types upon data provided by the Transport Research Laboratory (TRL).[76]

To enable inclusion of transport within our wider modelling, it is necessary to calculate the emissions contribution per tonne of waste transported. Whilst the payload of vehicles is therefore important, and the densities of different materials mean that payloads will vary, we believe any variation will have minimal impact on overall emissions. For all *solid* materials within in our analysis, we have therefore have used consistent figures of 5 tonnes payload for LGVs and 20 tonnes payload for HGVs.

This is somewhat different, however, in the case of gaseous fuels. Hydrogen has a very low energy density and even with technological advances, an HGV might deliver only about 560 kg of compressed gas.[77] Liquid hydrogen is potentially better to transport, but is not included within our technology options due to the high energy demands required by the liquefaction process.[78]

As discussed in Appendix 3, there is very limited data relating to major road transport of biogas and syngas, but road transport of compressed natural gas (CNG) does take place in limited cases in both the US[79] and Canada.[80] As discussed in Section 6.0, methane-rich syngas and biogas have similar properties to natural gas, and thus we have used this data for CNG to derive our assumptions. In London, it is unlikely that the same massive compression cylinders employed in the US or Canada could be used, and we have therefore assumed that smaller cylinders would be moved by HGV. Assuming that an HGV could transport a volume of 50m^3 of compressed gas[81] and if the gas had methane density of 0.717kg/m^3, we would estimate that each vehicle could transport 7 tonnes of compressed gas.

It should be noted that emissions of N_2O make a very low total contribution to GHG emissions from transport'[82] and can thus be considered to have a very insignificant impact upon overall emissions for each waste management scenario. As a result, these have been omitted from this part of our analysis, which focuses on emissions of CO_2 only.

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[76] Barlow, TJ, Hickman, AJ, Boulter, P, (2001) *Exhaust Emission Factors 2001: Database and Emission Factors*, TRL Report PR/SE/230/00, September 2001

[77] Personal Communication, Linde Group, Munich, March 2007

[78] As discussed in Section 6.7

[79] www.marlinenergy.com

[80] www.transcanada.com (http://divisions.asme.org/pipeline/news/Composite.pdf)

[81] And that the gas compression rate of cylinders was 3000psi (or 207bar), as in the cylinders used in both the US or Canada

[82] According to the Revised IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (1996) N_2O emissions represent only around 1% of CO2 emissions from a HGV vehicle

Based upon the above estimates of emissions and assumptions regarding distances of travel and payload, we have calculated the CO_2 emissions per tonne of material transported, as summarized in Table 5-10.

Table 5-10: Summary of assumptions for GHGs from transport

Journey Description	Assumption ($kgCO_2/t$)
	Mean
Fly ash from incinerator/gasifier to hazardous landfill	7.3
Bottom ash from incinerator/char from gasifier to landfill	4.4
Steel from incinerator to reprocessing	18.1
Bio-stabilised output from MBT / autoclave to landfill	4.4
Steel from MBT / autoclave to reprocessing	18.1
Aluminium from MBT / autoclave to reprocessing	20.7
Rejects from MBT / autoclave to landfill	4.4
RDF from MBT / autoclave to incinerator	1.6
Syngas (from gasifier) / biogas (from MBT) to steam reforming	1.8
Syngas (from gasifier) / biogas (from MBT) to stationary fuel cell	1.8
Hydrogen from steam reforming to vehicle refuelling points	22.9
Plastics from MBT / autoclave to pyrolysis	0.6
Synthetic diesel from pyrolysis to vehicle refueling points	0.6
Biogas to gas compression facility	0.0
Compressed biogas to vehicle refueling points	1.8

5.4 Waste Input Composition

The most recent analysis of waste composition in the London area was conducted by Waste Research Ltd (WRL) and AEA Technology in 2004,[83] which received third party support from both the Greater London Authority (GLA). The goals of this research were to:

- Assess variations in the composition of household collected waste between houses and high-rise housing;
- Assess variations in the composition of household collected waste in different ethnic groups; and
- Develop a predictive model for assessing information on waste composition in areas with a high percentage of ethnic households and areas of high - rise housing.

In conducting this research, a scoping study was produced by AEA Technology, whilst WRL followed a well established protocol developed for the Welsh Assembly Government 2002. The accepted socio-economic classification system, ACORN (A Classification of Residential Neighbourhoods), was used to identify the socio-economic profile of an area. The study was also designed to assess seasonal variations by conducting analyses in October/November 2003 and in June 2004. Sampling was conducted in the London boroughs of Enfield, Newham and Haringey and a sample size of 50 households was selected.

Using the predictive model outlined above it is possible not only to generate composition data for individual Boroughs, but also for the whole of London. We have therefore based the composition used in the modelling for this study upon the information presented in Table 5-11 and Table 5-12.

Table 5-11: Population of London by Ethnic Group in 2001

Ethnic Group	% Share
White	71
Asian or Asian British	12
Black or Black British	11
Chinese	1
Other	5

Source: Office for National Statistics

Table 5-12: Households by types of dwelling (%)

Dwelling Type	% Share

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[83] AEA Technology (2004) *Variations in the Composition of Household Collected Waste*, Report Produced for EB Nationwide (Shanks First Fund)

Detached House	4
Semi-detached House	19
Terraced House	28
Purpose-built Flat or Maisonette	37
Other (includes converted flats)	11

Source: Office for National Statistics

5.4.1 Plastic Polymer Types

The composition data derived from the WRL / AEAT model detailed in Appendix 4 does not divide the plastics content of the MSW into different polymer types. To provide sufficient data for some of the scenarios outlined in Section 4.0, we have therefore used information provided by Recoup to perform this analysis with regard to plastic bottles within the waste stream, as shown in Table 5-13.

Table 5-13: Composition of plastic bottles within residual MSW

Polymer	%
PET	54.7
HDPE	40.1
PVC	2.4
PP	1.8
PS	0.9
Total	100.0

Source: Recoup from industry consultations & market research from 18 different sources, 2006

5.4.2 Assumed Levels of Recycling

In Table 5-14, we have provided details of some essential characteristics of the waste stream modelled for this study, whilst full details of the residual composition are provided in Appendix 4. The composition derived from the WRL / AEAT study can be regarded as representative of a relatively low, i.e. 5-10% recycling rate within an urban authority area.

It should be acknowledged, however, that the composition of residual waste is likely to change significantly over the next 25 years during which waste management facilities procured now are likely to be operational. This is likely to be influenced primarily by greater levels of recycling at the kerbside and at household waste recycling centres (HWRCs). In the 2007 Waste Strategy for England, Defra has set a target of 50% recycling of MSW by 2020, which can be compared to that set by the Mayor for recycling of household waste in London of at least 45% by 2015.[84]

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[84] Greater London Authority (2006) The London Plan: Spatial Development Strategy for Greater London – Housing Provision Targets, Waste and Minerals Alterations

Furthermore, a range of other factors, such as a potential increase in the use of biodegradable plastics, and a reduction in food waste due to new household collections is likely to influence residual composition.

To reflect potential changes in residual waste composition, therefore, we have modelled a likely 'future' composition as part of the sensitivity analysis undertaken for this study in Section 7.2.

Table 5-14: Characteristics of assumed waste stream

Characteristic	
Moisture content	34.58%
Carbon content (fresh matter)	26.96%
Fossil carbon content (fresh matter)	10.39%
Non-fossil carbon content (fresh matter)	16.57%
Wet LHV (fresh matter)	9.35MJ/kg

6.0 Overview of Technology Specific Assumptions

Many of the technologies outlined below are well known to policy makers and are being considered as part of municipal waste treatment and disposal contracts in London and across the rest of the UK. For such technologies, for example incineration, we have therefore provided detail only on key parameters or assumptions which might be contentious. For other, more novel technologies, such as hydrogen fuel cells, greater depth of analysis is provided both below in terms of our assumptions, and in the form of individual literature reviews in Appendix 3.

As discussed in Section 2.0, it should be noted here that this study does not aim to assess the commercial or technical viability of the technology scenarios outlined below. On this basis, our appraisal is, in the cases of more novel variants, theoretical, although wherever possible, for individual technologies, we have based our assumptions upon *actual* data from operating facilities. In other cases, we have modeled information based upon how bidders are proposing to configure the technologies in local authority procurement contracts.

For each technology, we have been careful to undertake our modeling using assumptions which are based upon 'best-of-breed' processes operating today, i.e. technology 'brands' which are proven at commercial - or in the case of some of the novel processes – at demonstration scale. This approach ensures that as much as possible, we are comparing like with like in the context of potentially agreeing contracts for the construction of new facilities in the immediate term.

It should be acknowledged that the technologies being considered do not all operate optimally at the same scale or capacity, and it would not be sensible, for example, to compare the performance of a 60,000tpa gasification facility with a landfill of the same size. Our assumptions are therefore based upon different optimal throughput levels for different processes.[85] It should be acknowledged, however, that both the London Plan and the Mayor's Municipal Waste Strategy advocate a decentralised approach to the development of new waste infrastructure.[86] Such an approach seeks to promote small-scale, 'embedded' facilities so the heat from any energy generation process is more likely to have a useful outlet to maximize climate change benefits.

6.1 Landfill

Landfill is the most established and widespread of waste disposal routes in the UK. Gas capture and use for on-site energy generation, however, are more recent additions to many landfills, and there is some debate as to the efficiency of both of these technologies. The approach taken in our modeling of this option largely

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[85] In this regard, the potential scales for a limited number of technologies are illustrated in Appendix 8 in relation to discussion of likely electricity outputs

[86] GLA (2003) Rethinking Rubbish in London: The Mayor's Municipal Waste Strategy, September 2003; GLA, Draft Further Alterations to the London Plan, Greater London Authority, September 2006

follows that undertaken by Eunomia in 2006,[87] which was based upon two studies conducted on behalf of Defra by LQM[88] and Enviros.[89]

The most sensitive component within this model is the gas capture rate, from direct landfill of residual waste,[90] assumed by Eunomia in the previous study to be 50%. A subsequent study conducted by ERM on behalf of Defra, however, assumed a 75% capture rate over the 100 year timeframe assessed, but acknowledged (in a later iteration of the report) that if one moved the analysis beyond this (somewhat arbitrary) timeframe, lifetime capture rates might be around 59%.[91]

A comparative peer review of both studies has also been conducted, and on this issue a wide range of uncertainty is acknowledged.[92] Indeed, this type of analysis is beginning to acquire significance in the context of Joint Implementation (JI) projects involving landfill gas capture systems, and it is appropriate to add here that the Intergovernmental Panel on Climate Change (IPCC) has recently stated that lifetime gas capture rates may be as low as 20%.[93] We would consider, however, that landfills in the UK are somewhat better engineered than countries where JI projects are applicable.

The uncertainty surrounding gas capture rates and the likely impact of changing these upon the results of this study, suggests that sensitivity analysis on this parameter may have been appropriate in another context. As discussed in Section 3.0, however, the goal of this study is to deliver a set of rankings to inform policy-making, and therefore to make informed judgements on parameters which may materially affect the results. We feel, therefore, that our estimate of 60% capture, although higher than we believe may be the case in reality, is a sound assumption in respect of the overall evidence base

Further to the capture rate, we have assumed that 50% of this gas will be flared rather than used to generate energy. The total gas used in energy generation is therefore reduced to 30% of the total generated. This is the result of two key factors:

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[87] Eunomia (2006) *A Changing Climate for Energy from Waste?* Final report to Friends of the Earth, May 2006

[88] LQM (2003) *Methane Emissions from Landfill Sites in the UK*, Report for Defra, January 2003.

[89] Enviros, University of Birmingham, RPA Ltd., Open University and Maggie Thurgood (2004) *Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes*, Final Report to Defra, March 2004

[90] It should be noted that other rates apply to landfill of other pre-treated wastes, as shown in Table 6-1

[91] ERM (2006) *Carbon balances and energy impacts of the management of UK wastes*. Defra R&D project WRT 237. December 2006

[92] Holland, M (2007) *Peer Review of Recent Studies Characterising Greenhouse Gas Emissions from Waste Management in the UK*, EMRC

[93] IPCC (2007) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 600 pp.

- In early and latter years, gas emission rates are likely to be too low to support firing in gas turbines; and
- During times of high flux, the gas engines may not be of sufficient capacity to accommodate all of the gas captured.

Our central assumptions are shown in Table 6-1 for a variety of waste types, some which have already undergone treatment, and thus reductions in biodegradability. In such cases, the landfilled waste is assumed to behave differently, and parameters are adjusted accordingly. For such scenarios a designated 'stable' landfill cell is assumed, with an active oxidation layer reducing fugitive methane emissions to a minimal level. Although this might not be considered to be currently practicable in the UK, as noted in Section 2.0, this study focuses on a range of 'leading-edge' solutions and 'best-of-breed' technologies, and thus it is important to model this approach.

For all scenarios, an important simplification to note is that we have used the same rates of capture and oxidation of methane at the cap for all years of the model.

Table 6-1: Summary of central assumptions for landfill of different waste types

Parameter	Assumption				
	Direct Residual	Ex-MBT (AD)[1]	Ex-MBT (Biostab)	Ex-MBT (Biodry)[2]	Ex-Autoclave[3]
Lifetime gas capture rate	60%	0	0	0%	60%
Proportion of collected gas which is flared	50%	0	0	0%	50%
Proportion of total gas used in energy generation	30%	0	0	0%	30%
Efficiency of energy generation	35%	N/A	N/A	N/A	35%
Rate of oxidation of methane at the cap[4]	10%	90%	90%	90%	10%

Notes:

1. Assumes 5 weeks maturation of the organic fraction
2. Assumes 7 weeks maturation of the reject stream
3. Assumes 1 week maturation of reject stream
4. Where this value is 90%, we have assumed that stabilised waste is sent to a dedicated 'stable' landfill cell

6.2 Incineration

Incineration involves the combustion of residual MSW in the presence of oxygen, usually on a 'moving grate'. Typically, incineration plant temperatures are in excess of 850°C and the waste is converted into carbon dioxide and water. As not all waste burns, a proportion falls through the grate as ash. This 'bottom ash' contains all the steel and aluminium that entered the plant and so magnets and other equipment can be used to separate the former for recycling. The remaining ash is either sent to landfill or used in construction materials.

Incineration is a relatively well-established technology for the treatment or disposal of municipal solid waste in the UK. As a result, the assumptions associated with its use are perhaps less arguable than those for other, lesser-known technologies. A key point of discussion, however, in modeling the GHG impacts of incineration is the efficiency of energy recovery from the input waste stream. The approach undertaken in this study largely echoes that previously undertaken by Eunomia,[94] which highlights the importance of net energy production and the distinction between net and gross calorific values (CVs).

The efficiency of generation of electricity by an incinerator should be calculated net of any energy used in the plant itself. The energy use in the plant depends for the most part upon the nature of the flue gas cleaning system used, but also upon a range of other factors. The relationship to flue gas cleaning is important since it seems likely that as standards for abatement have improved, so the energy used in achieving those levels of abatement has increased also. For facilities currently being built, it would appear that internal use of energy accounts for around one sixth of electricity actually generated. We assume in the modelling an energy use of 92kWh per tonne of input based on using a bag filter with semi-dry acid gas removal, SNCR (De-Nox) and dioxin removal (activated carbon).

The distinction between the gross or net calorific values (GCVs or NCVs) of the input waste is equally important, as basing estimates on the latter would result in efficiencies inflated beyond achievable performance levels. There have been a number of recent studies published in the UK, which make estimates of efficiencies for incineration, but there appears to be some confusion with regard to their basis:

- ERM on behalf of Defra[95] uses an implied efficiency of 28% relative to reported NCVs. This is a gross figure and the energy use was 0.118kg of diesel plus 3.91kWh of electricity. No justification for these figures is provided in the report;
- Oakdene Hollins on behalf of the Institute of Civil Engineers (ICE)[96] used a figure of 25.4%. This was based upon work by C-Tech which reports this efficiency relative to NCVs. The study for the ICE appears to have applied the

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[94] Eunomia (2006) *A Changing Climate for Energy from Waste?* Final report to Friends of the Earth, May 2006

[95] ERM (2006) *Carbon Balances and Energy Impacts of the Management of UK Wastes*, Final Report for Defra, December 2006

[96] Oakdene Hollins (2005) *Quantification of the Potential Energy from Residuals (EfR) in the UK*, Report for the Institute of Civil Engineers and the Renewable Power Association, March 2005

efficiency figure to GCVs, consequently overstating the potential for electricity recovery;

- Fichtner, in a report for ESTET[97] quoted net electrical efficiencies for steam cycle combustion of 19-27% based upon NCV;
- CIWM reports efficiency of generation of 22%-25%, but this does not make reference to any measure of the CV used.[98]
- CEWEP indicates that for a sample of 28 plants producing *mainly* electricity, the net electricity generation averaged 17.7% with 2.6% of heat energy exported. For electricity generation, plants generating *mainly* electricity exhibited a range in their efficiencies of net export from 8.4% to 24.3%.[99]

The above estimates can in many ways be considered "theoretical" in that most are not based upon performance data from operational facilities. When compared to estimates of efficiencies from wider studies, which use data from "actual" facilities, they appear somewhat high.

As part of the development of the Best Available Technology (BAT) standard for incineration as part of the EU Best Available Reference (BREF) document for waste treatment processes, measurements were made at 8 German plants and efficiencies ranged from 12.9% - 22%, with an average of 18%. However, this did not account for the plant's own use of electricity, which reduced net efficiencies to 8.7% - 18%, with an average of 13%.[100] The BREF document also noted that for new French facilities, efficiency of production was 16.4%, with net efficiencies at 13.4%[101], whilst a recent report for the German Umweltbundesamt stated an efficiency of approximately 21% in terms of gross output.[102]

As shown in Table 6-2, we feel, however, that it is prudent to base our central analysis upon an estimate of 25% efficiency (NCV). This is at the high-end of efficiencies of plants currently in operation.[103]

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[97] Fichtner Consulting Engineers Limited (2004) *The Viability Of Advanced Thermal Treatment Of MSW In The UK*, ESTET, March 2004

[98] CIWM (2003) *Energy from Waste: A Good Practice Guide*, Northampton: IWM Business Services Group, November 2003

[99] Dieter O Reimann (2006) *Results of Specific Data for Energy, Efficiency Rates and Coefficients, Plant Efficiency factors and NCV of 97 European W-t-E Plants and Determination of the Main Energy Results*, Report to CEWEP, Updated July 2006

[100] Energysub-group (2002) Energy Recovery from Waste Incineration Plants, cited in European Commission (2005) Integrated Pollution Prevention and Control: Reference Document on the Best Available Techniques for Waste Incineration, July 2005

[101] European Commission (2005) Integrated Pollution Prevention and Control: Reference Document on the Best Available Techniques for Waste Incineration, July 2005.

[102] Dehoust et al (2005) *Status Report on the Waste Sector's Contribution to Climate Protection and Possible Potentials*, Research Report 2005 33 314, UBA-FB III, German Federal Environmental Agency, August 2005

[103] As discussed in the main body of the text, this is above the net efficiencies used in the recent German study, and well above the higher end efficiency looked at in the report for CEWEP. However,

A final point that should be noted is the presence of biodegradable carbon within the ash from moving-grate incineration. Research has shown that bottom ash is likely to result in some emissions of CO_2 and CH_4 once in landfill.[104] It should be acknowledged that although these emissions will be relatively small, and thus represent a level of detail beyond the scope of this study, should incineration form part of any further analysis to consider a hierarchy of options in more detail, we would propose to include these emissions within our Atropos© model.

Table 6-2: Summary of central assumptions for Incineration

Parameter	Assumption
Net electrical efficiency (electricity only mode) based upon NCV	25%
Net electrical efficiency (CHP mode) based upon NCV	16%
Heat efficiency (CHP Mode) based upon NCV	50%
Heat efficiency (Heat only mode) based upon NCV	90%
Electricity demand for flue gas cleaning	92kWh/t input
Recovery rate for ferrous metals from bottom ash	60%
Bottom ash production	21%

6.3 Gasification

Gasification is a far newer technology than incineration for the treatment or disposal of waste. It involves the partial oxidation of waste. This means that oxygen is added but the amounts are not sufficient to allow the fuel to be completely oxidised and for full combustion to occur. The temperatures employed are typically above 750°C. The main product is a syngas, which contains carbon monoxide, hydrogen and methane. The CV of this syngas will depend upon the composition of the input waste to the gasifier. The other main product produced by gasification is a solid, non-combustible 'char'.

Gasification has received significant recent attention in the municipal waste market as a potential alternative to incineration, but thus far only two commercial-scale facilities have planning permission and none are currently operating only on MSW or MSW-derived feedstocks in the UK.[105] There are, however, a handful of facilities

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one facility operating in Amsterdam, reports a net efficiency close to 30%, and this relies on a range of process adaptations including the use of intermediate superheating

[104] From Hanne L. Erichsen and Michael Hauschild (2000) *Technical Data for Waste Incineration - Background for Modeling of Product Specific Emissions in a Life-cycle Assessment Context*, April 2000, S. Dugenest, H. Casabianca and M.F. Grenier-Loustalot (1999) *Municipal solid waste incineration bottom ash: Physicochemical characterization of organic matter*, D. P. Komilis R. K. Ham R. Stegmann (1999) *The effect of municipal solid waste pretreatment on landfill behavior: a literature review*, Waste Management and Research, Volume 17 Issue 1 Page 10 - February 1999

[105] Permission has been granted for the construction of a Novera / Enerkem gasification facility in East London and for the construction of a Compact Power pyrolysis/gasification facility in Avonmouth, Bristol

operating at commercial scale within the EU, although these are not always treating a mixed waste stream, along with many high-temperature facilities in Japan. In many cases, gasification technologies are planned to treat refuse-derived fuels (RDF)[106] from MBT or autoclave facilities,[107] as is the case for a facility planned for East London Waste Authority.

Performance data is therefore perhaps less reliable than that for incineration, especially if operating in CHP mode, upon which this study focuses. As a result, we have based our central estimates of efficiencies in Table 6-3 on information provided only by technology providers which have commercial-scale facilities already operating in other EU Member States. Again, it is important to present these figures according to the NCV of input waste, and separate to any energy used by the process itself. Once more, our assumptions are based on mass flows and energy balances quoted by technology providers. The figures quoted in Table 6-3 are based on gasification of RDF produced by a MBT (biodrying) process as is discussed in Section 6.5.2.

Table 6-3: Summary of central assumptions for gasification

Parameter		Assumption
Boiler/Steam turbine	Net electrical efficiency (electricity only mode)	25%[1]
	Net electrical efficiency (CHP mode)	18%[1]
	Heat efficiency (CHP Mode)	48%
Gas engines[2]	Net electrical efficiency (electricity only mode)	35%[1]
	Net electrical efficiency (CHP mode)	35%[1]
	Heat efficiency (CHP Mode)	36%
Electricity demand for flue gas cleaning		72kWh/t input
Carbon content of char		10%
Biodegradable carbon content of char		0%

Notes:

1. It should be noted that the efficiencies quoted relate to the power generation (steam turbine or gas engine) element of the process only. To determine overall system efficiencies, the efficiency of conversion of the waste to syngas within the gasification chamber must also be taken into consideration. If this efficiency (taken from our Atropos© model) is applied to the efficiencies of the power generation phase, the overall system efficiencies for each of the above (from top down) are 17%, 11%, 25% and 25% respectively
2. As noted in Section 6.2 for incineration, we have positioned our analysis at the high-end of likely generation efficiencies. With some systems we acknowledge there may be technical difficulties to achieving such levels

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[106] Also often know as solid-recovered fuels (SRF)

[107] Discussed in Section 6.6

In addition to the use of syngas from the gasification process to produce energy in either on-site steam turbines or gas engines, for which the key assumptions are shown in Table 6-3, syngas can undergo treatment to produce a hydrogen stream for use in fuel cells, as discussed in Section 6.7.

6.4 Plasma Gasification

Plasma waste destruction concepts have been around for a number of years, primarily focused upon treatment of hazardous and clinical wastes. Integration of plasma technologies into systems for energy recovery from municipal waste, however, is a relatively recent development and the market remains embryonic.

Direct plasma treatment of solid wastes is largely perceived to require too great an amount of energy and thus dual systems combining a more traditional gasification stage for the solid waste, followed by refining of the syngas in a subsequent plasma chamber (along with treatment of the remaining solid char) are now being marketed.

In such systems, extreme temperatures are created by a plasma arc – effectively, lightening bolts created between a graphite electrode and the anode base of the chamber. This both promotes thermal cracking of the condensable tars present in the syngas and alters its composition, whilst converting remaining combustible carbon in the char to syngas and reducing the ash to a hard vitrified slag. Although tars will be destroyed in the plasma furnace and do not require condensing out, the syngas will still contain metals and trace gas impurities which can corrode the power production unit. A gas clean-up system, therefore, is still required prior to utilisation of the syngas.

Plasma gasification technology suppliers are tending to promote oxygen blown gasifiers. If coupled with a H_2 fuel cell, the greater amount of hydrogen produced by such systems means that significantly more energy can be generated than if using a more 'conventional' air-blown gasifier, as described in Section 6.3.[108]

In contrast, when coupled with a gas engine for power generation, a 'conventional' gasifier is likely to deliver a better net energy balance due to its lower energy use. It should be noted, however, that at least one plasma technology supplier is currently marketing a process which not only employs a gas engine for electricity production, but which also recovers waste heat into steam turbines for co-generation of electricity. To ensure direct comparisons with other technology scenarios, however, we have not modelled this mode of operation. We have instead assumed the waste process heat is used in a CHP configuration, the core assumptions for which are summarised in Table 6-4.

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[108] It should be noted, however, that 'conventional' gasifiers could also be oxygen blown

Table 6-4: Summary of central assumptions for plasma gasification

Parameter		Assumption
Gas engines[1]	Net electrical efficiency (electricity only mode)	35%[1]
	Net electrical efficiency (CHP mode)	35%[1]
	Heat efficiency (CHP mode)	36%
Electricity demand for plasma unit, flue gas cleaning and gas compression		111 kWh/t input
Recoverable heat losses (not including that from combusted syngas) available for cogeneration / heat recovery		170 kWh/t input
Carbon content of char		2%
Biodegradable carbon content of char		0%

Notes:

1. Efficiencies quoted relate to the power generation element only. Including conversion of the waste to syngas, the overall system efficiencies for each of the above (from top down) are 16%, 16% respectively

6.5 Mechanical-biological Treatment

Mechanical-biological treatment (MBT) can mean many different things to many different people. Essentially each process comprises of a mechanical component, usually used to screen, separate, capture or shred certain elements of the input stream and a biological component, which may be aerobic or anaerobic (or both at different times), and can be used for a range of purposes. These steps can come in either order, which has led to some processes being labeled 'BMT', but for the purposes of this study, we will refer to MBT only.

There has been limited commercial application of MBT in the UK, with only 5-7 plants currently operating commercially, though several tenders have recently been awarded. Our technology scenarios involving MBT also incorporate a range of additional novel processes, for example, steam reforming for hydrogen production. Where appropriate, therefore, we have based our assumptions upon data from facilities outside the UK.

We have segmented our analysis according to the three core types of MBT configuration:

- 'Biostabilisation' of the organic fraction for subsequent landfill;
- 'Bio-drying' of residual waste for use in developing an RDF for subsequent thermal treatment (with a reject fraction undergoing subsequent maturation prior to landfill); and
- Anaerobic digestion (AD) to produce biogas for energy generation (with the organic and reject fractions undergoing subsequent maturation prior to landfill).

Each of these forms of MBT will include the capture of metals from the input waste, and as detailed in Section 3.0, in some scenarios plastics will also be captured for either reprocessing or conversion by pyrolysis into synthetic diesel. Discussion of this latter technology can be found in Section 6.10 and in Appendix 3.

6.5.1 MBT ('Biostabilisation')

The key parameter for this form of MBT is the residence time and thus the biodegradability of the organic output sent to landfill. This will determine how much methane is emitted from the waste following the 'biostabilisation' process. Essentially, under the right temperatures, the longer the residence and maturation times, the lower the output biodegradability.

To meet the requirements of the EU and UK Animal By-products Regulations (ABPR), the 'biostabilisation' process might take place in-vessel/tunnel or in a closed hall. This will often be followed by a maturation period in open or housed windrows to reach the desired levels of biodegradability. It is often sensible to employ longer maturation times, typically 8-10 weeks, for local authorities seeking to use this technology as their principle approach to meet the targets set by the Landfill Allowance Trading Scheme (LATS).[109] Our assumptions for this and other key parameters are shown in Table 6-5. The maturation period reflects a process which delivers material of low fermentability to the landfill, which itself is assumed to operate with an active oxidation layer (reflected in the assumptions in Table 6-1 above).

Table 6-5: Summary of central assumptions for MBT ('biostabilisation')

Parameter	Assumption
Residence time	10 weeks
Electricity requirement	50kWh/t input
Recovery rate (post-stabilisation) for ferrous metals	80%
Recovery rate (post-stabilisation) for non-ferrous metals	70%

6.5.2 MBT ("Biodrying")

'Biodrying' is the term commonly given to MBT processes which essentially dry the input waste as part of a fuel preparation process to produce RDF for subsequent thermal treatment in a range of facilities; from dedicated gasifiers to cement kilns and waste incinerators. In the latter two cases, the tonnage of RDF input to the process will be limited by technical constraints, typically to maximum levels of 5-10% of other core fuels.

As mentioned above, one such facility is already operating in East London, with many more across other EU Member States. A key parameter for this configuration is the amount of energy required by the 'biodrying' process to ensure moisture content is low enough for use as a fuel. To add calorific value, plastics are shredded

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[109] See Section 8.0 for further discussion

and left in the treated stream, whilst in the scenario modelled for this study a reject fraction undergoes maturation prior to landfill.

Table 6-6: Summary of central assumptions for MBT ('biodrying')

Parameter	Assumption
Residence time in 'biodrying' phase	12 days
Residence time of rejects in maturation phase	7 weeks
Electricity requirement	60 kWh/t
RDF generated	49% of input waste
Calorific value of RDF (Wet LHV)	15.5 GJ/tonne
Recovery rate for ferrous metals	80%
Recovery rate for non-ferrous metals	70%
Recovery rates for glass (sent for aggregates production)	70%

6.5.3 MBT (Anaerobic digestion)

There is currently just one application of MBT in the UK which incorporates an AD component, although this is actually located at a different site from the mechanical processing component.[110] At alternative facilities in other EU Member States, however, both components are usually based at the same site, and it seems likely that the contract recently awarded to Global Renewables Ltd (GRL) in Lancashire for AD-oriented MBT processes will also adopt this approach. The key assumptions for this configuration of MBT relate to the volume and CV of the output biogas, which will be used for subsequent energy generation either in onsite combustion processes or in hydrogen fuel cells.[111]

As outlined in the technology scenarios in Section 4.0, further assumptions for this configuration relate to capture rates for plastics for subsequent use either in synthetic diesel production or for materials reprocessing.[112] Due to different limits on the concentrations of various polymer types for these two applications, the capture rates shown in Table 6-7 have different values. [113]

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[110] Both sites form part of Biffa's treatment solution for Leicester City Council

[111] See Section 6.7

[112] See Section 5.2

[113] See Section 6.10

Table 6-7: Summary of central assumptions for MBT (AD)

Parameter	Assumption
Residence in digester	14 days
Maturation time of reject stream and organic output	5 weeks
Electricity requirement	70kWh/t
Efficiency of gas engine for electricity generation (CHP mode)	37%
Efficiency of gas engine for heat generation (CHP mode)	40%
Recovery rate for ferrous metals	95%
Recovery rate for non-ferrous metals	75%
Recovery rates for glass (sent for aggregates production)	20%
Recovery of plastics (if sent for reprocessing)	37kg / t input[1]
Recovery of plastics (if sent for synthetic diesel production)	56kg / t input[2]

Notes:

1. Assumes recovery of 70% recovery of PET, HDPE and 50% recovery of plastics films only
2. Pyrolysis processes for synthetic diesel production can accept all polymer types, but have limits in terms of the percentages of PET and PVC. In scenarios incorporating these technologies, it is therefore assumed that most recovered PET is sent for materials reprocessing. See Section 6.10 for further discussion

6.6 Autoclaving

Autoclaving, otherwise often known as mechanical heat treatment (MHT) is being offered by a range of technology providers in the UK municipal waste management market. Thus far, however, there are no facilities operating commercially in the UK, and very few elsewhere in the world for the treatment of MSW. As a result, contrary to our approach for some of the technologies described above, we have not been able to base our assumptions upon *actual* performance. The data presented below, however, founded upon information provided by technology providers, and thus represents the best available approach for this type of exercise.

Autoclaving is essentially a sterilization technology and is commercially proven in a variety of other industries. There are two key variations upon the core concept, which use either steam or direct heat to treat the waste, which has often resulted in the technology being referred to as a large ‘pressure cooker’. As a result, the energy requirement to heat the waste is a key parameter for autoclaving technologies, but varies according to the exact approach undertaken.

We have focused within our modeling upon the use of steam autoclaving, which results in the addition of significant amounts of water to the process. As a result, the output RDF material or ‘fibre’ will have very high moisture content, usually up to 50%. For use in thermal treatment processes, this ‘fibre’ must be dried, which requires a significant heat input. As each of our scenarios incorporating autoclave technologies couple these with a dedicated thermal plant, for example a gasifier or

CHP boiler, our Atropos© model assumes that the energy required for this drying process is derived from waste heat generated on-site, which will also feed the main autoclave unit. Both of these heat applications will thus reduce the amount of heat potentially available for use in residential and commercial installations to displace that derived from fossil sources. It should also be noted that if an autoclave is not co-located with a dedicated thermal plant, this heat will require an alternative source, usually from fossil fuel generation.

As for MBT, autoclaves treating MSW will always be accompanied by mechanical components to segregate recyclable materials, usually after the sterilization process. According to suppliers of the technology, because the heat in the autoclave (up to 150°c) changes the physical characteristics of the waste, both recovery rates and the quality of recyclable materials are higher than for MBT technologies. This is especially important for plastics, as a greater tonnage of cleaner material may be available for processing into higher value applications that deliver greater GHG benefits. Our contact with technology providers as part of this study has shown, however, that whilst this may be true for dense plastics, such as PET and HDPE, it is not the case for plastic films, which under high temperatures form into solid 'balls' that trap putrescible contamination meaning they cannot be recycled into similar products. As a result, following autoclaving, if not sent to landfill, plastics films could either be manufactured into lower value applications such as 'plaswood' or sent for manufacturing of synthetic diesel. [114]

The core goal of autoclave processes is usually to produce a fuel with very high biomass content both to meet potential client specifications and maximise ROC revenues.[115] Somewhat perversely, therefore, autoclaving MSW can result in significant tonnages of biodegradable material being sent to landfill. This takes place because of the mechanical separation of an oversize, reject fraction, which removes both non-biodegradable waste and biodegradable materials, such as garden waste and textiles / shoes. Autoclaving does not reduce the biodegradability of the waste to any great effect, and thus, as indicated in Table 6-8 we have assumed that after exiting the core plant, this reject stream undergoes a brief maturation phase, which would also allow for moisture loss prior to landfill.[116]

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[114] See Section 5.2 for further discussion of plastics recycling / reprocessing

[115] Under the RO, to gain ROCs for combustion of wastes, the input calorific value must be >90% biomass. For advanced treatment technologies (ATTs) such as gasification, pyrolysis and anaerobic digestion ROCs are given according to the percentage biomass present in the fuel, with no minimum value. For ATTs, 2 ROCs are awarded per MWh of electrical output

[116] If not, one might argue, the technology would be unattractive to local authorities which seek both to reduce the biodegradability of waste to be landfilled to meet LATS targets, and to reduce the weight of waste to reduce the level of landfill tax due

Table 6-8: Summary of central assumptions for autoclaving

Parameter	Assumption
Electricity requirement for operation of autoclave	45 kWh/t input
Heat / steam requirement for operation of autoclave	144 kWh/t input
Heat / steam requirement for drying of output 'fibre'	244 kWh/t output
Moisture content of fibre after drying	15%
Calorific value of fibre (wet LHV) following drying	13.2 GJ/t
Recovery rate for ferrous metals	90%
Recovery rate for non-ferrous metals	90%
Recovery rates for glass (sent for aggregates production)	80%
Recovery of plastics (if sent for reprocessing only)	18kg / t input[1]
Recovery of plastics (if synthetic diesel production included)	79kg / t input[2]
Residence time for maturation and moisture loss	1 week

Notes:

1. Assumes 76% recovery of PET and HDPE only
2. Pyrolysis processes for synthetic diesel production can accept all polymer types, but have limits in terms of the percentages of PET and PVC. In scenarios incorporating these technologies, it is therefore assumed that most recovered PET is instead sent for materials reprocessing. See Section 6.10 for further discussion

6.7 'Biomass' Boiler for Combined Heat and Power

More than one supplier of autoclave technologies is currently marketing their process alongside a combustion process and boiler to generate steam for combined heat and power (CHP). The potential to produce a fuel to a particular specification and with very high biomass content[117] is such that smaller scale, often more cost-effective technologies can be employed other than conventional moving-grate incineration. It should be noted, however, that as the fuel will continue to be considered a waste under the EU Waste Incineration Directive (WID), similar abatement equipment to that outlined in Section 6.2 for incineration, will still require installation and operation.

As mentioned in Section 6.6, the heat generated from by such 'biomass' boilers can be used both to provide steam to an autoclave and to dry the core output fibre. This significantly reduces the amount of fossil fuel energy required and thus reduces the overall GHG impacts of the overall system.

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[117] Up to 98% biomass has been quoted by some suppliers

Table 6-9: Summary of central assumptions for 'biomass' boiler

Parameter	Assumption[1]
Net electrical efficiency (CHP mode) based upon NCV	16.5%
Heat efficiency (CHP Mode) based upon NCV	50%
Electricity demand for flue gas cleaning	92kWh/t input

Notes:

1. Assumes fuel input from autoclave facility as described in Section 6.6

6.8 Production and use of Hydrogen

There has recently been much debate about the emergence of hydrogen as a new sustainable fuel to take us beyond the fossil fuel age and into a new energy paradigm. The use of hydrogen technology, however, is only as sustainable as the approach undertaken to generate the hydrogen used as a fuel. In the context of this study, gasification and anaerobic digestion of waste can be used to generate syngas and biogas, respectively, for conversion to hydrogen for use in fuel cells to produce electricity and heat. The purpose of this analysis is therefore to provide a basis for modelling the GHG emissions from hydrogen-based scenarios so that they might be compared with other waste management options.

6.8.1 Hydrogen Pathways

The scenarios outlined in Section 4.0 include the production of hydrogen for use in both transport applications and stationary energy generation, but there are many different pathways for both of these options. Much previous emphasis has been on the possibility of conversion of methane into methanol for conversion to hydrogen whilst on-board a vehicle. Arguably the most comprehensive research conducted in Europe, by Edwards et al on behalf of the EU Joint Research Centre, however, found this approach to be less efficient than alternative methods and it has also largely been abandoned due to technical difficulties and toxicity problems.[118] Furthermore, carbon capture and storage (CCS) from vehicles is currently considered impractical and thus we have omitted it from our analysis.

To facilitate greater ease of transport and storage, significant research is also being undertaken into the use of liquid hydrogen.[119] The amount of energy required to liquefy hydrogen, however, is reported to be up to 30-33% of its total energy value.[120]

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[118] Edwards et al (2006) *Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*, EU Joint Research Centre, May 2006 Update

[119] In Germany, Linde Group and BMW are working on a joint initiative and have several distribution points

[120] See Appendix 3 for detailed discussion

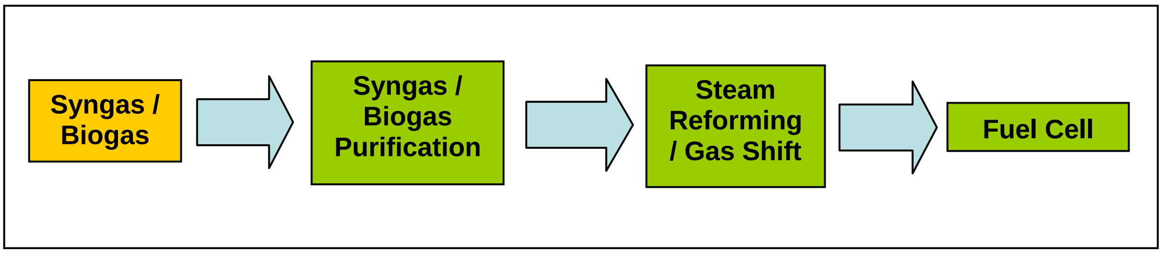
The limitations of this study are such that we have focused on one pathway for each scenario (transport and stationery generation) only. This choice has been made with regard to two parameters:

- Likely commercial viability within the lifetime of waste management facilities, i.e. usually a 25 year period; and
- Reliability of the data currently available to form reasonable assumptions in the context of such an immature technology.[121]

Figure 6-1 and Figure 6-2 represent the two chosen process pathways for the use of syngas / biogas in fuel cells to produce electricity for use in either transport or stationary power generation.

The type of fuel cells now most commonly being developed for use in transportation require very highly refined hydrogen.[122] Thus, prior to conversion to hydrogen through steam reforming, the syngas / biogas requires refining to remove impurities that can be damaging to these fuel cells. The GHGs emitted during these processes (steam reforming and gas refining) will therefore be the main emissions from the technology chain, as only water and a small amount of heat are emitted from the fuel cell.

Figure 6-1: Hydrogen Use in Transportation



Note: Another transportation pathway involves methanol reforming on-board vehicles

For stationary applications, following biogas upgrading and purification, it is possible for steam reforming to take place internally (within the fuel cell). In this configuration, most of the GHG emissions come from the fuel cell itself.[123]

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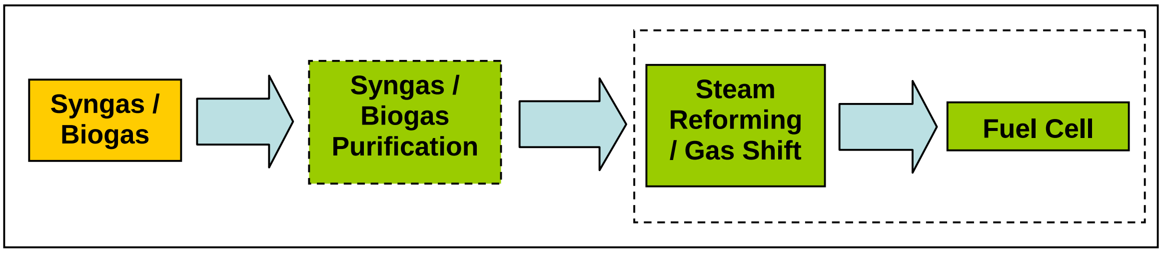
[121] As discussed in the Literature Review in Appendix 3, there is a large amount of uncertainty surrounding the performance of most elements of hydrogen energy technologies.

[122] See Appendix 3 for detailed discussion

[123] See Appendix 3 for detailed discussion

Figure 6-2: Hydrogen Use in Stationary Fuel Cells



Note: Many new stationary fuel cells contain the steam reforming process internally

For both transport and stationery applications, it should be noted that the use of syngas from gasification for subsequent conversion to hydrogen is, technically, a far more difficult proposition than the use of biogas from AD, as discussed below.

Appendix 3 provides both detailed descriptions and analysis of all technologies included in these hydrogen scenarios, along with a summary of the advantages and disadvantages of each approach.

6.8.2 Central Assumptions

It should again be noted here that there is significant uncertainty associated with modelling hydrogen technologies. There have been very limited examples of commercial production and use of hydrogen from waste feedstocks and most of the literature focuses upon the conversion of methane (CH_4) from natural gas into hydrogen. This is relevant for conversion of biogas, which contains significant amounts of methane, but not useful for analysing the production of hydrogen from syngas which has been generated from treatment of MSW.[124]

MTU CFC Solutions GmbH has a 250kWe Molten Carbonate Fuel Cell (MCFC) operating in CHP model using biogas generated by anaerobic digestion of green / kitchen wastes and sewage sludge.[125] We have therefore used this as our base scenario for biogas conversion to stationary power generation with regard to both emissions and efficiency.

For the transportation pathway from biogas, we have modelled external reforming followed by use of purified hydrogen in Polymer Electrolyte Membrane Fuel Cells (PEMFCs).

As mentioned above, syngas is by far the more problematic fuel. This is the result of its relatively low methane and high nitrogen (N_2) content if an air-blown gasification process is used, as may well be the case for treatment of MSW in the UK.[126] As a result, for both stationary and transport scenarios, following steam reforming, pressure swing adsorption (PSA) and gas filtration processes will be required to raise

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[124] Bjorklund, A, Melaina, M, Keoleian, G (2001) "Hydrogen as a transportation fuel produced from thermal gasification of municipal solid waste: an examination of two integrated technologies" Int J Hydrogen Energy 26: 1209-1221

[125] This plant was visited by members of the PSG group, facilitated by the London Hydrogen Partnership

[126] See Section 6.3 for further discussion of gasification technologies

the H_2 content of the gas stream, which will reduce the efficiency of the whole conversion process.

As mentioned above, a limiting factor for this particular element of our analysis has been that investment in both academic and commercial research programmes has focused upon the use of natural gas and biogas in fuel cells, and the little data that does exist for syngas is based upon compositions derived from the gasification of coal, not MSW. Coupling gasification and fuel cell technologies together, therefore, along with PSA and gas filtration would today represent a technical risk that is likely to be beyond that which might attract commercial finance.

These factors suggest our results for this particular scenario should be treated with caution.[127] As stated in Section 2.0, however, one of the goals of this analysis is to report upon 'leading edge' configurations which have the potential to deliver both GHG benefits and which fit with wider policy goals at national and city level.[128] The PSG were therefore keen that such scenarios be included within the study.

We have therefore modelled both transport and stationary applications for syngas based upon a range of literature, and some basic scientific logic applied within Atropos©. For transport applications, we have again assumed the use of a PEMFC to convert a pure hydrogen gas stream, whilst we have modelled the use of a solid oxide fuel cell (SOFC) to convert a hydrogen rich stream for stationary power generation.[129]

Concerns over the lack of infrastructure for hydrogen delivery should also be acknowledged, but consideration of this issue is outside the scope of this study. Hydrogen must be compressed, however, before it is transported by road and then once more (to a different level) for storage and dispensing to vehicles at the pump. This whole process requires significant energy input, which may be around 16% of the total energy value of the hydrogen.[130] Assumptions relating to the emissions from transportation of hydrogen by road for use in fuel cell applications within London are outlined in Section 5.3.

The central assumptions that will be used in the modelling the production and use of hydrogen for transport and stationary power generation are summarised in Table 6-10.

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[127] As should those for all syngas-derived hydrogen scenarios

[128] See Section 8.0 for more detailed discussion

[129] These technologies and associated efficiencies are discussed in Appendix 3

[130] Personal Communication, Linde Group, March 2007

Table 6-10: Summary of central assumptions for hydrogen technologies

Parameter	Assumption
Energy demand for biogas upgrading prior to entry into molten carbonate fuel cell (MCFC) or steam reforming process	0[1]
Efficiency of conversion of upgraded biogas to useful energy in a stationary molten carbonate fuel cell (MCFC) in electricity only mode[2]	50%
Efficiency of conversion of upgraded biogas to useful energy in a stationary molten carbonate fuel cell (MCFC) in CHP mode[2]	47% electricity 23% heat
Emissions of CO_2 from a stationary MCFC (using upgraded biogas) for electrical output	300 g CO2 eq./KWh
Efficiency of external steam reforming process for biogas (expressed in terms of conversion of energy in methane to hydrogen energy)	78%
Total emissions from steam reforming process for biogas (including both energy use and process losses)	74 g CO2eq./MJ fuel produced
Efficiency of conversion of H_2 in vehicles using a polymer electrolyte membrane fuel cell (PEMC) to useful energy	0.94 MJ / km
Emissions from vehicles using PEMC's	H_20 + heat
Emissions avoided from extraction, refining and transport of diesel	13.63 g CO_2 / MJ produced
Efficiency of external steam reforming process for syngas (expressed in terms of conversion of energy in methane and other hydrocarbons to hydrogen energy)	37%
Separation efficiency of gas filtration process	90%
Energy demand of PSA and gas filtration processes	0[3]
Efficiency of conversion of H_2 (derived from syngas and following gas filtration and PSA) in a solid oxide fuel cell (SOFC) in CHP mode	60% electricity 20% heat

Notes:

1. Whilst this is acknowledged here, a lack of reliable data is such that we have not been able to include any emissions data within our modelling. However, it should be acknowledged that this requirement is likely to be minimal in the context of other elements of the scenario
2. These figures are based upon the performance of an operational facility in Leonberg, Germany, which was visited by some members of the PSG
3. These may be significant, especially for the PSA process, but we have not been able to source relevant data on which to base assumptions. As outlined above, therefore, the results of scenarios involving syngas should be treated with caution

6.9 Upgrading and Compression of Biogas for Transportation

In 2002, less than 1% of biogas produced in Europe was used as vehicle fuel,[131] the majority of which came from municipal landfills. Early use of upgraded biogas has tended to be for municipal vehicles such as buses, car fleets and waste collection trucks. The picture appears to be changing fairly swiftly, with a number of anaerobic digestion facilities now focusing on the generation of biogas for upgrading and compression for use as vehicle fuel. Interestingly, this has become popular in some countries which are limiting access to city centres to those vehicles run on biofuels only (for example, Gothenburg in Sweden).

In the technology scenarios outlined in Section 4.0, Scenario 17 involves the production of biogas from Anaerobic Digestion (AD) and the upgrading of biogas to vehicle fuel, followed by its use in compressed biogas (CBG) vehicles. The assumptions relating to this scenario are discussed here, whilst those relating to the offset of fossil fuel vehicle emissions are contained in Section 6.11.

For biogas to be used as vehicle fuel it must be enriched in methane. This is primarily achieved by carbon dioxide removal which then enhances the energy value of the gas to give longer driving distances with a fixed gas storage volume. Removal of carbon dioxide also provides a consistent gas quality with respect to energy value. Gas quality standards need to be strict to provide a consistent high calorific gas containing a low level of contaminants and corrosive contaminants. The minimum methane content is usually 95%, with the rest being mostly CO_2. The key GHG impacts in the process therefore relate to both energy use in production and emissions associated with the process itself, for example, methane is emitted during the water scrubbing process.

There is little available data for modelling these emissions, and thus we have sourced information from both published literature and directly from technology providers, as discussed in more detail in Appendix 3. The central assumptions are summarised in Table 6-11 and are based upon a study conducted by industry and the EU Joint Research Committee.[132] This project data has been reviewed and updated twice since the first publication in 2003, and additional data have been included on biogas produced from municipal wastes. We therefore feel it is the most robust available source. It should be noted, however, that estimates are likely to vary as a function of plant design and waste composition.

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[131] Trendsetter (2003) *Clean Vehicles in Europe*. Report No 2003:2. Stockholm, Sweden.

[132] CONCAWE, EUCAR, JRC. (2006) *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Well- to- Wheels Report. Version 2b. May 2006

Table 6-11: Summary of assumptions for biogas conversion to vehicle fuel

Parameter	Assumptions
Energy use (of electricity/gas from network or biogas) for treatment, upgrading and compression	0.09 MJ/MJ fuel produced
Process losses of methane	0.2%
Emissions avoided from extraction, refining and transport of diesel	13.63 g CO_2 / MJ produced

6.10 Pyrolysis of Plastics to Synthetic Diesel

This section focuses specifically on the pyrolysis of plastics to produce synthetic diesel, and relates to the technology scenarios outlined in Section 4.0 in which the plastics are recovered from an MBT process. Pyrolysis is not currently a widely used process for treating waste, and this specific application is even less common. The pyrolysis of plastics results in a range of outputs such as gaseous and liquid paraffin, olefins, naphthenes, petrol, light gas oil and aromatics and solid char. The relative quantities of these depend upon:

- Composition of input polymers;
- Input handling;
- Residence time;
- Temperatures employed;
- Reactor type; and
- Condensation arrangement.

A review of available literature revealed that most data relates to laboratory scale reactors and experiments, and within this no information is available on energy input or emissions. We have therefore attempted to source information directly from technology suppliers, but little quantitative data is available and mostly relates to the Thermofuel technology, as discussed in Appendix 3.

During discussions with these suppliers, however, it was made clear that energy use and fuel yield depend largely on the composition of the feedstock, and therefore the data presented in Table 5-11 should be interpreted within this context.

Table 6-12: Summary of central assumptions

Parameter	Assumptions
Maximum concentrations of PET	5% in total[1]
Maximum concentrations of PVC	
Litres of diesel equivalent produced per tonne input	904 litres
	782 tonnes
Energy use	6.5MJ / tonne input
Emissions avoided from extraction, refining and transport of traditional diesel	13.63 g CO_2 / MJ produced
Notes: 1. We have assumed that PET which is separated from the other polymer streams, but not used in the process, is sent for reprocessing	

6.11 Use of Biogas and Synthetic Diesel in Transportation

To model the total GHG balances from the relevant transportation scenarios in Section 4.0, the emissions from the use of synthetic diesel (from plastics) and biogas in vehicle must be included. Appendix 3 reviews available data on emissions from use of these fuels, which can be used to calculate their differential impact compared to conventional fossil fuels.

The literature review detailed in Appendix 3 revealed that only one study quantifies emissions from synthetic diesel, and this relates to fuel produced from wood wastes, coal and natural gas.[133] To be marketed as vehicle fuel, however, synthetic diesel must meet EN590 standards. Assuming that synthetic diesel made through pyrolysis of plastics will also meet this standard, as is claimed by the technology suppliers interviewed for this study, we feel that it is reasonable to use this wider emissions data. [134]

Although in the literature review, there are three key studies that quantify emissions from these different fuel types, the CONCAWE study is the only one to investigate all transport fuels in a consistent and comparable way. Data from this study detailing likely emissions from vehicles with internal combustion engines is shown in Table 6-13. These figures relate to forecasts for 2010, which are based upon the assumption that gasoline and diesel engines comply with currently legislated specifications. This data has been used in our wider modelling of these transport scenarios, with the delivered CO_2 reductions assumed to be constant over time.

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[133] CONCAWE, EUCAR, JRC. *Well- to- Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Tank to- Wheels Report. Version 2b. May 2006

[134] See Section 6.10

Table 6-13: Summary of assumptions for emissions from vehicles in 2010

Parameter	Emissions (gCO_2 eq/km)	Reduction (gCO_2 eq/km)	% change
Emissions from Diesel car (reference)	129.4	-	-
Emissions from CNG/CBG car	105.2	24.2	18.7
Emissions from Synthetic Diesel car	125.1	4.3	4.1
Emissions from Diesel hybrid car (reference)	106.6	-	-
Emissions from CNG/CBG hybrid car	78.4	28.2	26.5
Emissions from Synthetic Diesel hybrid car	103.1	3.5	4.5

7.0 Results of Scenario Modelling

In Section 4.0, all scenarios which have been modeled for this study are shown in terms of the individual technologies of which they are comprised, along with more detailed schematics within Appendix 1.

As stated in Sections 2.0 and 3.0, the core objective of this study is to provide a ranking of waste technology scenarios with regard to their performance on GHG emissions. Towards establishing a clear ranking of scenarios it is necessary to form clear judgements upon a set of fundamental, underlying parameters which underpin the analysis within our Atropos© model. We are fully aware, however, that there will never be complete consensus upon all our assumptions, but as detailed in Sections 5.0 and 6.0 and in Appendix 3, we have based these upon the widest possible evidence base, which includes not only upon a thorough review of published information, but also upon primary data and personal communications with technology providers.[135]

It should again also be noted here that this study, and thus our methodology for undertaking the analysis, has received formal peer review.[136]

7.1 Results based upon Central Assumptions

As discussed in Section 3.2, to take into consideration the effect of time upon the impact of GHG emissions from different waste management scenarios the central results from our analysis in Table 7-1 and Figure 7-1 are presented in monetary values and are based upon treating one tonne of input waste. As explained in more detail in Section 3.0 and Appendix 3, these are based upon estimated rising marginal damage costs for each year of release, which have been discounted according to the Treasury Green Book methodology.

Table 7-1 reflects net externalities, thus taking into consideration the emissions from different technology elements within each scenario, along with the emissions avoided from both alternative energy generation and materials recovery/reprocessing.

A more detailed view of all scenarios, broken down according to the performance of each technology element, is provided in Appendix 5.

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[135] See Appendix 3

[136] Holland, M (2007) Peer review of a study by Eunomia for the GLA into the greenhouse gas balances of waste recovery technologies, EMRC on behalf of the Greater London Authority, October 2007

Table 7-1: Ranking of Scenarios under Central Assumptions

Rank	Scenario Number	Scenario Description	Net Externality (£s)
1	11	MBT (AD and maturation) with output to landfill and export of biogas for conversion to H_2 for use in vehicles	4.48
2	21	Plasma gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	4.83
3	13	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (CHP)	5.25
4	12	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (electricity only)	5.45
5	5	Gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	5.75
6	9	MBT (AD with maturation) with CHP, output sent to landfill and plastics to reprocessing	6.01
7	14	MBT (AD with maturation) with output to landfill and compression of biogas for use in vehicles	6.21
8	10	MBT (AD with maturation) with CHP, output to landfill and plastics sent for pyrolysis to synthetic diesel	6.47
9	20	Plasma gasification (following autoclaving) export of syngas to H_2 fuel cell for power generation (CHP) and plastics to reprocessing	6.50
10	6	Gasification (following autoclaving) export of syngas to H_2 fuel cell for stationery power generation (CHP) and plastics to reprocessing	6.90
11	15(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.35
12	16b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for pyrolysis to synthetic diesel	7.53
13	17	'Biomass' boiler (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	7.67
14	19	Plasma gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.98
15	15(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	8.38
16	16(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for pyrolysis to synthetic diesel	8.57
17	8(b)	Gasification (following MBT biodrying and maturation of rejects) using a gas engine (CHP)	9.01
18	7	MBT (biostabilisation) with output sent to landfill	9.55
19	3	Incineration (with CHP)	10.21
20	8(a)	Gasification (following MBT biodrying and maturation of rejects) using a steam turbine (CHP)	10.71
21	18	Incineration (following MBT biodrying and maturation of rejects) using a steam turbine (electricity only)	10.97
22	2	Incineration (with electricity only)	11.45
23	4	Incineration (with heat only)	11.66
24	1	Landfill (with electricity only)	31.90

As can be seen from both Figure 7-1 and Table 7-1, the best performing scenarios are those either based upon MBT (AD with maturation) or upon gasification (or plasma gasification), coupled with hydrogen (H_2) fuel cell technologies. This is the result of the far greater conversion efficiencies of fuel cells when compared to other energy generation technologies. Consequently, a greater amount of alternative energy generation is avoided, which delivers significant GHG reductions. The use of H_2 fuel cell vehicles delivers the best performance due to the avoidance of burning diesel, rather than the avoidance of electricity generation, as is the case with stationery fuel cells.

It should be acknowledged that there has been limited investment and research into the use of waste-derived syngas in hydrogen applications. In addition to the inclusion of an autoclave, a gasifier and a fuel cell within such scenarios, the syngas generated by a gasification facility treating municipal solid waste (MSW) would require processing with a number of intermediate technologies.[137] Today, this would represent a technical risk that is likely to be beyond that which might attract commercial finance. This suggests that our results for Scenarios 5, 6, 20 and 21 should be treated with caution. One of the key goals of this analysis, however, is to report upon 'leading edge' configurations which have the potential to deliver both GHG benefits and which fit with wider policy goals at national and city level. The PSG for this study were therefore keen that such scenarios be included within the project scope.

In contrast to the conversion of waste-derived syngas into hydrogen, the use of biogas in fuel cells is proven at commercial scale for stationary power generation, albeit this is a process still in its infancy.[138] This report does not seek to analyse financial viability, but it should be noted in this context that scenarios coupling MBT (AD with maturation) with gas engines (in CHP mode), or with biogas-fuelled vehicles, are the highest ranked configurations which might currently be affordable to local authorities.

When coupled with H_2 fuel cells, plasma gasification (Scenarios 20 and 21) performs better than more 'conventional' gasification (Scenarios 5 and 6). This is because vendors of such plasma technologies are tending to promote oxygen (rather than air) blown gasifiers, which produce significantly more hydrogen.[139] The subsequent additional energy generated by the fuel cell offsets the greater energy use of the plasma gasifier. When coupled with a gas engine, however, the 'conventional' gasifier performs better than plasma gasification. Whilst the energy generated by the two systems is similar, the greater energy use of the plasma gasifier results in greater overall externalities, as demonstrated by the rankings for Scenarios 15(b) and 19.

Similarly, coupling gasification technologies using a gas engine (whether this is following MBT or autoclaving) demonstrates the greater efficiencies, and thus lower GHG emissions, when compared to using a steam turbine for energy generation. The positioning of Scenario 17 above Scenarios 15(a) and 16(a) also shows that

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[137] These technologies would include steam reforming (gas shift), pressure swing adsorption (PSA) and gas filtration

[138] A stationary 250kW Molten Carbon Fuel Cell (MCFC) designed by MTU CFC Solutions is operating at 47% electrical efficiency (in CHP mode) at an anaerobic digestion facility in Leonberg, Germany

[139] It should be noted, however, that 'conventional' gasifiers could also be oxygen blown, and could thus perform better than plasma gasification if configured as such

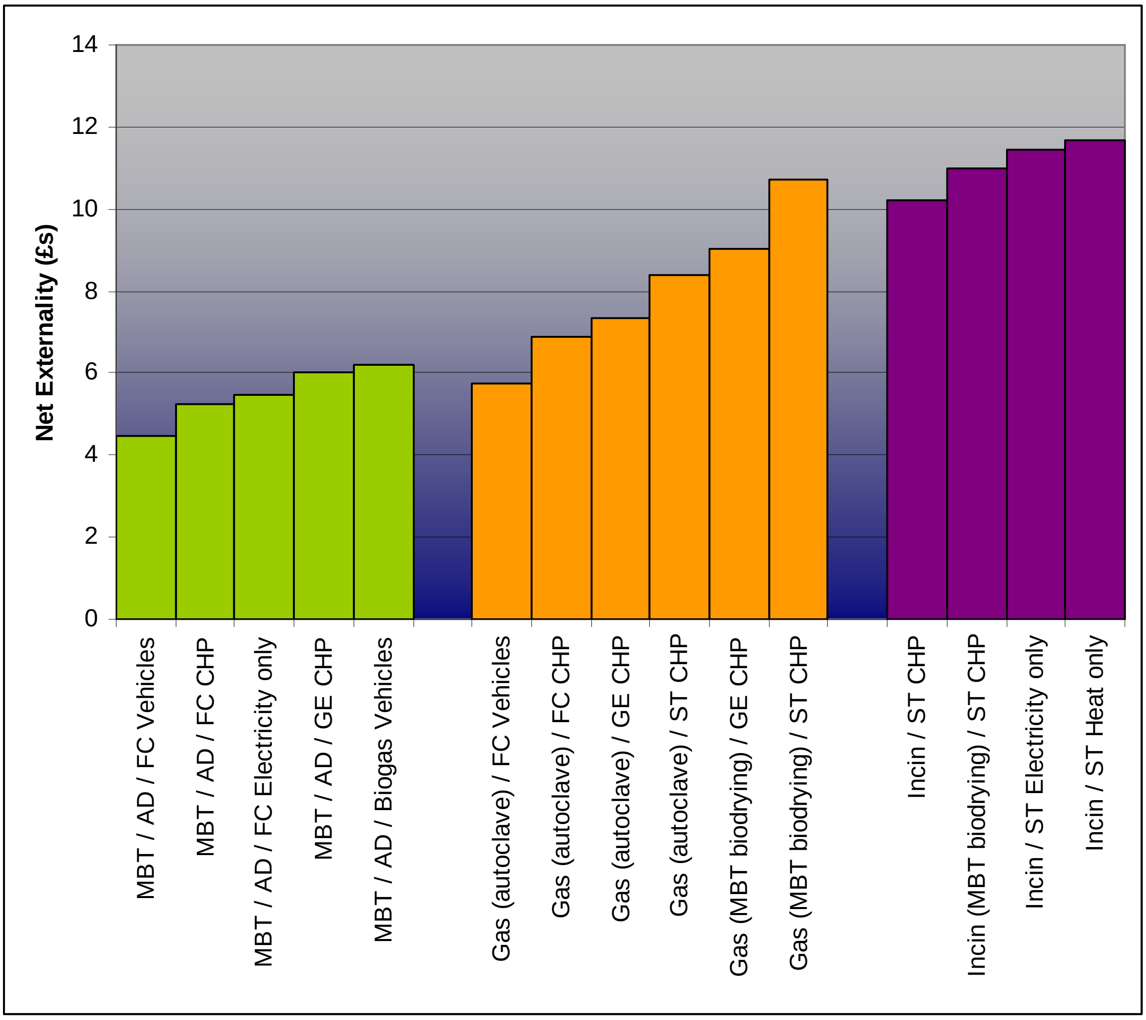
combustion technologies can deliver GHG benefits over gasification if this is coupled with a steam turbine.

Perhaps surprisingly, when compared to many LCA studies, MBT ('biostabilisation') process performs better than many of the configurations generating energy due to both the lack of any release of GHGs associated with fossil carbon from energy generation and reduced emissions of methane in landfill. For this scenario a designated 'stable' landfill cell is assumed, with an active oxidation layer reducing fugitive methane emissions to a minimal level. As mentioned above, although this might not be considered to be currently practicable in the UK, this study includes a range of 'leading edge' configurations and thus it is important to model the approach.

Whether preceded or not by MBT ('biodrying'), scenarios incorporating traditional incineration technologies perform poorly. This is the result of significant emissions from wholesale combustion of plastics at relatively low efficiencies, which negates the benefits derived from avoided emissions associated with energy generation. Only Scenario 1 (landfill with electricity only) performs at a lower level than all these scenarios, and is the only approach for which it has been assumed that no metals are recovered, which would offset emissions from manufacturing processes using raw materials.

To demonstrate and compare the performance of core technology types which can be used to generate energy, in Figure 7-1 we have highlighted the performance of all scenarios incorporating AD, gasification and incineration. This demonstrates the better performance not only of AD over gasification and incineration, but also of fuel cells over gas engines and steam turbines. With regard to GHG balances, a key advantage of AD and gasification over incineration, therefore, is that these two technologies can be coupled with more efficient generation technologies, whilst incineration remains locked to the use of a steam turbine.

Figure 7-1: Performance of Core Technology Types under Central Assumptions



Note: FC = Fuel Cell, GE = Gas Engine, ST = Steam Turbine

7.2 Sensitivity Analysis

As mentioned above, due to the nature of this study, some of our assumptions are likely to be controversial. It should again be emphasised, however, that in no way is this study intended as an academic paper, which might seek to explore every possible form of sensitivity analysis using wide ranges of potential variation in assumptions. To deliver a relevant ranking of technology scenarios and thus to function as a useful policy tool, we have therefore chosen to focus upon a limited number of sensitivities within our Atropos© model:

1. Using a greater ‘carbon intensity’ for avoided electricity generation;
2. Assuming a higher degree of heat utilization from processes to displace heat from alternative sources;

3. A ‘non-monetised, non-discounted’ approach (but with all non-fossil CO_2 equivalents still included within the balance); and
4. A ‘traditional LCA approach’, with exclusion of all non-fossil emissions aside from methane from landfill;
5. Using a likely ‘future’ waste composition, designed to reflect higher levels of recycling.

As discussed in Section 3.0, all proposed sensitivity analysis was summarized in a report to the PSG and agreed during several subsequent project meetings. The results of this sensitivity analysis are presented in Sections 7.2.1 to 7.2.5.

7.2.1 Greater carbon intensity for avoided electricity generation

As discussed in Section 5.1.1, there was some debate over the carbon intensity to ‘ascribe’ to avoided electricity generation, but this was within a very limited range. For reasons discussed in detail in Section 3.0, therefore, we have restricted our sensitivity analysis for this parameter from 447g CO_2/kWh under our central assumptions, to 0.522kg CO_2/kWh, which was the value proposed in the Mayor’s Climate Change Action Plan (CCAP).

Perhaps unsurprisingly, the outcome of this test is by no means dramatic - and far less so than might occur, for example, if one was to assume the marginal avoided source of electricity generation was switching from gas to coal. As one would expect, some scenarios generating relatively higher levels of electricity move upwards as a result of the greater amount of CO_2 being avoided from alternative generation capacity. There is, however, very little noteworthy change in the rankings in that no scenario moves more than one place in either direction.

Figure 7-2: Scenario rankings using greater carbon intensity for avoided electricity

Rank	Scenario Number	Scenario Description	Net Externality (£s)
1	11	MBT (AD and maturation) with output to landfill and export of biogas for conversion to H_2 for use in vehicles	4.68
2	13	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (CHP)	4.95
3	21	Plasma gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	5.05
4	12	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (electricity only)	5.12
5	9	MBT (AD with maturation) with CHP, output sent to landfill and plastics to reprocessing	5.79
6	5	Gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	5.87
7	20	Plasma gasification (following autoclaving) with export of syngas to H_2 fuel cell for power generation (CHP) and plastics to reprocessing	6.14
8	10	MBT (AD with maturation) with CHP, output to landfill and plastics sent for pyrolysis to synthetic diesel	6.28
9	14	MBT (AD with maturation) with output to landfill and compression of biogas for use in vehicles	6.38
10	6	Gasification (following autoclaving) export of syngas to H_2 fuel cell for stationery power generation (CHP) and plastics to reprocessing	6.63
11	15(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.01
12	16b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for pyrolysis to synthetic diesel	7.20
13	17	'Biomass' boiler (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	7.45
14	19	Plasma gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.73
15	15(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	8.28
16	8(b)	Gasification (following MBT biodrying and maturation of rejects) using a gas engine (CHP)	8.43
17	16(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for pyrolysis to synthetic diesel	8.46
18	7	MBT (biostabilisation) with output to landfill	9.61
19	3	Incineration (with CHP)	9.70
20	18	Incineration (following MBT biodrying and maturation of rejects) with electricity only	10.36
21	8(a)	Gasification (following MBT biodrying and maturation of rejects) using a steam turbine (CHP)	10.49
22	2	Incineration (with electricity only)	10.64
23	4	Incineration (with heat only)	11.78
24	1	Landfill (with electricity only)	31.75

7.2.2 Higher external utilisation rate for heat generated

As discussed in Section 5.1.3, as result of fluctuations in day/night and seasonal demand from both residential and commercial off-takes, our central assumption is such that only 55% of heat generated by any waste management facility is used to displace alternative sources. In situations where more embedded generation might be possible, however, there is likely to be greater potential for heat use, as smaller facilities might be more easily switched on and off to accommodate local heat demand. Consequently, to provide limited sensitivity analysis on this parameter, we have raised the rate of heat utilisation to 80%. As shown in Table 7-2, compared to our central results, most scenarios which produce relatively large amounts of heat perform better; most notably, Scenario 4 (incineration with heat only), whilst scenarios without any heat generation fare worse. Again, however, perhaps unsurprisingly, across all scenarios the order of magnitude of change is insignificant.

Table 7-2: Scenario rankings according to higher external utilisation of heat produced

Rank	Scenario Number	Scenario Description	Net Externality (£s)
1	11	MBT (AD and maturation) with output to landfill and export of biogas for conversion to H_2 for use in vehicles	4.48
2	21	Plasma gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	4.83
3	13	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (CHP)	5.25
4	12	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (electricity only)	5.45
5	9	MBT (AD with maturation) with CHP, output sent to landfill and plastics to reprocessing	5.74
6	5	Gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	5.75
7	20	Plasma gasification (following autoclaving) export of syngas to H_2 fuel cell for power generation (CHP) and plastics to reprocessing	5.92
8	10	MBT (AD with maturation) with CHP, output to landfill and plastics sent for pyrolysis to synthetic diesel	6.19
9	14	MBT (AD with maturation) with output to landfill and compression of biogas for use in vehicles	6.21
10	6	Gasification (following autoclaving) export of syngas to H_2 fuel cell for stationery power generation (CHP) and plastics to reprocessing	6.49
11	15(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.34
12	17	'Biomass' boiler (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	7.42
13	16b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for pyrolysis to synthetic diesel	7.53
14	19	Plasma gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.77
15	15(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	8.25
16	8(b)	Gasification (following MBT biodrying and maturation of rejects) using a gas engine (CHP)	8.37
17	16(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for pyrolysis to synthetic diesel	8.43
18	3	Incineration (with CHP)	8.81
19	4	Incineration (with heat only)	9.14
20	7	MBT (biostabilisation) with output to landfill	9.55
21	8(a)	Gasification (following MBT biodrying and maturation of rejects) using a steam turbine (CHP)	9.84
22	18	Incineration (following MBT biodrying and maturation of rejects) with electricity only	10.97
23	2	Incineration (with electricity only)	11.45
24	1	Landfill (with electricity only)	31.90

7.2.3 Adoption of a non-monetised, non-discounted approach

As discussed in detail in Sections 3.2 and 3.3 and in the Technical Appendices, discounting and monetisation (using the SCC) both influence the results of our analysis. Whilst the former has the effect of reducing impacts over time, the SCC modelled for the latter increase year-on-year and thus heighten the impact of each tonne of CO_2 equivalent emitted. These contrary effects are thus complementary in the sense of cancelling each other out to some degree and are regarded interdependent parts of CBA methodology. To remove either from the model in isolation would thus distort any results significantly, and we have therefore run this part of sensitivity analysis without either function.

Table 7-3 shows, however, that the adoption of this 'non-discounted, non-monetized' approach results in little material change to the rankings when compared to those under our central assumptions. 'Slow' degrading, non-fossil carbon (i.e. lignin) sent to landfill has a greater impact when not discounted and thus all scenarios incorporating gasification (following autoclaving) move upwards at the expense of scenarios incorporating MBT (AD with maturation), which send stabilised wastes to landfill. In the bottom half of the table, however, there is no change to the rankings.

Table 7-3: Scenario rankings according to a non-monetised, non-discounted approach

Rank	Scenario Number	Scenario Description	Net Emissions (kg/CO_{2e})
1	21	Plasma gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	190.30
2	5	Gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	244.48
3	11	MBT (AD and maturation) with output to landfill and export of biogas for conversion to H_2 for use in vehicles	255.08
4	20	Plasma gasification (following autoclaving) export of syngas to H_2 fuel cell for power generation (CHP) and plastics to reprocessing	289.06
5	13	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (CHP)	300.78
6	12	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (electricity only)	312.03
7	6	Gasification (following autoclaving) export of syngas to H_2 fuel cell for stationery power generation (CHP) and plastics to reprocessing	312.23
8	15(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	338.78
9	9	MBT (AD with maturation) with CHP, output sent to landfill and plastics to reprocessing	345.55
10	16(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for pyrolysis to synthetic diesel	349.65
11	14	MBT (AD with maturation) with output to landfill and compression of biogas for use in vehicles	357.53
12	17	'Biomass' boiler (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	358.06
13	10	MBT (AD with maturation) with CHP, output to landfill and plastics sent for pyrolysis to synthetic diesel	374.48
14	19	Plasma gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	376.08
15	15(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	400.18
16	16(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for pyrolysis to synthetic diesel	411.05
17	8(b)	Gasification (following MBT biodrying and maturation of rejects) using a gas engine (CHP)	531.98
18	7	MBT (biostabilisation) with output to landfill	556.28
19	3	Incineration (with CHP)	604.03
20	8(a)	Gasification (following MBT biodrying and maturation of rejects) using a steam turbine (CHP)	632.36
21	18	Incineration (following MBT biodrying and maturation of rejects) with electricity only	647.88
22	2	Incineration (with electricity only)	672.90
23	4	Incineration (with heat only)	685.39
24	1	Landfill (with electricity only)	1130.99

7.2.4 Typical LCA Approach

Perhaps the most interesting and important comparison for this study (and one which in many senses represents an entirely different methodology rather than a form of sensitivity analysis) is the adoption of a typical LCA approach, the results for which have also been generated by Atropos©. The results in Table 7-4 show, however, that this has little impact on the rankings compared to our central results. Some scenarios which generate significant non-fossil CO_2 emissions through energy generation move upwards but this is usually by no more than one place in the rankings.

Changes in ranking under an LCA approach also occur partly because we have assumed – as many LCA studies do – a 100 year cut-off for the emissions. In doing so, we have attributed – which many LCAs do not do (when logically they should) – a credit in respect of non-fossil carbon still sequestered in landfill after 100 years. Also, in accounting for methane emissions from landfilled residues, we have credited back to the process those emissions which would otherwise have been associated with the carbon in the landfilled material if it had been released as CO_2 (which is consistent with the assumption that emissions of non-fossil derived CO_2 should be given zero weighting in the analysis).

Another point worth making is that effectively, to ignore most of the non-fossil carbon emissions (and how they occur over time) implies shifting the baseline. Some technologies now appear to reduce net emissions of GHGs, whilst others make net contributions to GHG emissions. It seems to us to be counter-intuitive to speak in terms of processes ‘contributing to reductions in GHG emissions’ when in the round, they do not.[140] To the extent that they do relies upon a particular accounting convention which is only appropriate in a limited context.

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[140] To suggest that waste management can reduce overall CO_2 emissions would imply that producing more waste is good for climate change, when in reality it clearly is not

Table 7-4: Scenario rankings according to traditional LCA Approach

Rank	Scenario Number	Scenario Description	Net Emissions (kg/CO_2)
1	21	Plasma gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	-413.26
2	11	MBT (AD and maturation) with output to landfill and export of biogas for conversion to H_2 for use in vehicles	-365.73
3	5	Gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	-327.69
4	13	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (CHP)	-297.29
5	12	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (electricity only)	-285.95
6	9	MBT (AD with maturation) with CHP, output sent to landfill and plastics to reprocessing	-281.42
7	14	MBT (AD with maturation) with output to landfill and compression of biogas for use in vehicles	-274.01
8	20	Plasma gasification (following autoclaving) export of syngas to H_2 fuel cell for power generation (CHP) and plastics to reprocessing	-273.03
9	6	Gasification (following autoclaving) export of syngas to H_2 fuel cell for stationery power generation (CHP) and plastics to reprocessing	-259.71
10	10	MBT (AD with maturation) with CHP, output to landfill and plastics sent for pyrolysis to synthetic diesel	-252.48
11	15(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	-206.28
12	17	'Biomass' boiler (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	-200.62
13	16b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for pyrolysis to synthetic diesel	-195.41
14	19	Plasma gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	-186.01
15	15(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	-144.88
16	16(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for pyrolysis to synthetic diesel	-134.01
17	7	MBT (biostabilisation) with output to landfill	-93.28
18	8(b)	Gasification (following MBT biodrying and maturation of rejects) using a gas engine (CHP)	-48.57
19	18	Incineration (following MBT biodrying and maturation of rejects) with electricity only	-36.84
20	3	Incineration (with CHP)	1.55
21	8(a)	Gasification (following MBT biodrying and maturation of rejects) using a steam turbine (CHP)	51.82
22	2	Incineration (with electricity only)	70.42
23	4	Incineration (with heat only)	82.92
24	1	Landfill (with electricity only)	299.52

7.2.5 Likely 'Future' Waste Composition

As outlined in Section 5.4, in response to various policy and regulatory drivers, the composition of residual waste is likely to change significantly over the next 25 years, during which facilities procured now are likely to be operational. To reflect potential changes in residual waste composition, therefore, we have modelled a likely 'future' waste composition.[141] This 'future' composition has been adapted from that derived from the WRL / AEAT study used under our central assumptions, to broadly reflect the potential 45% recycling target for household waste set by the Mayor for 2015.[142] The materials upon which it is assumed recycling efforts at the kerbside are focused include glass, garden waste and paper. Whilst it is assumed plastics are recycled, this is largely restricted to HDPE and PET, and thus the overall percentage of plastics increases significantly. It is assumed that a range of other materials are recycled at HWRCs, whilst the only stream from which there is no additional recycling is disposable nappies.

As can be seen from Table 7-5, the impact of this new composition upon the results under our central assumptions is minimal, with only one scenario moving more than one place in the rankings. What should be noted, however, is that in terms of overall externalities, the Scenarios focusing on generating energy through thermal treatment processes such as incineration and gasification perform worse than under our central assumptions, whilst those scenarios employing biological treatment deliver an improved score. This is the result of two key factors:

- Due to increased garden waste collection, a slightly lower percentage (-1.7% compared to the central composition) of slow-degrading, non-fossil carbon is present in the waste stream, and thus GHG emissions from landfill are lower;
- A significantly higher percentage (+5.5% compared to the central composition) of fossil carbon (plastics) is present within the waste stream, and thus there are increased CO_2 emissions from thermal treatment processes.

Similarly, it can also be seen from Table 7-5 that Scenario 1 (landfill) delivers a much improved score compared to under our central assumptions.

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[141] See Appendix 4 the 'future' waste composition and that modelled under our central assumptions

[142] Greater London Authority (2006) The London Plan: Spatial Development Strategy for Greater London – Housing Provision Targets, Waste and Minerals Alterations

Table 7-5: Scenario rankings using a likely ‘future’ waste composition

Rank	Scenario Number	Scenario Description	Net Externality (£s)
1	11	MBT (AD and maturation) with output to landfill and export of biogas for conversion to H_2 for use in vehicles	3.74
2	13	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (CHP)	4.45
3	12	MBT (AD and maturation) with output to landfill and export of biogas to H_2 fuel cell for stationery power generation (electricity only)	4.63
4	21	Plasma gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	4.96
5	9	MBT (AD with maturation) with CHP, output sent to landfill and plastics to reprocessing	5.16
6	14	MBT (AD with maturation) with output to landfill and compression of biogas for use in vehicles	5.34
7	5	Gasification (following autoclaving) with export of syngas for conversion to H_2 for use in vehicles and plastics to reprocessing	5.88
8	10	MBT (AD with maturation) with CHP, output to landfill and plastics sent for pyrolysis to synthetic diesel	5.90
9	20	Plasma gasification (following autoclaving) export of syngas to H_2 fuel cell for power generation (CHP) and plastics to reprocessing	6.35
10	6	Gasification (following autoclaving) export of syngas to H_2 fuel cell for stationery power generation (CHP) and plastics to reprocessing	6.82
11	16b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for pyrolysis to synthetic diesel	7.22
12	15(b)	Gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.34
13	17	‘Biomass’ boiler (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	7.47
14	19	Plasma gasification (following autoclaving) using a gas engine (CHP) and plastics sent for reprocessing	7.72
15	16(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for pyrolysis to synthetic diesel	8.08
16	15(a)	Gasification (following autoclaving) using a steam turbine (CHP) and plastics sent for reprocessing	8.19
17	7	MBT (biostabilisation) with output sent to landfill	8.61
18	8(b)	Gasification (following MBT biodrying and maturation of rejects) using a gas engine (CHP)	10.77
19	3	Incineration (with CHP)	12.12
20	18	Incineration (following MBT biodrying and maturation of rejects) with electricity only	12.60
21	8(a)	Gasification (following MBT biodrying and maturation of rejects) using a steam turbine (CHP)	12.82
22	2	Incineration (with electricity only)	13.51
23	4	Incineration (with heat only)	13.75
24	1	Landfill (with electricity only)	28.80

8.0 Interaction with Policy Mechanisms

The emphasis upon climate change and the drive towards alternative technologies for waste treatment and recycling is principally derived from the EU Landfill Directive, and the policies used to implement the Directive in the UK. Additional mechanisms such as the EU Emissions Trading Scheme (ETS) are also creating change in waste markets in the UK, the influence of which is only likely to become more widespread in determining how we manage wastes from all sectors of the economy.

The focus of this section is to provide some analysis of the impact of existing mechanisms, at both international, national and city levels, upon the different scenarios described above, specifically for the management of MSW. Whilst the goal is not to rule out any of the scenarios, it is important to present a clear picture of potential barriers and drivers, which might affect the implementation of certain approaches to waste management in the UK and London.

8.1 EU Emissions Trading Scheme

The EU ETS is a policy mechanism that has not been transposed as a piece of national legislation across Member States and thus is briefly explored here with regard to its impact on waste management in the UK.

The waste sector is not currently included within the EU ETS, which is restricted to ‘energy intensive’ sectors only.[143] The biomass fraction of wastes used as a fuel by companies within these sectors, however, can (under ETS rules) contribute to reductions in CO_2 emissions from fossil fuels and thus have a value to such organisations.[144] This value can translate into a reduction in the gate fee paid by an operator per tonne of waste used as a fuel for industrial energy generation.

Such practises are already taking place in the UK in the cement industry, and are under consideration within the power sector, although there are issues for the latter in meeting the demands of the EU Waste Incineration Directive (WID). As outlined in Appendix 2 and in Section 8.3.2 with regard to self-sufficiency, as these industries are not present in London, such co-firing options have not been included within the scope of our modelling.

8.2 National Policy Mechanisms

8.2.1 The Landfill Allowance Trading Scheme

The Landfill Allowance Trading Scheme (LATS) requires waste disposal authorities, as a group, to progressively reduce the quantity of biodegradable municipal waste

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[143] Although there is discussion within the Commission that the waste sector may sometime in the future be included. The mechanics or timing of this have, however, not yet been determined

[144] For example, cement manufacture or power generation

(BMW) they send to landfill.[145] They can do this either through managing BMW in ways other than landfilling (prevention, recycling, composting / digestion, treatment) or through reducing the *biodegradability* of what is landfilled. In England, the Landfill Allowances Trading Scheme (LATS) allows for allowances for landfilling BMW to be traded. The LATS penalises local authorities which send more BMW to landfill than they hold allowances for (which they may acquire through trading).[146] Sending material directly to landfill is, therefore, an option which is losing its attraction for most authorities, and the attraction will diminish over time.

One can define the 'LATS-efficiency' of a process as the extent (in percentage terms) to which the process reduces the biodegradability of waste which is landfilled as a result of the process. Under the approach developed by the Environment Agency, this figure is likely to be close to 100% for thermal processes, but may be rather less so for biological processes which send considerable quantities of material to landfill.[147]

A key point to make here is that for scenarios based upon biological or autoclaving technologies, LATS efficiency depends to a large degree upon how these technologies are configured. If not configured to keep as much biomass as possible within the fuel fraction (rather than in a reject stream), MBT (biodrying) and autoclaving technologies are likely to result in low LATS efficiencies. Although still unproven at commercial scale on MSW, due to the physical nature of the output from autoclave processes, this is likely to be easier than with MBT (biodrying) technologies. Market failure, which resulted in a fuel recipient no longer accepting material, however, would be more disastrous for autoclave scenarios, which would have delivered minimal reduction in the biodegradability of waste which would then be sent to landfill.

Along with MBT (biostabilisation), all scenarios which incorporate MBT (AD) with maturation of the output *can* deliver impressive LATS performances as long as segregated fractions which are sent direct to landfill are not rich in unstable biodegradable material. Depending upon residence times, which can be adjusted according to the particular LATS profile of any one authority, these forms of MBT are likely to be capable of providing reductions in biodegradability of the order 90% for fractions undergoing biostabilisation/maturation, which is not significantly below the performance of incineration technologies.

In this context, it should be noted that support for AD has been given by Defra in the Waste Strategy for England[148] in that it acknowledges its benefits and states that the Government wishes to encourage support for the technology. Such support comes in terms of funding through the New Technologies Programme, additional

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[145] BMW might be summarised as any waste from the municipal stream which will biodegrade and thus emit methane from landfill

[146] The magnitude of the fine is £150 for each tonne of biodegradable municipal waste (BMW) landfilled outside a particular authority's holding of allowances. Although currently, LATS allowances are trading for significantly less, market prices in future are uncertain.

[147] Technically, thermal processes will probably not deliver a 100% reduction given the remaining organic carbon in bottom ash and air pollution control residues

[148] Defra (2007) Waste Strategy for England 2007, April 2007

support through the Renewables Obligation (discussed in Section 8.2.2) and in the development of a standard for digestate from AD systems.[149]

8.2.2 The Renewable Obligation

The Renewable Obligation (RO) will provide financial benefit to technology scenarios which generate energy derived from non-fossil sources, since where they are accredited, operators are able to produce, and sell, Renewable Obligation Certificates (ROCs).[150] There are strict rules for qualification as a 'ROCable' generator, and only the following technology / fuel configurations are accepted by the DTI (now DBERR):

- Any form of ATTs (gasification/pyrolysis and AD);
- Incinerators incorporating good quality CHP (GQCHP); and
- Incinerators burning fuel with more than 90% biomass (measured by calorific value).

All of the above can generate ROCs according to the proportion of energy generated from non-fossil sources, as measured by the percentage of calorific value related to biomass present in the input stream. Many of the technology scenarios detailed above are likely, therefore, to benefit from the RO, and with BERR stating its intent, in the latest review of the mechanism, to increase the waste sector's contribution to delivering 'renewable' energy in the UK, this seems likely to increase. [151] Subsequent publication of DBERR's Energy White Paper shows this increase, subject to consultation, to be to double the amount of ROCs offered to ATTs per MWh of electricity generated.[152]

8.2.3 Climate Change Levy

The Climate Change Levy (CCL) is effectively a Government charge on fuel or power usage aimed at promoting energy efficiency.[153] In the form of Climate Change Agreements (CCAs) with DEFRA, organisations (or industries under 'umbrella' CCAs) can gain 80% reductions on the CCL by reducing 'primary' energy consumption on 1990 baseline levels by 2010.

The result of this focus on 'primary energy' consumption is that the use of any waste derived fuel (irrespective of biomass content) is counted as zero energy use and thus only traditional fossil fuel energy, i.e. coal, gas and oil, along with non-renewable electricity, is included in the calculation.

The influence of the CCL is, however, likely to be limited. Not only is it likely to be phased out in 2010, but similar to the discussion in Section 8.1 with regard to the

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[149] Currently under development by WRAP

[150] Currently trading at £40-45/MWh of energy produced

[151] DTI (2006) Reform of the Renewables Obligation and Statutory Consultation on the Renewables Obligation Order: An Energy Review Consultation, October 2006

[152] DTI (2007) Meeting the Energy Challenge: A White Paper on Energy, May 2007

[153] For coal usage, these charges were set in 2001 at 1.17p/kg or £11.70 / tonne (equivalent to 0.15p/kWh)

impact of EU ETS, there is limited scope for use of waste fuels within industry in London.

8.2.4 Local authority recycling and composting targets

At the time of writing, in England, these statutory targets exist in the form of Best Value Performance Indicator (BVPI) 82(a) and 82(b). Performance can, therefore, have a bearing upon Comprehensive Performance Assessment scores, with potential knock-on implications for the amount of funding received by a local authority from central government. Technology scenarios involving pre-treatment and separation, such as MBT and autoclaving, may deliver higher levels of recycling than incineration or gasification (with only rudimentary fuel preparation).

This would suggest that such approaches might be viewed more favourably by local authorities. In reality, however, the impact of performance against BV82(a) and (b) is likely to be secondary to LATS efficiency due to the potential for financial penalties for local authorities associated with the latter. Any 'financial penalty' associated with BV82(a) and (b) is more likely to reflect performance in other parts of the waste management system, and as yet, there is no intention to impose financial penalties on authorities who fail to meet these targets.

8.3 Strategic Policy-making in London

Alongside or within the GLA, there are a range of strategic bodies which are indirectly working towards sustainable waste management in London. As outlined in Section 3.0, an important part of this project has been to involve within the PSG a range of stakeholders from the London Climate Change Agency, the London Energy Partnership, the London Hydrogen Partnership and the London Development Agency. The sections below therefore are based upon an integrated approach to waste, energy, environment and planning which is essential for a first class capital such as London.

8.3.1 Waste recovery, recycling and composting

The Mayor's Municipal Waste Management Strategy (MWMS) sets out clear targets for London to recover value from 40% of municipal waste by 2005, 34% by 2010, and 67% by 2015.[154] The London Plan sets targets for London to exceed recycling or composting levels for municipal waste of 35% by 2010 and 45% by 2015.[155] Furthermore, in the London plan, the Mayor sets out to support appropriate developments for manufacturing related to recycled waste.

Although this study has focused upon residual waste only, it should be acknowledged that collecting materials in source separated form will deliver the highest GHG benefits from reprocessing. This clear emphasis on resource recovery, however, fits comfortably with a number of the high-scoring scenarios which involve

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[154] Greater London Authority (2003) Rethinking Rubbish in London; The Mayor's Municipal Waste Management Strategy, September 2003

[155] Greater London Authority (2006) Draft Further Alterations to the London Plan (Spatial Development Strategy for Greater London, September 2006

some form of pre-treatment (i.e. MBT or autoclaving). These aim to recover both metals and plastics from waste, which can make significant positive contributions to overall GHG balances.

8.3.2 Self Sufficiency

The London Plan sets out a goal for London to manage 50% of its own MSW by 2010, 75% by 2015 and 80% by 2020. The final target does not attempt to seek 100% self-sufficiency in the acknowledgement that all forms of waste treatment will result in the need for landfill, for which there are limited possibilities for additional developments within Greater London. These high targets, therefore, represent a desire to manage as much waste as is feasible within the city, and is why we have omitted such options as exporting solid and gaseous fuels derived from waste to power stations in Essex and Kent, despite the potential significant GHG benefits of directly displacing coal-fired energy.[156]

There is no doubt that this policy goal is not consistent with either Scenario 1 or Scenario 9, which are both based upon landfill. It is debatable, however, whether it can accommodate the full range of MBT scenarios, some of which may result in up to 50% of input waste (by weight) being sent to landfill. Yet, even incineration generates in excess of 20% of input tonnage in the form of bottom ash which must either be sent to landfill, or which must be prepared to be used as road substrate. Hazardous residues in the form of 'fly ash' also require landfilling or other treatment. Finally, the Greater London area is not without its areas of more contaminated and degraded land. MBT solutions do not lend themselves to the production of quality composts, but there may be possibilities to make use of MBT residues (or fractions thereof) in remediating contaminated sites. Therefore, it might not be reasonable to rule out alternative technologies on this basis, especially as they score far higher with regard to GHG emissions.

8.3.3 New technologies

In both the Mayor's MWMS, the London Plan and Alterations to the London Plan, it is stated that preference will be given to forms of new and emerging technologies over new conventional incineration capacity. Furthermore, the Mayor's Energy Strategy[157] provides detailed analysis of hydrogen technologies, which has been developed and presented in the specific context of waste by the London Hydrogen Partnership.[158] The London CCAP is also clear in its support of new technologies to deliver reductions in GHG emissions.[159]

There is thus no conflict with the best performing scenarios involving the use of biogas from MBT (AD) technologies within hydrogen fuel cell applications, and it is

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[156] As discussed in Appendix 2

[157] Greater London Authority (2004) Green light to clean power: The Mayor's Energy Strategy, February 2004

[158] London Hydrogen Partnership (2006) The Potential for Hydrogen Production from Waste in London, October 2006

[159] Greater London Authority (2007) Action Today to Protect Tomorrow: The Mayors Climate Change Action Plan, February 2007

likely that these would receive support from the Mayor in line with the aforementioned strategic policies.

8.3.4 Energy efficiency through CHP and distributed generation

Alongside support for new technologies to reduce GHG emissions from waste management, both the London Plan, Early Alterations to the London Plan and Energy Strategy emphasize the importance CHP and distributed generation. These documents combine to set a goal for London of maximising its contribution to meeting the national target for CHP by at least doubling capacity by 2010.

In recognition of this challenging goal, the GLA has also funded a specific study to analyse the potential for development of community heating with London.[160] Furthermore, the London Plan also requires the provision of suitable waste and recycling storage facilities in all new developments, which complements a CHP-based approach within building developments.

In Section 7.0, the best performing technology scenarios, under both the central model and the three forms of sensitivity analysis, demonstrate the benefits of CHP. Further policy development and promotion of such an approach within the GLA can therefore be justified in terms of improving the GHG balance of waste management operations in London.

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[160] Greater London Authority (2005) The London Community Heating Development Study: Summary Report, May 2005

9.0 Conclusions and Recommendations

As mentioned above, the goal of this study is to measure and rank a range of waste technology scenarios with regard to their performance on greenhouse gas (GHG) emissions. We do not attempt to pass judgement upon issues such as cost, planning or a host of environmental issues other than GHG emissions from waste management. Again, as mentioned throughout this report, we are fully aware that there will never be complete consensus upon all the assumptions we have used within our Atropos© model. Towards establishing a clear ranking of scenarios, however, it has been necessary to form clear judgements upon a set of fundamental, underlying parameters which underpin our analysis.

Climate change, however, is recognised as a core problem facing society and therefore our conclusions and recommendations, although remaining in context, are intended to contribute to guiding waste policy development in London and beyond. Our key conclusions and recommendations can therefore be summarised as follows:

- Scenarios incorporating MBT (AD with maturation) perform most consistently well both under our central assumptions and in each form of sensitivity analysis. Currently an under-exploited approach across the UK, the GLA could bring together and integrate related research into specific planning and cost analysis, to build upon the results of this study and promote development of best-of-breed MBT (AD with maturation) facilities across the city;
- MBT (AD with maturation) delivers the greatest GHG benefit when coupled with highly efficient hydrogen fuel cell technologies. Stationary power generation using molten carbonate fuel cells (MCFCs) fueled by biogas is proven at commercial scale[161], but is currently significantly more capital-intensive than generation with more conventional steam turbines or gas engines. The case for commercial roll-out would therefore benefit significantly from the first installation of the technology within a building in London;[162]
- There has been too little research to make clear judgment as regards the potential use of fuel cells to generate energy from hydrogen converted from syngas from gasification (or plasma gasification) processes. The results of our analysis demonstrate that there is clear potential for such approaches, but we again urge caution as to the context in which they should be used. To reduce uncertainty and promote development such scenarios, the GLA should consider funding additional research of this specific area;
- The results generated by our Atropos© model have clearly shown that CHP generation delivers far greater GHG benefits than generation based upon electricity or heat only solutions. Again, there may be potential for the GLA to intervene in future planning applications to promote heat off-take in addition

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[161] One such facility is operating in Leonberg, Germany

[162] Toward this end, the GLA and London Climate Change Agency are considering potential installation of a MCFC at a regional government office building in London

to electricity generation, or encourage developers to select sites which offer clear potential for embedded generation, either in communities or in industrial applications;

- Under our central assumptions and the five forms of sensitivity analysis, however, incineration with CHP reaches a high of only 18th place in the scenario rankings. The other two incineration scenarios fare worse still, and do not emerge from the bottom six positions, whilst Scenario 18, involving MBT (biodrying) prior to incineration does not fare much better. This poor performance is largely the result of wholesale combustion of plastics, which results in significant CO_2 emissions. On this basis, unless coupled with both significant kerbside recycling programmes and clear provision for good quality CHP (GQCHP), the GLA position regarding mass-burn incineration within London receives some qualified support (in that the analysis undertaken here does not cover all relevant factors and issues);
- The results from our analysis have shown that materials recycling / reprocessing, particularly of plastics, makes a considerable difference to GHG balances by avoiding emissions from virgin manufacturing processes. Compared to emissions avoided by energy generation using waste technologies, these benefits are not insignificant and are far higher than those delivered by conversion of plastics to synthetic diesel.[163] The GLA should thus ensure that they are not overlooked as a result of related stakeholders' desire to meet targets for installed 'renewable' energy capacity;
- This study has shown that autoclave technologies, if implemented and operated as planned by technology suppliers, have potential to be part of relatively well performing scenarios. As stated above, this study is not concerned with assessing the technical viability of particular technologies. Until autoclaving has been commercially proven in the UK, however, only limited conclusions should be drawn from this particular aspect of our analysis;
- It should be acknowledged that the maturation time of reject streams from 'pre-treatment' technologies such as MBT and autoclaving has a key impact on scenario performance. As outlined for each technology in Section 6.0, we have set these maturation times according to how they are being presented by bidders for local authority procurement contracts. In reality, however, all scenarios can be tweaked to incorporate greater or lesser maturation times according to the Landfill Allowance Trading Scheme (LATS) requirements of a particular authority.
- A key point ot note is that under our central assumptions, the difference in GHG-related externalities between the first 10 scenarios is, in monetary terms, only £3.05 per tonne of input waste. This would indicate that based upon the assumptions used within this study, should any of these scenarios incur significant capital or operating expenditure above the others, it is

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[163] As can be seen from the detailed breakdown of results provided in Appendix 5

unlikely to be justifiable through reference to GHG-related externalities alone. It should be highlighted, however, that there are wide-ranging estimates of the SCC, as discussed in Section 3.3.[164] Thus, if higher values had been employed within Atropos©, this difference in externalities between the first 10 scenarios might have been significantly greater; although similarly if a lower SCC had been modelled, far smaller differences would have been recorded; and

- Finally, although there is still further research to be undertaken, this study has shown that new technologies can deliver far lower GHG emissions than using conventional incineration or landfill. As the potential to utilise hydrogen fuel cell technology develops, and becomes more affordable, such benefits are likely to increase further.

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[164] Also, discussed in more detail in Appendix 3