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Comparison of Greenhouse Gas Emissions from the Centralised and Household Treatments of Food Waste

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Executive Summary

There are two basic acceptable approaches for dealing with household food waste, namely centralised treatment using a biological process, such as in-vessel composting or anaerobic digestion, and household treatment using Food Waste Digesters (FWDs). A typical FWD is a purpose designed and built unit that is located in a household's garden for the disposal of all food waste, including vegetable scraps, raw and cooked meat or fish, bones, dairy products and other organic food waste such as bread and pasta.

The greenhouse gas emissions from the life cycles of specified centralised and household management strategies for food waste have been compared in terms of CO_2 equivalents (CO_2E). The centralised approach includes the kerbside collection of uncontaminated, segregated food waste from households, transportation to an in-vessel plant and treatment, bulk transportation of the resulting compost to suitable application sites and the subsequent spreading of the compost on the land. The household treatment approach is based on the same uncontaminated segregation of the food waste but with the waste being put directly into a FWD. All significant components of the life cycles of both the centralised and household management strategies for food waste have been included in the calculations.

The greenhouse gas emissions associated with manufacture and end-of-life disposal of the capital plant, such as the in-vessel treatment facility, the waste transport vehicles and the FWDs, are relatively small. Depending on household dispersion, annualised values for the centralised approach range from about 12 to 16 kg CO_2E/tonne of food waste, with a value for household treatment of about 5 kg CO_2E/tonne for all situations.

The major contribution to the anthropogenic greenhouse gas emissions for the centralised approach arises from the day-to-day operations of the transport vehicles and the treatment plant, which annually generate about 38 to 198 kg of CO_2E/tonne of food waste, depending on household dispersion and the waste collection strategy. By contrast, the household treatment approach using FWDs produces zero day-to-day operational anthropogenic emissions.

The total anthropogenic greenhouse gas emissions for the centralised approach range from about 50 to 214 kg of CO_2E/tonne of food waste. These figures would reduce by 14 kg CO_2E/tonne if the compost produced by the in-vessel treatment plant could genuinely replace existing emission intensive inorganic fertilisers, soil improvers or peat. The total anthropogenic greenhouse gas emission for household treatment is about 5 kg CO_2E/tonne of food waste.

In summary, the anthropogenic greenhouse gas emissions from the centralised collection and in-vessel treatment of food waste are greater than those associated with household treatment by about a factor of between 10 and 40. Realistic optimal household food waste management strategies for the majority of areas, in terms of delivering targets, minimising costs and achieving acceptable health, safety, environmental and operational risk management, should be a combination of both centralised treatment and household treatment.

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1. Introduction

Over 36 million tonnes of Municipal Solid Waste (MSW) is generated annually in the UK (Reference 1). The management of this waste is estimated to produce greenhouse gas emissions equivalent to 4 million tonnes of CO_2 per year (Reference 2), 90% of which is attributable to the use of landfill for disposal.

There are two key legally and financially binding drivers to the reduction of greenhouse gas emissions, namely the Kyoto Protocol (Reference 3) and the EU Landfill Directive (Reference 4). The Kyoto Protocol requires the average emissions of six specified greenhouse gases to reduce to 12.5% below defined base year levels over the period from 2008 to 2012. The Landfill Directive requires the UK to reduce the amount of biodegradable waste going to landfill in the target years of 2010, 2013 and 2020 to 75%, 50% and 35% respectively, of the amount landfilled in 1995.

As a result of these two drivers, the waste management policies and strategies of central government, the devolved administrations and local authorities are focused on establishing treatment and disposal routes that avoid the use of landfill. One of the primary challenges is the reduction of the quantity of landfilled biodegradable waste, which mainly comprises similar amounts of paper, garden and food waste. The highly putrescible nature of food waste, coupled with a range of environmental and public health concerns, has limited the development of options and strategies for dealing with household food waste.

The complete life cycle of food from its production through to its waste residues is estimated to be responsible for 22% of the UK's total greenhouse gas emissions (Reference 5), which amounts to approximately 140 million tonnes of CO_2 equivalents per year (Reference 6). These emissions mainly result from the fossil energy sources used in mechanised farming production methods, the manufacture of fertilisers and pesticides, food processing, storage, packaging, transport, retailing, preparation and waste management. Recent research by WRAP (Reference 7) indicates that households dispose of 6.7 million tonnes of food every year, which is one third of the food purchased and of which half is edible.

Food waste and greenhouse gas emissions are now a priority for the Government, with a raft of relevant research reports and initiatives commissioned by the Department for Environment, Food and Rural Affairs (Defra), the Waste and Resources Action Programme (WRAP), the Office for the Deputy Prime Minister and the Engineering and Physical Sciences Research Council (e.g. References 2, 8-12). The recent 2007 waste strategy for England (Reference 13) includes food waste as a key target for reducing greenhouse gas emissions.

There are two basic acceptable approaches for dealing with household food waste, namely collection and treatment at a centralised facility and household treatment using Food Waste Digesters (FWDs). A range of biological and thermal centralised waste treatment options are available, which are described in Reference 12. The biological processes, such as in-vessel composting and anaerobic digestion, are preferable to thermal treatment technologies because of the high moisture content of food waste.

A typical FWD is a purpose designed and built unit that is located in a household's garden for the disposal of all food waste, including vegetable scraps, raw and cooked meat or fish, bones, dairy products and other organic food waste such as bread and pasta. Household food waste should not be put into the traditional garden compost bin, particularly non-green food waste, because of a number of health, safety and environmental issues. These include attracting vermin and potential access, through animal and human (particularly children) activity, to the surface soil around the compost bin and the compost material itself (Reference 14).

Good practice in determining local waste management strategies, particularly those involving high public expenditure and high public impact, requires a systematic approach to the decision making process supported by detailed health, safety, environmental, social, economic and operational risk assessments. Reliable information exists on most aspects of both the centralised and household treatments of food waste. Central to determining an optimum waste management strategy is the minimisation of greenhouse gas emissions from all sources over the life cycle of the operation. However, no specific comparison of the greenhouse gas emissions associated with the centralised and household treatment approaches is available.

This report identifies the sources of greenhouse gas emissions that would be expected to arise from the life cycles of specified centralised in-vessel and household management strategies for food waste. The greenhouse gas emissions for both approaches have also been quantified in two sets of calculations. The data and assumptions made in these calculations are provided in an Appendix to the report, together with the workbook models used in the analysis.

2. Background to Calculating Greenhouse Gas Emissions

The United Nations Framework Convention on Climate Change (UNFCCC) established international conventions for the treatment of certain activities and waste streams (Reference 15). All signatories to the UNFCCC agreed to develop inventories of greenhouse gas emissions as part of the stated goal of stabilising emissions and climate change. The Intergovernmental Panel on Climate Change (IPCC) has developed a set of inventory methods to be used as the international standard guidelines in determining these greenhouse gas inventories (Reference 16).

Greenhouse gas emissions are generally expressed in terms of delayed time (20, 100 or 500 years) after initial emission in carbon dioxide equivalents (Reference 17). The six greenhouse gases defined in the Kyoto Protocol of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6) are very different in terms of their global warming potential (GWP). Relative to a GWP of 1 for CO_2, CH_4 has a GWP of 21 and N_2O a GWP of 310 (100-year timescale). PFCs have the most potent greenhouse gas emissions in this analysis, where tetrafluoromethane (CF_4) and hexafluoroethane

(C_2F_6) are emitted during the reduction of alumina to aluminium in the primary smelting process. The 100-year GWP is 6,500 for CF_4 and 9,200 for C_2F_6.

The main gases of concern with respect to biodegradable waste management are CO_2, CH_4 and, to a lesser extent, N_2O. The majority of emissions result from the use of energy, particularly fossil fuel combustion to generate power directly in stationary and mobile machinery or indirectly to produce electricity. This energy is used in the extraction and processing of raw materials, the manufacturing of usable end products, managing by-products and the end products at their end-of-life and transporting materials, products and waste throughout their life cycle.

Greenhouse gas emissions also occur during the manufacture of certain materials that are not associated with energy consumption. The main non-energy emissions relevant to this analysis are associated with the materials used in the construction of the centralised treatment plant and the transport vehicles. Significant quantities of lime are used in the production of cement, steel and aluminium and CO_2 is emitted when limestone is converted to lime. Also, as noted above, the perfluorocarbons CF_4 and C_2F_6 are emitted during aluminium smelting (see Appendix A).

The main sources of emissions in this analysis arise from the energy used in day-to-day plant and transport operations. Of lesser importance are the embodied energy emissions resulting from the energy and non-energy processes associated with the production of an end product, whether it is a long life item such as a building, an intermediate life item such as a vehicle or short life consumable items.

Embodied energy comprises several components. Firstly, there is the energy and non-energy process emissions related to activities such as raw material extraction, processing, manufacturing and end-of-life treatment. Secondly, there are emissions from the combustion of the fuels used to transport raw materials from extraction through the various stages of processing and manufacturing an end product and onward transportation to distribution centres, retail outlets and the end user. At the products end-of-life there is the transportation involved in the collection and transfers associated with recycling and disposal.

A third possible component is the energy contained within a raw material used to manufacture a product such as plastic, which is referred to in publications as the feedstock energy, rolled-up feedstock energy or embedded energy (with the latter term also being used in publications interchangeably with the term embodied energy). As the oil and gas used to make plastic has an inherent energy value, the amount of energy that is saved through recycling and source reduction is directly related to the energy that could have been produced if the petroleum had been used as an energy source rather than as a raw material input. Aluminium is the other material in this analysis that includes an embedded energy component (see Appendix A).

Generally, only greenhouse gas emissions resulting from human activity, known as anthropogenic processes, are considered in emission studies. Natural decomposition processes, such as aerobic decomposition, are known as biogenic processes. If the biogenic source materials are grown on a sustainable basis, the associated emissions are considered to close the loop in the natural carbon cycle and are usually excluded from the analysis i.e. the assumption is that biogenic sources of carbon are part of the natural carbon cycle, where the carbon dioxide absorbed by growing plants is in balance with the carbon dioxide emitted by the decay of plant matter.

Most greenhouse gas emission calculations use a Life Cycle Assessment (LCA) approach. LCA is a methodology for assessing the environmental impacts associated with a product, process or service throughout its life cycle, from the extraction of the raw materials through to processing, transport, use, reuse, recycling or disposal. For each of these components of the life cycle the use of resources and the associated environmental impacts are determined. This has the added benefit of identifying possible areas for improvement. The methodology is particularly powerful for comparing products, processes or services designed to fulfil the same process, as is the case in this study. There are two ISO standards specifically designed for LCA application, namely ISO 14040:2006, which describes the principles and framework for LCA and ISO 14044:2006, which specifies requirements and provides guidelines for LCA (Reference 18).

Independent LCA calculations of greenhouse gas emissions for apparently similar situations often show widely differing results. This is due to variations in real-life data for a given activity (e.g. freight transport emissions), ill-defined model boundaries (e.g. excluding activities that make a significant contribution such as support infrastructure), partial life cycles (e.g. excluding raw material extraction or end-of-life disposal), double counting (e.g. transport emissions already included in process emissions), the exclusion of embodied energy (e.g. the energy consumed in all the processes associated with the construction of a factory), poor assumptions and process not represented in sufficient detail (e.g. production losses in manufacturing) and the use of inappropriate data (e.g. process energy costs in one country being applied to a manufacturing process in another).

It is therefore essential that all processes, material flows and energy flows are identified in a LCA calculation and that system boundaries are clearly specified. The greenhouse gas emission model developed for this analysis is based upon calculated emissions for each specified component of the life cycle irrespective of their geographic source. Emission factors, which are the CO_2 equivalent (CO_2E) emissions for a specified unit variable, such as mass or distance over a given time, have been taken or derived from a range of secondary sources. The emission factors are multiplied by the appropriate unit variables and the resultant emissions summed to give the total greenhouse gas emission for the centralised or household treatment of food waste.

For this analysis, calculations were first performed to determine the main contributory factors and the life cycle boundaries. A description of the final scope of the centralised and household treatment models is provided in Section 3. The main assumptions necessary in the development of the models and the sources of data used in the calculations are provided in the Appendices.

3. Specified Food Waste Management Systems

In this type of study it is not possible to define "average" or "representative" food waste management systems. Reference management systems have therefore been specified for both the centralised and household approaches that contain the major components of typical strategies and use realistic and consistent input variables where possible.

The options for centralised waste management facilities are profiled in the research study by Enviros Consulting (Reference 12). For this comparison, an in-vessel treatment facility was selected as the reference treatment plant, where fully automated aerobic digestion is undertaken within an enclosed container.

The centralised system model includes the kerbside collection of uncontaminated, segregated food waste from households in purpose supplied Food Waste Collection Receptacles (FWCRs), transportation to the in-vessel treatment plant, bulk transportation of the resulting compost to suitable application sites and the subsequent spreading of the compost on the land. A transfer station can be included in the model to allow for the bulk transportation of the waste to the treatment plant where this is more cost or emission efficient.

The Green Cone FWD system (Reference 19), which was studied in some depth during a Defra funded trial (Reference 20) and is well characterised (e.g. References 14, 21 & 22), has been used as the reference FWD for this study. The household treatment model assumes the same uncontaminated segregation of the food waste but with the waste being put directly into a supplied FWD. The reference FWD accelerates the natural decomposition process by raising the temperature, maintaining aerobic conditions and encouraging the growth of the micro-organism population. The food waste is converted into water, CO_2 and a small residue of humic substances comprising lignin and protein.

Greenhouse gas emissions associated with the construction of capital plant such as manufacturing, process and treatment facilities, transport vehicles and associated infrastructure are often excluded from this type of analyses. This is mainly because the contribution is small relative to that from operational activities but also due to the availability of detailed information. However, for the purposes of this comparison of a system requiring significant capital investment and a system that involves very little major plant, the embodied energy greenhouse gas emissions of dedicated plant and equipment have been included for consistency. Thus, the in-vessel treatment plant, the waste collection and transport vehicles and the FWCRs and FWDs are included. The embodied energy emissions associated with the ships and freight delivery vehicles for the FWCRs and FWDs are not included as these are not dedicated to the system model but used to a much larger extent for other applications. This also applies to the bulking, handling, moving and loading vehicles, tractors and manure spreaders.

Because of the complexity of the LCA calculations, greenhouse gas emissions from secondary and indirect sources that individually contribute less than about one per cent of total system emissions are generally not included in this analysis. This covers the embodied and operational energy emissions associated with management offices and infrastructure, work related transport and consumption of food by staff, non-dedicated plant and equipment (e.g. transport and energy infrastructure), minor components and consumables (e.g. operatives uniforms, cleaning products) and health and safety (e.g. plant, transport and staff emergency service support for accidents and fire and the emissions associated with a fire itself). With regards this final point it is worth noting that the number of fatal incidents involving both staff and the general public in the UK waste industry is over ten times the national average and that overall accident rates are four times the national average (Reference 23).

The sources of greenhouse gas emissions for the reference centralised waste management system can be separated into 12 major components, which may be sub-divided further:

- Manufacturing/construction and end-of-life recycling/disposal of the dedicated waste treatment plant and equipment
- Manufacturing and end-of-life recycling/disposal of the dedicated waste collection and bulk transport vehicles
- Bulk transportation of the FWCR units and/or feedstock materials
- Manufacturing and end-of-life recycling/disposal of the FWCRs
- Household delivery and end-of-life collection of the FWCRs
- Segregated household food waste collection and transportation to a transfer station (if required)
- Bulk transportation of the waste from the households or transfer station to the treatment plant
- Handling and bulking of waste at the transfer station
- Treatment of the waste in an in-vessel composting plant
- Bulk transportation of the compost end product from the treatment plant to application sites
- Application of the compost to the land using agricultural tractors and spreaders
- Compost decomposition on the land

The household waste management system has 4 major components:

- Bulk transportation of the FWD units and/or feedstock materials
- Manufacturing and end-of-life recycling/disposal of the FWDs
- Household delivery and end-of-life collection of the FWDs
- Decomposition of the food waste in the FWD

4. Results of Calculations

The base case calculation using the Excel Workbook Greenhouse Gas Emission Estimator for Household Food Waste is reproduced in full in Appendix C. Although the results presented here are for a UK situation, they are broadly applicable to other western countries.

The number of households in the base case of 250,000 represents 1% of the total for the UK, with the average annual quantity of food waste of 0.2 tonne per household being taken from Reference 21. Using this specification, separate calculations were performed for centralised and household food waste management strategies to highlight the differences in greenhouse gas emissions from both approaches. Realistic optimal household food waste management strategies will be a combination of both centralised treatment and household treatment. The relative proportions of the two approaches will depend on factors such as household dispersion, the mix of single and multi-occupancy dwellings and socio-economic groupings, the number of households with gardens suitable for FWDs, existing strategies for dealing with other waste streams, the location of centralised treatment facilities relative to population densities and planning consent issues.

Because of the availability of data for benchmarking the model (i.e. checking and validating), the base case represents a combined urban and semi-rural situation (i.e. small towns with dispersed households in between) and excludes very rural environments. For the combined base case, an average of 2 km is travelled by the waste collection vehicles for the co-collection of every tonne of MSW. The sources of data used in the calculations are identified in Appendix B (References 24 to 58) and referenced in the worksheets in Appendix C.

The calculated anthropogenic greenhouse gas emissions for the combined base case centralised treatment approach amount to 2485 t CO_2E/y, with the major contributions coming from the in-vessel treatment plant (42%) and the waste collection operations (25%). This compares to a total of 253 t CO_2E/y for the household treatment approach, where the major contribution is from the manufacturing of the FWD (92%). The total biogenic emission for both systems is 13,383 t CO_2E/y.

The calculated contributions to the anthropogenic greenhouse gas emissions for the combined base case centralised and household treatments of food waste are summarised in Table 1. Although the results are presented in terms of emissions per tonne of waste treated, it should be noted that these values are only strictly applicable to the specified base case outlined above and detailed in Appendix C. The contributions have been separated into emissions associated with the manufacturing/construction, transportation and end-of-life recycling/disposal of the dedicated waste treatment plant, vehicles and FWCRS/FWDs and emissions associated with day-to-day waste and compost operations.

The results in Table 1 show that the emissions associated with the capital plant for both the centralised and household treatment approaches are relatively small, with annualised values of 12 and 5 kg CO_2E/tonne of food waste, respectively. However, the table highlights the major difference in day-to-day operations, where household treatment produces zero anthropogenic emissions and the centralised treatment generates 38 kg of CO_2E/tonne of food waste. This results in total greenhouse gas emissions for the centralised and household treatments of 50 and 5 kg CO_2E/tonne of food waste, respectively.

There are three main contributions to the uncertainty associated with the calculated anthropogenic emissions, namely the assumptions and limitations inherent in the model itself, the soundness of the model described by the input variables and finally the uncertainties associated with set input database values (see Appendix B), such as fuel efficiency and material emission factors.

Table 1. Calculated Contributions to Anthropogenic Greenhouse Gas Emissions for Combined Base Case Centralised and Household Treatments of Food Waste

Phase	Component	Centralised Treatment kg CO2E/t_w	Household Treatment kg CO2E/t_w
Capital plant & associated transportation	Manufacturing/construction & end-of-life recycling/disposal of waste treatment plant	3.77	
	Manufacturing & end-of-life recycling/disposal of waste collection vehicles	0.82	
	Manufacturing & end-of-life recycling/disposal of the bulk waste transport vehicles	0.19	
	Manufacturing & end-of-life recycling/disposal of bulk compost transport vehicles	0.18	
	Bulk transportation of FWCR or FWD units and/or feedstock materials	0.04	0.34
	Manufacturing & end-of-life recycling/disposal of FWCR or FWD units	6.41	4.68
	Household delivery & end-of-life collection of FWCR or FWD units	0.07	0.04
	Total capital plant & associated transportation	**11.48**	**5.06**
Day-to-day waste operations	Segregated household food waste collection & transportation to a transfer station	11.58	
	Handling and bulking of waste at transfer station	0.22	
	Bulk transportation of the waste from transfer station to treatment plant	1.42	
	Treatment of waste in an in-vessel composting plant	19.56	
	Bulk transportation of the compost end product from treatment plant to application sites	2.96	
	Application of compost to land using agricultural tractors & spreaders	2.47	
	Total day-to-day waste operations	**38.21**	**0.00**
	Total anthropogenic emissions	**49.69**	**5.06**

Input variables that are unrealistic, inconsistent or poorly optimised will undermine the reliability of the outputs from the overall model. For example, emissions from the waste collection vehicles are dependent upon vehicle capacity and utilisation, average speed and fuel efficiency, transfer distances and turnaround time, frequency of collections, number of working days and the length of the working day. The model allows for these variables to be individually varied to assist in optimising the inputs to minimise the output. Input variables such as the lifetime and maintenance overhead of capital items were cross-checked with a range of sources. The outputs from individual components of the model, such as the embodied energy of the treatment plant, transport vehicles and FWCR/FWD, have been benchmarked against other published studies.

Assuming that the required system is optimally described by the input variables, the main uncertainty associated with the model outputs is related to the set input database. Published emission factors for apparently similar situations can exhibit a wide range of values, up to a factor of two different, for the reasons outlined in Section 2. Where available, the emission factors used in this analysis were taken from the same secondary source and all emission factors in the set input database were validated against a wide range of published values. These comparisons indicate that the maximum uncertainty associated with individual material values in the set input database is 35%.

The largest single contribution to the total anthropogenic emission for the centralised treatment approach is from the in-vessel treatment plant operations. The quantity of diesel and electricity consumed per tonne of waste treated and the associated emissions are taken from a report for Defra by ERM Ltd. (Reference 8). Comparison of data from the ERM report with other treatment plant analyses (e.g. Reference 56) indicate a maximum uncertainty in the plant emissions of 30%, which translates to a 15% uncertainty in the total emission calculated for centralised treatment.

A range of sensitivity calculations was performed to assess the overall affect of the individual uncertainties on the calculated total greenhouse gas emissions. In addition, sensitivity calculations were carried out to determine the significance of the model boundaries, key assumptions and changes to the base case specification. The main investigations are described below and the results summarised in Table 2.

Waste Collection Efficiency

The second largest contribution to the greenhouse gas emission for the centralised treatment approach is from the waste collection vehicles. Assuming the collections are optimised as far as practical, with each truck utilised every working hour to capacity, the vehicle fuel efficiency is the single most important factor. A 20% improvement in fuel efficiency during the waste collection phase has therefore been modelled to represent the maximum possible error in the base case value or a potential improvement in emissions achieved through technological advances.

A wide range of geo-demographic factors affect the quantity and composition of both the MSW and the food waste generated by a household (Reference 14). The type and mix of households in a local authority area can have a significant influence on the waste collection strategy. The complexity and cost of MSW collection and treatment increases significantly with waste segregation. This has led to the introduction of alternate week collections for different waste streams, which may require different types of collection vehicles. The fortnightly collection of food waste has proved a particularly contentious issue with the public, despite Government assurances that there are no health, safety and environmental problems. WRAP is currently supporting a number of trials of food waste collection arrangements (Reference 13).

The base case model represents the minimum waste collection emission situation, where the segregated food waste is co-collected in a one-pass approach with the rest of the MSW. At the other extreme is the collection of household food waste using dedicated vehicles, which has been modelled in a sensitivity calculation. There are several more likely collection regimes, such as the separate collection of dry recyclables and the segregated co-collection of food waste and the residual MSW. The “dedicated” and “semi-dedicated” collection of food waste has been modelled in sensitivity calculations by reducing the total MSW input from 1 to 0.2 and 0.5 tonne per household per year, respectively. Unlike the combined co-collection base case, the gross and unladen weights of the waste collection vehicles were only adjusted to maintain the average utilisation at 90% and not matched to actual vehicles available on the market.

Use of Food Waste Compost

The use of compost on the land has the major benefits of improving the properties of the soil structure and fertility, mitigating land degradation and rehabilitating degraded land. If the compost produced by the in-vessel treatment process can be shown to be of sufficient quality to avoid the production of inorganic fertilisers, soil improvers or the use of peat, their greenhouse gas emissions can be offset against those generated by the centralised treatment process.

However, farmers and growers require convincing about the quality of compost made from household food waste with regards chemical and physical contamination, phytotoxicity, weed propagation and the transference of pathogens to plants and animals. There may also be limited markets for the compost in food production due to public concerns over the food waste feedstock containing GM derivatives, pesticide residues, food products from livestock reared under poor welfare conditions and illegal food imports. Despite reassurances from experts and governments, major food scares such as BSE/vCJD and avian influenza change people’s buying habits, albeit temporarily. A possible knock-on effect from such scares is the impact on the sales of food products grown or reared using compost made from feedstock containing household food waste, with the organic food market being particularly vulnerable.

The transportation of the compost from the treatment plant and its application to the land using agricultural tractors and spreaders should not be included within the system boundary where it is simply displacing the application of other composts. However, because of the possible concerns mentioned above, the majority of food waste compost may have to be spread on non-agricultural land that does not normally receive treatment. In this case the benefits are arguable and the emissions are more associated with disposal. It is also worth noting that the quantity of household food waste is only about 7% of the organic waste produced by the agricultural sector in the form of manure, slurry, and crop residues.

The ERM report (Reference 8) concluded that centralised composting “performs relatively poorly in carbon and energy terms as the use of compost products displaces alternatives which tend themselves to be organically-derived (with the exception of inorganic chemicals fertilisers) and are therefore not energy or carbon intensive to produce in the first place. The use of compost is likely to convey additional benefits, for example in terms of soil structure, fertility or the maintenance of carbon sinks, but these factors are difficult to quantify in carbon terms …”.

The impact of assuming that the food waste compost provides a high quality replacement for emission intensive alternatives has been calculated. The ERM report

(Reference 8) uses the relatively high offset value of 16.2 kg CO_2E per tonne of compost and for consistency is used in this analysis. It has been assumed that the emissions associated with transporting the compost and its application on the land are the same as the alternatives it is replacing and are therefore omitted from the total.

Significance of Recycling and Manufacturing Location

Although the contribution from embodied energy emissions is small relative to operational emissions for the centralised system, the significance of using recycled material in manufacturing feedstock and of recycling and reusing materials at the end-of-life has been investigated. A major assumption in this analysis is that the UK can provide the facilities for end-of-life reuse and recycling. The industrial growth of countries such as China has resulted in the export of significant quantities of end-of-life plastic, aluminium, iron and steel products. This export is limiting the availability of recycled material in Europe and resulting in the use of more primary material. Because a realistic calculation of emissions involving the export and recycling of material in China involves many unknowns, a sensitivity calculation has been performed to scope potential uncertainties by simply excluding the benefits of recycling capital plant materials.

The second largest contribution to the total emission calculated for the household treatment approach results from the transport by ship of the reference FWD from its manufacturer in Canada to the UK. Whilst local manufacturing of the FWDs would avoid the need to ship the final product to the UK, it would be necessary to ship primary feedstock. In addition, the benefit would be lost of indirect energy emissions in Canada being half those of the UK, which outweighs the shipping emissions by a factor of six. The base case analysis assumes that the recycled feedstock for the manufacture of the FWCR is sourced in the UK.

Household Dispersion

Waste management costs per household for rural areas are typically twice that for the urban situation because of the collection distances involved, with an associated increase in transport emissions. Waste collection statistics for rural environments are not readily available and to examine the sensitivity of the total anthropogenic emission to household density the combined urban and semi-rural base case was modified, with the average distance between households increased from 0.04 km to 0.20 km, the transfer phase at the start and end of the collection route increased from 5 km to 10 km and an associated increase in the average collection speed from 6 km/h to 12 km/h and increase in vehicle fuel efficiency of 40%. In addition, the distance from the transfer station to the treatment plant was increased from 18 km to 25 km for the rural situation. For consistency, the same reference waste collection vehicle was used for the rural co-collection base case as the combined co-collection base case, even though the average utilisation reduced to 78%.

To provide a measure of the potential uncertainty associated with the specified average 0.04 km between households in the combined urban and semi-rural co-collection base case, the distance was varied without any change in the average collection speed, fuel efficiency and transfer distances.

The anthropogenic emission calculations presented in Table 2 for 250,000 households each producing on average 20% of food waste in 1 tonne of MSW per year show the sensitivity of the results to household dispersion (i.e. urban-rural composition) and the key modelling assumptions. The results involving dedicated and semi-dedicated collection strategies should be considered as indicative as the sizing of the waste collection vehicles has been performed to achieve 90% utilisation and not taken into actual available vehicles as in the base case calculations.

Table 2. Summary of Anthropogenic Greenhouse Gas Emission Sensitivity Calculations for Centralised and Household Treatment of Food Waste

Case (250,000 households, 20% food waste in 1 tonne MSW/household/year)	**Centralised Treatment (t CO_2E/y)**	**Household Treatment (t CO_2E/y)**
Combined urban & semi-rural co-collection base case	2485	253
Combined co-collection base case with 20% fuel efficiency increase for waste collection vehicle	2377	253
Combined co-collection base case with no recycling of capital plant materials	2811	253
Combined co-collection base case without compost transport/land application	2205	253
Combined co-collection base case without compost transport/land application & with offset applied	1800	253
Combined base case with semi-dedicated food waste collection vehicle	3051	253
Combined base case with dedicated food waste collection vehicle	4744	253
Rural co-collection base case	3675	260
Rural base case with semi-dedicated food waste collection vehicle	5418	260
Rural base case with dedicated food waste collection vehicle	10713	260
Rural base case with semi-dedicated food waste collection vehicle & without compost transport/land application & with offset applied	4733	260

The sensitivity calculations show that the total anthropogenic emission for the combined centralised system base case reduce by about 5% for a 20% increase in the fuel efficiency of the waste collection vehicle and increase by 13% if capital plant materials are not recycled. If the compost produced from food waste by the treatment plant is assumed to replace existing emission intensive products, the emissions reduce by 14 kg CO_2E/tonne of food waste, which is 28% for the centralised combined base case.

Increasing the average distance between households to represent a rural environment increases the equivalent combined urban and semi-rural greenhouse gas emission by a factor of 1.5 to 2.3, depending on the waste vehicle collection strategy. In terms of day-to-day operations, where household treatment produces zero anthropogenic emissions, the centralised combined co-collection emissions increase from of 38 kg CO_2E/tonne of food waste to 198 kg CO_2E/tonne for dedicated collection in a rural environment. The greater collection and transfer distances involved in the rural environment increases the annualised embodied energy emissions from 12 kg CO_2E/tonne of food waste to 16 kg CO_2E/tonne. The dedicated collection vehicle strategy that produces the upper end value for the rural environment is likely to be impractical on operational and cost grounds.

As a measure of the uncertainty associated with the specified average distance between households, a 1 m reduction in the 0.04 km combined base case input value results in a reduction of 2.6% in waste collection vehicle emissions and 0.6% in the total centralised anthropogenic greenhouse gas emissions.

The total uncertainty associated with the calculated emissions for the household treatment of food waste will be less than the centralised treatment approach because the waste management strategy can be better defined due to fewer components in the life cycle and the availability of actual data. The exclusion of secondary and indirect sources discussed in Section 3 could result in an underestimate of greenhouse gas emissions for the centralised system of up to 4%, which is included in the total uncertainty. To a first approximation, the overall uncertainty associated with the calculated combined environment emissions for the centralised and household systems are of the order of 45% and 35%, respectively. Due to the lack of availability of actual collection data for benchmarking rural environments, the overall uncertainty for the calculated centralised emissions will be greater than the combined urban and semi-rural situation.

5. Conclusions

There are two basic acceptable approaches for dealing with household food waste, namely centralised treatment using a biological process, such as in-vessel composting or anaerobic digestion, and household treatment using Food Waste Digesters (FWDs). A typical FWD is a purpose designed and built unit that is located in a household's garden for the disposal of all food waste, including vegetable scraps, raw and cooked meat or fish, bones, dairy products and other organic food waste such as bread and pasta.

Greenhouse gas emissions have been calculated in terms of CO_2 equivalents (CO_2E) for the life cycles of specified centralised and household management strategies. The centralised approach includes the kerbside collection of uncontaminated, segregated food waste from households, transportation to an in-vessel plant and treatment, bulk transportation of the resulting compost to suitable application sites and the subsequent spreading of the compost on the land. The household treatment approach is based on the same uncontaminated segregation of the food waste but with the waste being put directly into a FWD. All significant components of the life cycles of both the centralised and household management strategies for food waste have been included in the calculations.

The greenhouse gas emissions associated with manufacture and end-of-life disposal of the capital plant, such as the in-vessel treatment facility, the waste transport vehicles and the FWDs, are relatively small. Depending on household dispersion, annualised values for the centralised approach range from about 12 to 16 kg CO_2E/tonne of food waste, with a value for household treatment of about 5 kg CO_2E/tonne for all situations.

The major contribution to the anthropogenic greenhouse gas emissions for the centralised approach arises from the day-to-day operations of the transport vehicles and the treatment plant, which annually generate about 38 to 198 kg of CO_2E/tonne of food waste, depending on household dispersion and the waste collection strategy. By contrast, the household treatment approach using FWDs produces zero day-to-day operational anthropogenic emissions.

For a combined urban and semi-rural environment with an average household separation distance of 0.04 km, the calculated total annual emissions for the centralised collection and in-vessel treatment of food waste range from about 50 to 95 kg CO_2E/tonne of food waste depending on the collection strategy. This range increases to about 74 to 214 kg CO_2E/tonne of food waste for a rural environment with an average household separation of 0.20 km. These figures would reduce by 14 kg CO_2E/tonne if the compost produced by the in-vessel treatment plant could genuinely replace existing emission intensive inorganic fertilisers, soil improvers or peat. The total anthropogenic greenhouse gas emission for household treatment is about 5 kg CO_2E/tonne of food waste.

In summary, the anthropogenic greenhouse gas emissions from the centralised collection and in-vessel treatment of food waste are greater than those associated with household treatment by about a factor of between 10 and 40.

Realistic optimal household food waste management strategies for the majority of areas, in terms of delivering targets, minimising costs and achieving acceptable health, safety, environmental and operational risk management, should be a combination of both centralised treatment and household treatment. The relative proportions of the two approaches will depend on factors such as household dispersion, the mix of single and multi-occupancy dwellings and socio-economic groupings, the number of households with gardens, existing strategies for dealing with other waste streams, the location of centralised treatment facilities relative to population densities and planning consent issues.

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Appendix A

Greenhouse Gas Emission Estimator for Household Food Waste

A1. Introduction

This Appendix describes the model developed to estimate the greenhouse gas emissions that would be expected to arise from the life cycles of typical centralised and household approaches to dealing with household food waste. Justification of the main assumptions necessary in the development of the model and the sources of data used in the calculations are also set out in the Appendix. The model has been specified in an Excel workbook (Greenhouse Gas Emission Estimator for Household Food Waste) comprising four worksheets, which is outlined in Appendix B. Beta version worksheets of the two systems described in the main text of this report are provided in Appendix C.

A2. Modelling Approach

The model developed for this analysis includes the greenhouse gas emissions associated with the energy consumed in day-to-day plant and transport operations and the embodied energy resulting from both energy and non-energy sources, expanded to include the end-of-life treatment. The model does not include the embodied energy of the food waste itself.

In practice, some emissions can be assigned as either operational or embodied energy emissions. For example vehicle tyre wear is an operational emission. However, as in this model, the retreading of a worn tyre results in new additional material that can be included as part of the embodied energy emissions of the manufactured vehicle.

Time dependent input data to account for technological advances, changes in the energy mix for electricity production or transport and variations in other factors, such as the quantity of food waste, can be modelled using sensitivity analyses or repeating the analysis over a range of time periods and summing the results. A consequence of the use of emission factors in the model is that emissions are a linear function of their unit variable (mass or distance). As a result, non-linear or step function variables resulting from manufacturing throughput affects and waste volume treatment affects are not modelled explicitly. However, as with possible time dependent variables, this can be accounted for by performing a series of calculations using appropriate emission factors. The model does assist in optimising the input variables related to waste collection.

The mixes of energy sources used in published estimates of emissions factors reflect those of a particular country or some form of global average. Such values have therefore been adjusted to account for a more appropriate fuel mix and, where necessary, other variables such as the associated mass of material and transport distance. The same emission factors were used for both the centralised and household treatment analyses to reduce comparison uncertainties through systematic inconsistencies rather than random errors. The model was developed using a common LCA approach that adhered to the basic principles of the relevant ISO standards.

To allow for direct comparison of the greenhouse gas emissions from the centralised and household treatment approaches, the main contributory gases have been converted to carbon dioxide equivalents (CO_2E) using the standard conversion factors (Reference 17).

A3. Embodied Energy Emissions

A3.1. End-of-Life Treatment

Over the life expectancy of the capital plant and equipment employed in this analysis the rates of recycling will increase significantly, particularly as new technologies are introduced. This is being driven to a large extent by EU legislation such as the Landfill Directive, the End-of-Life Vehicle (ELV) Directive and the Waste Electrical and Electronic Equipment (WEEE) Directive. The landfill disposal of the vast majority of materials making up the plant, equipment and infrastructure for the centralised and household treatment of food waste will no longer be an option over the timescales involved.

The construction industry already has a high collection rate of up to 99%, which means that most of the available material is recycled in one form or another (Reference 24). The material collection rate for the automotive sector is also very high at approximately 95%, resulting in most of the steel recovered for recycling. About 85% and 87% of steel is recycled from the construction and automotive sectors, respectively (Reference 25). According to the Aluminium Federation (Reference 26), virtually 100% of new aluminium is recycled and 73% of aluminium from long life products.

ISO 14041 recommends the procedure of system expansion, which means expanding the system to include end-of-life recycling. Materials are recycled either in “closed-loop” or “open-loop” processes. Closed-loop means that an end product is recycled into the same end product. Open-loop means that the secondary end product is different than the primary end product and often occurs when a material is changed or degraded by the recycling process. Allocation principles and procedures apply to recycling situations, where specific inputs and outputs are shared by more than one system. In such cases, the greenhouse gas emissions related to the extraction and processing of the raw materials and the final disposal of end products are shared with subsequent product life cycles.

In this analysis, recycling has been treated using the “substitution method”, where recycled material with the same inherent properties as the virgin primary material substitutes for primary material in the production of an end product. This approach is particularly applicable to aluminium, iron and steel. Where the recycled material has different properties to the primary material but is still serviceable, as in the case of mechanical recycled plastic described below, an allocation procedure using the so-called “value-corrected” substitution approach is appropriate. This method assumes that the substitution ability is reflected by the ratio between the market prices of the recycled and primary material.

When using the substitution method there is no requirement to know the fraction of recycled material entering the system, since only the unrecoverable material during the complete life cycle of the product is considered. However, IS0 14041 requires that allocation procedures be applied consistently to similar inputs and outputs of the system under consideration. Where value-correction is applied to recycled outputs it also has to be applied to the system inputs.

The model uses two basic end-of-life options. The first is the recycling of a segregated material through remelting, refining and reforming into a new base material equivalent to original. The life cycle of the dedicated plant and equipment was considered to end when the recycled material from the plant and equipment was rendered in a usable form for another system e.g. equivalent primary iron/aluminium ingot or plastic polymer. The greenhouse gas emissions related to the original extraction and processing of the raw materials and the final fate of the products were shared with subsequent product life cycles or other production lifecycles.

The second option is the reuse or disposal of a segregated material through reworking and combining into a useable product or energy source. This approach often makes the material unrecoverable in the future, where even if the technology existed the practicalities and costs would make it prohibitive e.g. rubber used in road construction. The "ownership" of the emissions associated with the production of the primary material in this situation requires careful consideration. The recycling of concrete, tyres and other materials employed in the dedicated plant and equipment fall into this category. In the model the primary production emissions are assigned to the system, with any appropriate offset.

In all processes used to convert raw materials into end products there is an inevitable arising of scrap material. This results from the start-up and shutdown periods of the processing machinery, from out of specification products and from quality control samples. Material of this type is termed 'industrial scrap', where the recovered end product is generally referred to as 'reprocessed' material to distinguish it from 'recycled' material, which is derived from post-use products. From an analysis perspective, reprocessed and recycled material can be treated in the same way.

A3.2. Materials

The most significant materials in terms of embodied energy emissions in this analysis are concrete, aluminium, iron/steel, plastic and the materials used in commercial vehicle tyres. These materials cover 99% by weight of the materials in the in-vessel treatment plant (excluding materials used in transport infrastructure), 96% of those in the vehicles and 100% of the FWCR and FWD.

An understanding of the extraction and processing of the relevant raw materials into products and the options for recycling materials at end-of-life is helpful in understanding the derivation of the relationships described in Section A3.3. The following references and background information are therefore included.

A3.2.1. Aluminium and Steel

The aluminium manufacturing and recycling processes are described in Reference 27. The perfluorocarbons (PFCs) tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) emitted during the reduction of alumina to aluminium in the primary smelting process are the most potent greenhouse gas emissions in this analysis. The source of fluorine for CF_4 and C_2F_6 is the molten cryolite (Na_3AlF_6) where the reduction of alumina occurs. PFCs are formed when the fluorine in cryolite reacts with the carbon in the anode and cathode. These carbon components, which are produced from coal, are consumed during the electrolytic reduction process and represent a source of embedded energy.

The steel manufacturing process is described in Reference 28, with information on recycling in References 24 and 25.

A3.2.2. Plastic

The polypropylene and high density polyethylene (HDPE) used in the manufacture of the FWCRs and the FWDs are both olefin polymers. These polyolefins are produced commercially from olefin monomers using three main techniques, namely high pressure technology, solution or slurry processes and gas phase polymerisation. The raw polymer is then bulk shipped to a compounder, which mixes it with additives to provide the polymer with the required properties. The polymer is then shipped to an injection moulder, where further additives such as colouring may be added before the polymer is transformed into a finished product. The manufacturing of plastic from extraction through to the injection moulding of end products is described in References 29 to 31.

Plastic is not recycled to the same extent as iron/steel and aluminium for a number of reasons, not least the availability of suitable technologies. However, the end-of-life treatment of plastics is undergoing significant developments. The conventional approach is mechanical recycling, where the plastics are reformed into moulding granules to make new products. The complete process involves collection, sorting, melting, size reduction, washing and drying. Following sorting, the plastic is either melted down directly and moulded into a new shape or melted down after being shredded into flakes and processed into granules called regranulate. This is then re-compounded with additives and/or more virgin raw material, extruded and chopped into pellets ready for reuse.

Advanced recycling technologies cover chemical recycling and feedstock recycling that convert solid plastic materials, through the use of heat and pressure, into smaller molecules. These chemical intermediates, usually liquids or gases, but sometimes solids or waxes, are suitable for use as feedstock for the production of new petrochemicals and plastics. Feedstock recycling is defined as a change in the chemical structure of the material, where the resulting chemicals are used for a purpose other than producing the original material. The term feedstock recycling is most often applied to the thermal depolymerisation of polyolefins into a variety of smaller hydrocarbon intermediates. Chemical recycling implies a change of the chemical structure of the material such that the resulting chemicals can be used to produce the original material again. The term chemical recycling is most often applied to depolymerisation back to monomers. The resulting synthesis chemicals can then be used to make new plastics that can be indistinguishable from the primary polymers.

Alternatives to the conventional and advanced recycling of plastics include energy recovery through cement kilns and municipal solid waste incinerators.

A3.2.3. Concrete

Concrete is a mixture of cement (typically 12% by weight), sand (34%), aggregate (48%) and water (6%), with actual proportions dependent upon the application. The main contributor to the greenhouse gas emissions related to concrete is in the manufacturing of cement. The processes involved in the production of cement and concrete are described in Reference 32. At its end-of-life concrete is used as hardcore for new building projects or crushed and used in place of virgin aggregate, such as sand and gravel, to manufacture new concrete. Useful descriptions of the issues associated with the life cycle of concrete and embodied energy and emission data are provided in References 33 to 35.

A3.2.4. Vehicle Tyres

The materials used in the manufacture of vehicle tyres include natural and synthetic rubber, carbon black, steel, zinc, silica, sulphur, textile materials and aromatic oils. A vehicle tyre can be considered to consist of a carcass, which accounts for about 70% of the weight of a car tyre, and the tread. During use, road wear removes the tyre tread and eventually renders the tyre unsafe.

Retreading is a generic term for tyre reconditioning, which extends the life of a worn tyre for its original purpose by the addition of new material and saves the energy and resources required to produce a new tyre. Under normal operations the tread rubber is the only part of a tyre to wear away, with the main carcass structure of the tyre remaining intact. Retreading involves the removal of the worn tread from the used tyre surface, followed by its replacement with new rubber compounds. According to the Retread Manufactures Association, all major truck tyre manufacturers produce tyres for multiple lives (Reference 36). A recent study into the environmental benefits and impacts of retreading (Reference 37) states that a truck tyre can be retreaded up to four times to prolong its life to almost 600,000 km.

Whilst reducing the number of tyres that need to be produced, retreading only defers any reuse and disposal. The steel strengthening cord in the carcass can be recycled into equivalent primary material. Shredding or crumbling processes have been developed to form the rubber into granules. These are used in various applications including road surfaces, where the pellets are mixed with bitumen to prolong road lifetime and reduce the amount of road noise, and in playgrounds to provide a softer surface. End-of-life tyres are also used as an energy source, both to burn to generate electricity and in cement kilns.

A3.3. Derivation of Model Relationships

This section sets out the derivation of the equations used in the model to calculate the embodied greenhouse gas emissions. The relationships provide a good approximation of the required emissions and the principals of ISO 14041.

The embodied greenhouse gas emission associated with the production of each intermediate material in an end product is given by:

$$\varepsilon_p = \varepsilon_e + \varepsilon_b$$

where

> ε_p represents the primary greenhouse gas emission factor for the given intermediate product and includes the emissions associated with the reprocessed scrap (kg CO_2E/kg of base material)
>
> ε_e represents the emission factor for the extraction and processing of “raw” material into a useable “base” material in the form of a metal ingot, plastic polymer etc (kg CO_2E/kg of base material)
>
> ε_b represents the emission factor for the conversion of the “base” material into an intermediate product such as building materials, steel sheet, aluminium sections (kg CO_2E/kg of base material)

The greenhouse gas emission, G' kg CO_2E, for the end product is given by the sum of the greenhouse gas emissions for all the materials in the product and the emissions associated with the energy used in the manufacture/assembly/construction:

$$G' = \acute{\varepsilon}_c + \sum m(\varepsilon_e + \varepsilon_b)$$

where

> $\acute{\varepsilon}_c$ represents the emissions associated with the total energy used in the manufacture/assembly/construction of final end product (e.g. vehicle, plant) using the intermediate products (kg CO_2E/kg of end product). The total emission for the process is used because emissions are not generally attributed to individual materials or components.
>
> m is the mass of material used to produce the final end product, which includes the scrap produced in the manufacture/assembly/construction phase (kg)

Over the complete life cycle of a given system, the end-of-life treatment of each of the materials in the final end product should be included (system expansion).

Firstly, the emissions associated with the disassembly or demolition of the end product and the segregation of materials are included. As with the energy used in the manufacture of the end product, these emissions are generally not available for the individual materials. Hence, the total greenhouse gas emission including disassembly/demolition and segregation into separate materials, G'' kg CO_2E, for the end product becomes:

$$G'' = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m(\varepsilon_e + \varepsilon_b)$$

where

> $\acute{\varepsilon}_d$ represents the emission factor for the disassembly/demolition and segregation of the final end product (kg CO_2E/kg of end product)

Secondly, the emissions associated with the end-of-life treatment must be included. As outlined above, this may be recycling into a base material equivalent to the original, into a base material that can fulfil most of the requirements of the original base material, into a new base material with qualities applicable to other applications or as a fuel source.

The substitution method greenhouse gas emission factor is given by:

$$\varepsilon_{er} = (1 - f_o)\varepsilon_e + f_o\varepsilon_r$$

where

> ε_{er} represents the greenhouse gas emission factor attributable to a base material in a system with a fraction f_o recycled output base material that is equivalent to the original (kg CO_2E/kg of base material)
>
> ε_r represents the emission factor for the recycling of the segregated material (kg CO_2E/kg of base material)
>
> f_o is the fraction of material recycled in the output base material

The value-corrected substitution method greenhouse gas emission factor is given by:

$$\varepsilon_{erq} = (1 - f_i + f_i q_i - f_o q_o)\varepsilon_e + f_o\varepsilon_r$$

where

> ε_{erq} represents the greenhouse gas emission factor attributable to a base material in a system with $(1 - f_i)$ primary input material, f_i recycled input material of value/quality q_i and f_o recycled output base material of value/quality q_o
>
> f_i is the fraction of material recycled in the input base material
>
> q_i is the quality/value of material recycled in the input base material
>
> q_o is the quality/value of material recycled in the output base material

The total greenhouse gas emission including disassembly/demolition, segregation and recycling, G kg CO_2E, for the end product becomes:

$$G = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m((1 - f_i + f_i q_i - f_o q_o)\varepsilon_e + \varepsilon_b + f_o\varepsilon_r)$$

Thus, with equivalent inputs and outputs and no quality/value change:

$$q_i = 1 \;\&\; q_o = 1$$

$$G = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m((1 - f_o)\varepsilon_e + \varepsilon_b + f_o\varepsilon_r)$$

For equivalent inputs and outputs with no quality/value change and all materials recycled:

$$q_i = 1,\ q_o = 1 \;\&\; f_o = 1$$

$$G = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m(\varepsilon_b + \varepsilon_r)$$

For equivalent inputs and outputs with no quality/value change and no material recycled:

$$q_i = 1,\ q_o = 1 \;\&\; f_o = 0$$

$$G = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m(\varepsilon_e + \varepsilon_b)$$

Greenhouse gas emission data for individual materials are most readily available for virgin or primary material (ε_p) and recycled or secondary material (ε_s), where:

$\varepsilon_p = \varepsilon_e + \varepsilon_b$
$\varepsilon_s = \varepsilon_b + \varepsilon_r$

For equivalent inputs and outputs with no quality/value change where $q_i = 1$ & $q_o = 1$:

$$G = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m((1 - f_o)\varepsilon_p + f_o\varepsilon_s)$$

For equivalent inputs and outputs with no quality/value change and all material recycled where $q_i = 1$ & $q_o = 1$ & $f_o = 1$:

$$G = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m\varepsilon_s$$

For equivalent inputs and outputs with no quality/value change and no material recycled where $q_i = 1$ & $q_o = 1$ & $f_o = 0$:

$$G = \acute{\varepsilon}_c + \acute{\varepsilon}_d + \sum m\varepsilon_p$$

The approach described above takes account of unrecoverable losses through the breakage of materials into small fragments, erosion, oxidation etc. by attributing the emissions associated with the loss of material to the system under study. The calculated emission factor for each stage of the life cycle should include any emissions related to production losses and transportation, although where these are particularly significant they may be treated separately.

A3.4. Treatment Plant

Published data on the embodied energy of buildings per unit floor area exhibit wide differences due to variables such as the number of floors, the materials employed and the recycled content, location, service requirements and maintenance overhead during the buildings lifetime (e.g. References 38 to 41). There are also the issues outlined in Section 2 of the main text regarding the specification of the model and whether factors such end-of-life demolition and recycling are included. The maintenance and refit overhead is very dependent on the type of building and any change of use over its lifetime (Reference 39).

In-vessel composting plants are large enclosed structures constructed mainly from concrete and steel, typically containing centrifugal blowers, scrubbers and biofilters. Instrumentation detects conditions throughout the plant and basically controls batch moisture content, temperature, oxygen and carbon to nitrogen ratios. Prior to composting, the food waste must be mixed with other shredded biodegradable organic waste in a pre-treatment facility. Also associated with in-vessel treatment plants are storage or maturation facilities, mobile loading equipment and large areas for vehicle movements. The model developed for the analysis presented in the main text contains a specification for a 20,000 tonne throughput in-vessel treatment plant, together with its associated facilities and equipment. The specification is based on a representative mass for each of the major materials taken from the Environment Agency's Waste and Resources Assessment Tool for the Environment (WRATE) database (Reference 42).

The end-of-life assumption for the iron and steel is that 95% is recycled, which is modelled using the substitution approach. As outlined in Section A3.2.3, concrete can be recycled into concrete aggregate, thereby avoiding the greenhouse gas emissions associated with the extraction, processing and transportation of virgin aggregate. As the recycling emissions are approximately the same as those associated with producing the virgin aggregate, the system concrete emissions are simply given by the product of the emission factor and mass. Excluding materials used in the site transport infrastructure, the other materials cover a wide range of metals, wood, glass, plastic, paint etc. and represent about 1% of the total. The reuse and recycling of these materials is limited and the model assumes that the emissions from recycling activities offset any benefits. The total material emission factor for the plant was calculated using the University of Bath Inventory of Carbon and Energy (ICE) database (Reference 43). There is no greenhouse gas emission factor for bitumen, which is used to varying degrees in tarmacadum surfaces, in the ICE database due to both availability and the very wide range of published values. For the purposes of this analysis a nominal quantity of tarmacadum was included with the other materials. The total embodied energy emission factor for the in-vessel treatment plant was validated by comparisons with other calculations for buildings and equipment (References 38 to 41).

The material embodied energy emissions were increased by 5% to account for losses during construction. The emissions associated with the energy used at the site to construct the plant were estimated to be 5% of the total material embodied energy emissions (Reference 38). A maintenance and refit overhead over the lifetime of the plant of 15% of the total material emissions has been included in the analysis. The emissions associated with demolition of the plant and the segregation and transport of the separated materials was assumed to be 15% of the construction emissions based on Reference 38.

In the model, the total greenhouse gas emissions associated with the embodied energy of the reference treatment plant are linearly scaled to the required throughput calculated from the input variables. The capacity of the plant is increased by 20% over the annual mass of waste collected to allow for seasonal effects. The worksheet output provides an emission factor per kg of compost produced.

Although the majority of the embodied energy emissions are produced at the plant's start-of-life, the emissions have been divided equally on an annual basis over a plant lifetime of 25 years (Reference 12). Centralised biological treatment systems require a feedstock of combined food waste and other green waste to produce quality compost. In this analysis only the emissions attributable to the collection and treatment of the food waste fraction are considered i.e. the emissions associated with the necessary additional plant capacity and operations are attributable to the other green waste.

A3.5. Transport Vehicles

Embodied energy estimates are included for the dedicated transport vehicles in the system model i.e. waste collection vehicles, bulk waste vehicles and bulk compost vehicles. The embodied energy of the non-dedicated modes of transport are considered a second order impact i.e. FWCR and FWD delivery and collection vehicles, shipping and tractors for compost spreading.

As with buildings, the published embodied energy emissions associated with transport vehicles show a wide variation. In the model, the emissions for the waste collection and bulk transport vehicles are calculated on the basis of the breakdown of materials in the 20 tonne gross weight reference vehicle described in Reference 44. Over 88% of the mass of the truck comprises aluminium and iron/steel, with the remainder made up of plastic, rubber, glass, paint and other secondary materials. The substitution approach was used for the aluminium and iron/steel. Reference 44 also includes an estimate of the mass of maintenance parts and tyres for a driven distance of 900,000 km over the 10-year lifetime of the vehicle. On the basis of the user input data, the mass of spare parts for the reference vehicle are linearly scaled and added to the manufactured vehicle mass.

The model allows for the retreading of vehicle tyres, which is likely to become standard practice for commercial vehicles. Based on the input life expectancy of the tyre's tread, the mass of the tyre, the number of tyres on the vehicle and the number of retreads per tyre, the model calculates the mass of each material used in the construction and retreading of the tyres over the lifetime of the vehicle using the data specification provided in Reference 37. The masses of the individual tyre materials employed over the model vehicle's lifetime are added to the mass of the total manufactured vehicle and parts.

The model calculates the total emission factor associated with the vehicle over its lifetime on the basis of material weighted emission factors. The material emission factors were sourced from the ICE database, with the exception of carbon black that was taken from Reference 45. The total embodied energy emissions were divided by the unladen weight of the reference 20 tonne vehicle to provide embodied energy emissions per tonne of vehicle over its lifetime distance.

Reference 44 includes an estimate of 80 GJ for the energy used in manufacturing, which was converted to emission per tonne of unladen vehicle using a representative fuel mix and the Defra emission data (Reference 46). This was added to the vehicle's material embodied energy emission.

The material embodied energy emissions were increased by 2% to account for material losses during manufacturing. Based upon a range of data, a vehicle lifetime maintenance overhead of 20% of the total material emission has been included in the analysis. The emissions associated with the disassembly of the vehicles and the segregation and transport of the materials was assumed to be 15% of the manufacturing emission.

The design of a waste collection strategy for a given local authority area is dependent on many inter-related variables. Whilst the greenhouse gas emission model is not designed to develop waste collection strategies, to assist the user develop realistic transport operations, the model compares input reference vehicle specifications with capacity requirements calculated on the basis of average speed, fuel efficiency, transfer distances and working times. For the combined urban and semi-rural base case analysis presented in the main text, two reference vehicles were selected to provide the gross and unladen weights of the waste collection, bulk waste and bulk compost vehicles. The Phoenix High Capacity Twin Pack (Reference 47) was selected as typical of the type of vehicle that can be employed for the co-collection of segregated waste with other MSW streams, with gross and unladen weights of 26 tonnes and 15.42 tonnes, respectively. The Volvo FM 300 (Reference 48), adapted as a tipper, was selected as a typical bulk transport vehicle, with gross and unladen weights of 32 tonnes and 12 tonnes, respectively.

The lifetimes of the vehicles are integral values of the in-vessel treatment plant lifetime. Waste collection vehicles have relatively shorter lifetimes before reconditioning or disposal due to the nature of the putrescible loads and the load structures. If a non-integral lifetime is input the assumption is made that the greenhouse gas emissions for the remaining life of the vehicle at the end-of-life of the treatment plant can be assigned to another system.

A3.6. FWCR & FWD

The specification of the FWCR is based upon the product described in Reference 49, which uses 100% recycled polypropylene. It has been assumed in the analysis that the FWCR is manufactured in the UK from locally sourced recycled plastic.

The specification of the reference FWD is provided in Reference 50. The inner cone and the digestion basket are made from 100% recycled polypropylene and the outer cone from 10% recycled HDPE. Only 10% recycled HDPE is used in the manufacture of the outer cone due to injection moulding requirements and to ensure outdoor longevity, particularly with respect to exposure to ultra violet light. A 4.5 litre receptacle made from 100% recycled polypropylene is provided with the system for collecting and carrying the food waste from the kitchen to the FWD. The total weight of the FWD and receptacle is 6.9 kg, with an average recycled content of 64%.

The lifetime of the FWCRs is defined as 0.25 of the treatment plant lifetime compared to 0.5 for the Green Cone FWD to approximately reflect advertised guarantee periods of 5 years and 10 years, respectively (References 19 & 49), and the fact that the average lifetime of the FWCRs is likely to be shorter due to repeated manual handling by waste collection operatives, mistreatment & losses.

To use the value-corrected substitution method (i.e. q_i & q_o have values) it is necessary to know the value of ε_b. The ICE database does not separate out the embodied energy for the various stages of plastic manufacturing or include emissions for recycled plastic. The data provided in References 29 to 31 has therefore been used to derive appropriate embodied energy emission factors, which were increased by 5% to account for manufacturing losses. Generic embodied energy emission factors based on the continual recycling of the plastic material were derived to cover both polypropylene and HDPE, which is acceptable in view of uncertainties involved.

The embedded feedstock energy in the FWCR and FWD plastic could be recovered by incineration at their end-of-life, although gains would be partially offset by a further release of greenhouse gases.

A4. Operational Anthropogenic Emissions

A4.1. Transfer Station

The centralised treatment model allows for the inclusion of a transfer station for the sorting and bulking of waste prior to transportation to the treatment plant. The decision to use a transfer station is mainly dependent on the transport distances from the source of the waste to the treatment plant, as illustrated by the figure in Reference 51.

The centralised system model assumes that the food waste collected from households is perfectly segregated and uncontaminated, thereby requiring no further screening and sorting. Therefore, where a transfer station is included in a specified system, its function is solely as a bulking facility and only 10% of the emissions estimated to be associated with a transfer station in Reference 8 are ascribed in the model.

A4.2. Treatment Plant

Both anthropogenic and biogenic greenhouse gas emissions occur during in-vessel processing. The anthropogenic emissions originate from the use of stationary and mobile machinery and electricity. Composting operations may include front-end loaders, bulldozers, shredders, screening equipment and mixing equipment. The quantity of diesel and electricity consumed per tonne of waste treated by the in-vessel plant and the associated emissions are taken from the ERM report (Reference 8).

As pointed out in Section A3.4, food waste must be mixed with an appropriate proportion of other green waste to produce quality compost. Issues related to the collection, pre-treatment and availability of this green waste have not been considered. It has been assumed that the average mass of food waste produced per household per year remains constant i.e. there is no growth or reduction due to the reasons identified in Reference 14 and no reduction in food waste resulting from recent Government initiatives (References 7 &13)

A4.3. Transport

A4.3.1. Overview

Transportation is a significant source of greenhouse gas emissions for the centralised and household treatment models, which include both road and sea movements.

For the centralised treatment model the following waste and compost transport operations must be specified:

- Transportation of the food waste from the households to the transfer station or treatment plant using dedicated waste collection vehicles
- Bulk transportation of the waste from the transfer station to the treatment plant using dedicated HGVs (if required)
- Bulk transportation of the compost from the treatment plant to the application site using dedicated HGVs

For both the centralised and household treatment models, combinations of the following transport operations related to the FWCRs and FWDs can be included, where "feedstock" refers to the extracted raw materials required for producing plastic polymers, the polymers themselves or the end-of-life plastic products for recycling:

- Bulk transportation of the FWCRs/FWDs or feedstock material to an overseas port by HGV
- Bulk transportation of the FWCRs/FWDs or feedstock material from an overseas port to a home port by ship
- Bulk transportation of the feedstock material from a home port to processing and manufacturing plants by HGV
- Bulk transportation of the FWCRs/FWDs from a home port or manufacturing plant to a local authority distribution centre via a main distribution centre by HGV
- Household delivery and collection of the FWCRs/FWDs

A4.3.2. Food Waste Collection and Transfer

The fuel efficiency and associated emissions for road freight exhibit wide variations, as demonstrated by a recent German study (Reference 52). Overall fuel efficiency is not just dependent upon vehicle efficiency but vehicle speed, terrain (e.g. road gradient), the quality of the road infrastructure (e.g. availability of motorways, degree of congestion), driver ability and the sophistication of logistics (e.g. correct selection of vehicle and load factors).

An empirical relationship between the greenhouse gas emission factor and vehicle load for rigid freight vehicles published by Defra (Reference 46) provides a good representation of the data measured in the German study for the transport vehicles defined in this analysis:

$$\varepsilon_t = (u + lf)c$$

where

ε_t represents the transport greenhouse gas emission factor (kg CO_2E/km)

u is the unladen vehicle fuel efficiency constant (0.236 l/km)

l is the laden vehicle fuel efficiency per fraction load constant (0.104 l/km-fraction load)

f is the fraction loading of the vehicle (e.g. 0.0 is empty, 0.5 is 50% loaded, 1.0 is fully loaded)

c is the vehicle fuel conversion factor (2.63 kg CO_2/l)

Whilst the Defra empirical relationship is applicable to standard bulk transport vehicles, studies have shown that such fuel efficiencies factors are not appropriate for waste collection vehicles under practical operational conditions. Measurements of a typical urban collection cycle in Saint-Nicolas, Quebec (Reference 53) show that 76% of the time was occupied by the actual collection of waste from the households, 20% in waste transfers and 4 % in unloading the vehicles. Thus, the vast majority of fuel is consumed in collection mode, where the vehicle is much less efficient due to the "stop-go" nature of the operation and the use of the hydraulic handling equipment. The amount of fuel consumed to generate hydraulic power represents approximately 40% of the total fuel consumed in the collection mode.

Based on a wide range of sources, the fuel efficiency of waste collection vehicles averaged over a complete round trip vary from about 0.6 to 1.2 l/km, the actual value being very dependent on the distance travelled in collection mode relative to transfer mode. The equivalent Defra value for a half average load standard bulk transport vehicle of 0.288 l/km is therefore a factor of 2 to 4 less. The data from the Saint-Nicolas study indicates that the fuel efficiency during the waste collection phase is approximately a factor of 7 greater than the Defra data. This increase is therefore applied to the Defra emission factor during the combined base case collection phase. In the model, the waste collection vehicle operates as a conventional bulk transport vehicle whilst travelling empty to the first household pick-up of the day and whilst travelling laden to the transfer station or composting plant after the last household pick-up of the day.

The use of large gross weight vehicles to minimise greenhouse gas emissions per km-tonne may not be practical in terms of required manoeuvrability, particularly with waste collection operations. In the analysis presented in the main text, vehicle weights were generally selected to maintain a 90% load capacity utilisation. Whilst the selection of a lower weight vehicle may increase operational emissions by up to about 10%, there would be benefits of manoeuvrability, reduced road damage and lower emissions associated with the vehicle's embodied energy.

Transport backloading, which is the practice of making use of spare capacity on the return leg of a delivery journey, can be included in the analysis by an appropriate reduction in the transport distance.

The transport distances are model input variables and for this analysis are based on a number of sources. Household waste collection distances are clearly dependent on the density and type of dwellings, with FWDs most applicable to single occupancy dwellings with a suitable garden. The distances between dwellings in an urban environment typically range from about 4-5 m for terraced houses to 15-20 m for detached houses on a large plot. However, the average collection distance per household for a given collection round is affected by other factors. For example, the extent of commercial buildings and green spaces on the collection route increases the average distance whereas the opportunity for simultaneous collections from both sides of quiet residential roads effectively decreases the distance between households. For the purposes of the analysis presented in the main text of this report, an urban environment is defined as having an average collection distance per household of less than 0.02 km, a semi-rural area (i.e. small towns with dispersed households in between) of 0.02-0.10 km and a rural environment of greater than 0.10 km.

The analysis of UK greenhouse gas emissions performed by ERM (References 2) states that experience of assessing waste transport in the UK suggests that the typical distances travelled by wastes are as follows:

- Recycling collections: 2 km per tonne of waste collected
- Residual waste collections: 1.5 km per tonne of waste collected
- Transport to treatment facility: 30 km per tonne of waste treated

The Saint-Nicholas collection cycle has a value of 1.7 km/t, which excludes the transfers at the beginning and end of the collection round. The Plymouth City Council website (Reference 54) provides waste collection data that indicates a total travel distance of 6.8 km/t. Based on the available data, the required model distance inputs for a non-rural environment (i.e. average combined urban and semi-rural environments) were set at 0.04 km between households for the collection phase, transfers of 5 km in the waste collection vehicle at the beginning and end of the collection round and a bulk transport distance between the transfer station and treatment plant of 18 km. Waste collection statistics for rural areas are not readily available and have a greater associated uncertainty. For the analysis presented in the main text of this report the typical average distance between households is increased to 0.20 km, the transfer phase to 10 km and the bulk transport phase to 25 km. Because of the increase in the distance between households the average speed of the vehicle during the collection phase is increased from 6 km/h to 12 km/h and the factor change in fuel efficiency reduced from 7 to 4.2.

The emissions associated with the bulk transportation of the compost end product from the treatment plant to application sites should not necessarily be included in full, or in part, for the reasons outlined in Section A4.4.

A4.3.3. FWCR & FWD Transport

In the analysis it has been assumed that the FWCR is manufactured in the UK. The total average bulk road transportation distance associated with the FWD (feedstock and finished product) is estimated to be 350 km and this same distance has been used for the FWCR.

The reference FWD is manufactured in Canada and transported to the UK by ship. Canada was selected because of its proximity to the large North American market and because the electricity used in the production process has a large hydro and nuclear generation component that results in the associated greenhouse gas emissions being less than half that for UK generation (Reference 55).

Emissions from ships and aircraft are not yet regulated by international policies formulated by the UNFCCC or the Kyoto Protocol, largely because of the unclear situation regarding who is responsible for these emissions. The 2006 IPCC Guidelines state that emissions from ships or aircraft engaged in international transport should be reported separately to ensure global completeness.

In this analysis the Defra emission factor of 0.014 kg CO_2E/km-t (Reference 46) for a small bulk carrier has been used, with a shipping distance from Toronto to Liverpool of 5465 km.

As a first approximation, the local delivery distance to the individual households is set at the calculated distance travelled by the waste collection vehicles to all households. The model assumes that the end-of-life FWCRs and FWDs are picked up and delivered simultaneously over the lifetime of the treatment plant, with the obvious exception of the first delivery and assumed final collection. In the default set database the fuel efficiency is decreased by 50% to account for the stop-go nature of delivery and collection.

A4.4. Application of Compost to Land

Greenhouse gas emissions arising from the application of the compost produced by the in-vessel treatment plant to the land are dependent upon application rates and the type and size of the machinery employed. This component should not be included within the system boundary where it is displacing the application of other composts. However, because of the possibility that concerns from the farming community, supermarkets, vegetarian pressure groups and the general public limit this market, the food waste compost would have to be spread on non-agricultural land that does not normally receive compost. In this case the benefits are arguable and the emissions are more associated with disposal.

The emission factor for the application of compost on the land is based on the data in Reference 55.

A5. Operational Biogenic Emissions

A5.1. Food Waste Decomposition

For the purposes of this analysis, where the biogenic emissions are only included for completeness, an average emission of 190 kg CO_2 per tonne of wet feedstock has been used in the in-vessel treatment plant calculations (Reference 56). Decomposition during the stockpiling of food waste at households prior to collection, during transportation, at the transfer station and at the treatment plant prior to processing has not been estimated separately.

Composting may result in the production of some CH_4 from anaerobic decomposition in the centre of a compost pile. In most situations, the CH_4 oxidises to CO_2 before it escapes. If the resulting compost is spread onto the land, the majority of the remaining carbon will also be converted over time to CO_2 by further biological action (Section 5.2).

Much of the dry weight of food waste is attributable to proteins and in a natural environment the remains are eventually converted into soil through a continuous cycle of activity by a wide range of interdependent organisms and micro-organisms. The natural decomposition process is accelerated within the reference FWD by the design of the system raising temperature, maintaining aerobic conditions and encouraging the growth of micro-organisms. The food waste is therefore converted into water, CO_2 and a small residue of humic substances comprising lignin and protein. The reference FWD has been in use for about 15 years and there has been no evidence of methane (CH_4) generation in well operating systems. Any small amounts of CH_4 possibly produced due to a pocket of oxygen starvation would be reabsorbed and oxidised in the below ground digestion basket.

The main quantitative measure of food waste conversion efficiency for the reference FWD is defined in Reference 57 as:

$$E = (W_{food} - W_{residue}) / W_{food}$$

where

E is the food waste conversion efficiency (dimensionless)

$W_{residue}$ is the weight of the humic residue (kg)

W_{food} is the total weight of waste put into the system on a regular basis (kg)

Based on this conversion efficiency and the average water content of household food waste, the reduction in the dry mass can be calculated. A study of the composition of organic waste determined that the chemical composition of typical mixed food waste could be represented by $C_6H_{9.6}O_{3.5}N_{0.28}S_{0.2}$ (Reference 58). This formula is used to derive the associated biogenic emissions.

A5.2. Decomposition on the Land

Decomposition of the compost from the centralised treatment plant will continue once it is spread on the land. The CO_2 emission from this stage of biogenic decomposition has been defined as the difference between the biogenic emission for the FWD and the in-vessel plant. Thus, the total biogenic emissions from both systems are set as equivalent.

Appendix B

Workbook Model

The Greenhouse Gas Emission Estimator for Household Food Waste can be used to derive absolute and comparative emissions and investigate the sensitivity of emissions to input variables.

The Excel workbook models the two waste management systems described in Section 3 of the main text and comprises the following four worksheets:

Input: Input variables and associated derived parameters, model set variables, values and constants used in formulae
Centralised: Component emission factors and calculated greenhouse gas emission outputs for the centralised treatment of food waste
Household: Component emission factors and calculated greenhouse gas emission outputs for the household treatment of food waste
Summary: Comparison of the greenhouse gas emissions for the centralised and household treatment of food waste

A large number of input variables are required to specify the household and centralised treatment systems. To simplify this specification, particularly because of the difficulty in obtaining some variables, the user is only required to provide values for 52 inputs. The input worksheet contains 99 set variables, values and constants ("set input database"), which can also be changed if required.

The beta version of the workbook model used for the analysis presented in this report is reproduced in Appendix C.

Appendix C

Analysis Worksheets

Greenhouse Gas Emission Estimator for Household Food Waste

Input Worksheet (Beta Version 1.0)

Model Input Variables	Input	Derived	Notes
Case Title	**Base Case: combined urban/semi-rural**		
Household Waste Inputs			
Number of households	**250000**		
Average mass of MSW collected per household per year (tonne per household per year)	**1.00**		
Total mass of MSW collected (tonne per year)		**250000**	
Average mass of food waste collected per household per year (tonne per household per year)	**0.20**		Reference 21
Total mass of food waste collected (tonne per year)		**50000**	
Waste Collection Vehicle Inputs			
Frequency of household collections (number collections per household per year)	**52**		
Number of working household collection days per year (number working days per year)	**260**		
Average distance between households excluding initial & final transfers (km)	**0.04**		Typical km: 0.04 urban/semi-rural, 0.20 rural
Average speed of waste collection vehicle in collection mode (km/h)	**6.0**		Typical km/h: 6 urban/semi-rural, 12 rural
Factor change in vehicle fuel efficiency during waste collection mode (factor)	**7.0**		Typical factor: 7 urban/semi-rural, 4.2 rural
Average transfer distance travelled to first household (km)	**5**		
Average transfer distance travelled from last household (km)	**5**		
Required average payload of waste collection vehicle for single daily round per vehicle (tonne)		**22.22**	
Required average payload of waste collection vehicle for two daily rounds per vehicle (tonne)		**10.08**	
Gross weight of waste collection vehicle (tonne)	**26.00**		Reference 47
Unladen weight of waste collection vehicle (tonne)	**15.42**		Reference 47
Maximum payload of waste collection vehicle (tonne)		**10.58**	
Number of rounds per day for input waste collection vehicle (number rounds per vehicle per day)		**2**	
Average utilisation of input waste collection vehicle (fraction)		**0.90**	
Number of MSW waste collection vehicles (number)		**48**	
Effective number of waste collection vehicles for food waste (number)		**10**	Model assumes co-collection
Total MSW collection & transfer distance per year (km per year)		**769600**	
Total distance of single collection & transfer from all households (km)		**14800**	
Average life expectancy of waste collection vehicle (years)	**8.33**		Integral of treatment plant life expectancy
Average distance travelled over waste collection vehicle life expectancy (km per vehicle)		**133558**	
Number of tyres per waste collection vehicle (number)	**10**		Model assumes all vehicle tyres identical
Mass of single tyre on waste collection vehicle (kg)	**48.19**		Model assumes all vehicle tyres identical
Waste collection vehicle tyre life (km)	**112500**		Model assumes all vehicle tyres wear equally
Number of tread/retread per waste collection vehicle tyre carcass (number)	**4**		Includes original tread
Number of complete tyre cycles & number of tread/retread over life expectancy of vehicle (number)		**1.187**	Model assumes all vehicle tyres wear equally
Number of tyre carcass over life expectancy of vehicle (number)		**0.297**	Model assumes all vehicle tyres wear equally
Unladen weight of waste collection vehicle without tyres (tonne)		**14.94**	
Food Waste Collection Receptacle (FWCR) Inputs			
Mass of FWCR (kg)	**3.40**		Reference 49
Total mass of FWCRs for all households (tonne)		**850**	
Average life expectancy of FWCR (years)	**6.25**		Integral of treatment plant life expectancy
Fraction of FWCR manufactured from recycled materials (f_i fraction)	**1.00**		Reference 49
Bulk sea transport distance of feedstock &/or FWCR (km)	**0**		Non-dedicated shipping
Bulk sea transport km-tonne of feedstock &/or FWCR (km-tonne)		**0**	Mass of feedstock assumed same as FWCR
Bulk road transport distance of feedstock &/or FWCR (km)	**350**		Non-dedicated vehicle
Bulk road transport km-tonne of feedstock &/or FWCR (km-tonne)		**297500**	Mass of feedstock assumed same as FWCR
Total local FWCR delivery/collection distance (km)		**14800**	Model assumes same as single waste vehicle collection distance
Transfer Station Input			
Transfer station employed (0 for no; 1 for yes)	**1**		
Bulk Waste Vehicle Inputs			
Gross weight of bulk waste vehicle (tonne)	**32.00**		Reference 48
Unladen weight of bulk waste vehicle (tonne)	**12.00**		Reference 48
Maximum payload of bulk waste vehicle (tonne)		**20.00**	
Average bulk waste vehicle utilisation (fraction)	**0.95**		
Distance from transfer station to treatment plant (km)	**18.00**		

Average backloading fraction (fraction)	0.00		Fraction considered externality & attributable to another sector
Return distance between transfer station & treatment plant (km)		36.00	
Number of journeys from transfer station to treatment plant per year (number per year)		2632	
Average number of days bulk waste vehicle employed per year (days per year)	260		
Number of return journeys per vehicle per day (journeys per vehicle per day)		3	
Total number of waste bulk transport vehicles (number)		4	Dedicated vehicles
Average life expectancy of bulk waste vehicle (years)	12.5		Integral of treatment plant life expectancy
Average distance travelled over bulk waste vehicle life expectancy (km per vehicle)		296100	
Number of tyres per bulk waste vehicle (number)	12		Model assumes all vehicle tyres identical
Mass of tyre on bulk waste vehicle (kg)	48.19		Model assumes all vehicle tyres identical
Bulk waste vehicle tyre life (km)	112500		Model assumes all vehicle tyres wear equally
Number of tread/retread per bulk waste vehicle tyre carcass (number)	4		Includes original tread
Number of complete tyre cycles & number of tread/retread over life of vehicle (number)		2.632	Model assumes all vehicle tyres wear equally
Number of tyre carcass over life of vehicle (number)		0.658	Model assumes all vehicle tyres wear equally
Unladen weight of bulk waste vehicle without tyres (tonne)		11.42	
Treatment Plant Inputs			
Treatment plant waste conversion factor (fraction)	0.50		
Quantity of compost produced (tonne)		25000	
Average life expectancy of treatment plant (years)	25		Reference 13
Bulk Compost Vehicle Inputs			
Gross weight of bulk compost vehicle (tonne)	32.00		Reference 48
Unladen weight of bulk compost vehicle (tonne)	12.00		Reference 48
Maximum payload of bulk compost vehicle (tonne)		20.00	
Average bulk compost vehicle utilisation (fraction)	0.95		
Average distance from treatment plant to application site (km)	75.00		
Average backloading fraction (fraction)	0.00		Fraction considered externality & attributable to another sector
Return distance between treatment plant & application site (km)		150.00	
Number of journeys from treatment plant to application site per year (number per year)		1316	
Average number of days bulk compost vehicle employed per year (days per year)	260		
Number of return journeys per vehicle per day (journeys per vehicle per day)		2	
Total number of bulk compost transport vehicles (number)		3	Dedicated vehicles
Average life expectancy of bulk compost vehicle (years)	12.5		Integral of treatment plant life expectancy
Average distance travelled over bulk compost vehicle life expectancy (km per vehicle)		822500	
Number of tyres per bulk compost vehicle (number)	12		Model assumes all vehicle tyres identical
Mass of tyre on bulk compost vehicle (kg)	48.19		Model assumes all vehicle tyres identical
Bulk compost vehicle tyre life (km)	112500		Model assumes all vehicle tyres wear equally
Number of tread/retread per bulk compost vehicle tyre carcass (number)	4		Includes original tread
Number of complete tyre cycles & number of tread/retread over life of vehicle (number)		7.311	Model assumes all vehicle tyres wear equally
Number of tyre carcass over life of vehicle (number)		1.828	Model assumes all vehicle tyres wear equally
Unladen weight of waste collection vehicle without tyres (tonne)		11.42	
Food Waste Digester Inputs			
Mass of FWD (kg)	6.90		Reference 50
Total mass of FWDs for all households (tonne)		1725	
Average life expectancy of FWD (years)	12.5		Integral of treatment plant life expectancy
Fraction of FWD manufactured from recycled materials (f_i fraction)	0.64		Reference 50
Bulk sea transport distance of feedstock &/or FWD (km)	5465		Non-dedicated shipping
Bulk sea transport km-tonne of feedstock &/or FWD (km-tonne)		9427125	Mass of feedstock assumed same as FWD
Bulk road transport distance of feedstock &/or FWD (km)	350		Non-dedicated vehicle
Bulk road transport km-tonne of feedstock &/or FWD (km-tonne)		603750	Mass of feedstock assumed same as FWD
Total local FWD delivery/collection distance (km)		14800	Model assumes same as single waste vehicle collection distance

Model Set Values & Variables	Value		Source
Unladen vehicle fuel efficiency per km (l/km)	**0.236**		Reference 46
Laden vehicle fuel efficiency per km per fraction load (l/km-fraction load)	**0.104**		Reference 46
Vehicle fuel conversion factor (t CO2/l)	**2.63**		Reference 46
Factor change in vehicle fuel efficiency during FWCR/FWD delivery/collection mode (factor)	**1.5**		Best Estimate
Length of waste collection working day (hours)	**8.0**		Best Estimate
Average minimum waste collection vehicle utilisation (fraction)	**0.95**		Best Estimate
Average speed of waste collection vehicle in transfer mode (km/h)	**55.0**		Best Estimate
Average waste collection vehicle turnaround time for weighing/loading/unloading (hours)	**0.5**		Best Estimate
Length of bulk waste transfer working day (hours)	**8.0**		Best Estimate
Average speed of bulk waste vehicle (km/h)	**55.0**		Best Estimate
Average bulk waste vehicle turnaround time for weighing/loading/unloading (hours)	**1.5**		Best Estimate
Length of bulk compost transfer working day (hours)	**8.0**		Best Estimate
Average speed of bulk compost vehicle (km/h)	**55.0**		Best Estimate
Average bulk compost vehicle turnaround time for weighing/unloading (hours)	**1.0**		Best Estimate
Mass fraction of aluminium in reference vehicle (fraction)	**0.1535**		Reference 44
Mass fraction of iron/steel in reference vehicle (fraction)	**0.8055**		Reference 44
Mass fraction of "other" material in reference vehicle (fraction)	**0.0410**		Reference 44
Fraction of aluminium recycled at end-of-life (f_o fraction)	**0.95**		Best Estimate
Fraction of steel recycled at end-of-life (f_o fraction)	**0.95**		Best Estimate
Reference vehicle manufacturing energy emissions (kg CO2E/kg of truck w/o tyres)	**1.2018**		Best Estimate from Reference 44
Reference vehicle disassembly energy emissions (fraction of manufacturing energy emissions)	**0.15**		Best Estimate based on range of data
Reference vehicle construction losses (fraction of materials embodied emissions)	**0.02**		Best Estimate based on range of data
Reference vehicle maintenance energy emissions (fraction of materials embodied emissions/life km)	**2.222E-07**		Best Estimate based on range of data
Mass of maintenance spares relative to mass of reference vehicle per life km (fraction/life km)	**8.345E-08**		Reference 44
Mass fraction of tread/retread in reference tyre (fraction)	**0.318**		Reference 37
Mass fraction of steel cord in reference tyre recycled (fraction)	**0.950**		Best Estimate
Mass fraction of natural rubber in reference tyre carcass (fraction)	**0.2456**		Reference 37
Mass fraction of synthetic rubber in reference tyre carcass (fraction)	**0.1578**		Reference 37
Mass fraction of carbon black in reference tyre carcass (fraction)	**0.2340**		Reference 37
Mass fraction of steel cord in reference tyre carcass (fraction)	**0.1720**		Reference 37
Mass fraction of "other" material in reference tyre carcass (fraction)	**0.1906**		Reference 37
Mass fraction of natural rubber in reference tyre tread/retread (fraction)	**0.0049**		Reference 37
Mass fraction of synthetic rubber in reference tyre tread/retread (fraction)	**0.4421**		Reference 37
Mass fraction of carbon black in reference tyre tread/retread (fraction)	**0.3441**		Reference 37
Mass fraction of "other" material in reference tyre tread/retread (fraction)	**0.2089**		Reference 37
Tyre carcass manufacturing energy emissions (kg CO2E/kg carcass)	**1.5946**		Reference 37
Tyre tread/retread manufacturing energy emissions (kg CO2E/kg tread)	**0.4658**		Reference 37
Fraction of FWCR recycled at end-of-life (f_o fraction)	**1.00**		Best Estimate
Fraction of FWD recycled at end-of-life (f_o fraction)	**1.00**		Best Estimate
Quality/value of FWCR material recycled in the input base material (q_i fraction)	**0.90**		Best Estimate
Quality/value of FWD material recycled in the input base material (q_i fraction)	**0.90**		Best Estimate
Reduction in quality/value of FWCR material each recycle (fraction)	**0.90**		Best Estimate
Reduction in quality/value of FWD material each recycle (fraction)	**0.90**		Best Estimate
FWCR manufacturing losses (fraction)	**0.050**		Best Estimate
FWD manufacturing losses (fraction)	**0.050**		Best Estimate
Ship transport emissions per km - tonne FWCR/FWD (kg CO2/km-t_f)	**0.020**		Reference 46
Payload of non-dedicated FWCR/FWD bulk transport vehicle (tonne)	**20.0**		Best Estimate
Non-dedicated FWCR/FWD bulk transport vehicle average utilisation (fraction)	**0.95**		Best Estimate

Transfer station diesel per tonne of waste (kg diesel/t_w)	**0.3**		Reference 8
Transfer station electricity per tonne of waste (kW-h/t_w)	**1.9**		Reference 8
Fraction of transfer station diesel & electricity attributable to food waste (fraction)	**0.1**		Best Estimate
Mass of concrete in 20000 tonne/year reference treatment plant (kg)	**4000000**		Best Estimate based upon Reference 42
Mass of steel in 20000 tonne/year reference treatment plant kg)	**700000**		Best Estimate based upon Reference 42
Mass of "other" materials in 20000 tonne/year reference treatment plant (kg)	**100000**		Best Estimate based upon Reference 42
Fraction of steel recycled at end-of-life (f_o fraction)	**0.95**		Best Estimate
Treatment plant construction energy emissions (fraction of materials embodied emissions)	**0.05**		Best Estimate
Treatment plant demolition energy emissions (fraction of construction energy emissions)	**0.15**		Best Estimate
Treatment plant construction losses (fraction of materials embodied emissions)	**0.05**		Best Estimate
Treatment plant maintenance & refit emissions (fraction of materials embodied emissions)	**0.15**		Best Estimate
Ratio of treatment plant capacity & total mass of food waste collected (ratio)	**1.2**		Best Estimate
Treatment plant diesel per tonne of waste (kg diesel/t_w)	**3.0**		Reference 8
Treatment plant electricity per tonne of waste (kW-h/t_w)	**9.0**		Reference 8
Treatment plant CH4 anthropogenic emissions per tonne of waste (kg CH4E/t_w)	**0.018**		Reference 8
Treatment plant N2O anthropogenic emissions per tonne of waste (kg N2OE/t_w)	**0.0099**		Reference 8
Treatment plant biogenic emissions per tonne of waste (kg CO2E/t_w)	**190**		Reference 56
Treatment plant/transfer station diesel CO2E emissions (kg CO2E/kg diesel)	**3.66**		Reference 8
Treatment plant/transfer station electricity CO2E emissions (kg CO2E/kW-h)	**0.57**		Reference 8
Tractor/spreader application of compost to soil CO2E emissions (kg CO2E/t_c)	**4.93**		Reference 56
Dry mass reduction per tonne of food waste (fraction)	**0.15**		Reference 57
Fraction carbon in food waste (fraction)	**0.487**		Reference 58
Primary iron/steel emission factor (kg CO2E/kg material)	**2.82**		Reference 43
Secondary iron/steel emission factor (kg CO2E/kg material)	**0.45**		Reference 43
Primary aluminium emission factor (kg CO2E/kg material)	**11.9**		Reference 43
Secondary aluminium emission factor (kg CO2E/kg material)	**1.69**		Reference 43
FWCR primary plastic emission factor (kg CO2E/kg material)	**3.43**		Derived from References 29-31
FWCR secondary plastic emission factor (kg CO2E/kg material)	**2.07**		Derived from References 29-31
FWCR base production plastic emission factor (kg CO2E/kg material)	**1.95**		Derived from References 29-31
FWCR intermediate production plastic emission factor (kg CO2E/kg material)	**1.48**		Derived from References 29-31
FWCR recycled plastic emission factor (kg CO2E/kg material)	**0.59**		Derived from References 29-31
FWD primary plastic emission factor (kg CO2E/kg material)	**2.73**		Derived from References 29-31
FWD secondary plastic emission factor (kg CO2E/kg material)	**1.37**		Derived from References 29-31
FWD base production plastic emission factor (kg CO2E/kg material)	**1.95**		Derived from References 29-31
FWD intermediate production plastic emission factor (kg CO2E/kg material)	**0.78**		Derived from References 29-31
FWD recycled plastic emission factor (kg CO2E/kg material)	**0.59**		Best Estimate based on range of data
Primary concrete emission factor (kg CO2E/kg material)	**0.163**		Reference 43
Primary natural rubber emission factor (kg CO2E/kg material)	**1.54**		Reference 43
Primary synthetic rubber emission factor (kg CO2E/kg material)	**4.25**		Reference 43
Primary carbon black emission factor (kg CO2E/kg material)	**1.91**		Reference 45
Primary steel rod emission factor (kg CO2E/kg material)	**2.68**		Reference 43
Secondary steel rod emission factor (kg CO2E/kg material)	**0.42**		Reference 43
Primary "other" materials emission factor (kg CO2E/kg material)	**2.00**		Best Estimate representative average derived from Reference 43
Waste capacity of reference treatment plant (tonne waste)	**20000**		Reference 42

Constants in Formulae	Value		Source
Conversion kg - tonne	**1000**		SI units
Conversion of carbon to CO2	**3.664**		IUPAC Commission on Atomic Weights and Isotopic Abundances
Global warming potential CH4 (100year)	**21**		Reference 17
Global warming potential N2O (100 year)	**310**		Reference 17
Fully laden vehicle fraction load (fraction)	**1**		By definition
Half laden or half average laden vehicle fraction load (fraction)	**0.5**		By definition
Empty vehicle fraction load (fraction)	**0**		By definition