National Food Waste Programme (Work Package 1.1) Comparison of the Sustainability of Food Waste Disposal Options

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Glossary

ABPR – Animal By-Products Regulations

AD – Anaerobic Digestion

BOD – Biochemical Oxygen Demand

CCS – Carbon Capture and Storage

CHP – Combined Heat and Power

COD – Chemical Oxygen Demand

DS – Dry Solids

EC – Embodied Carbon

EF – Emission Factor

FOG – Fat Oil, Grease

FWD unit – Food Waste Disposal unit

GHG – Greenhouse Gas

GWP – Global Warming Potential

IPCC – International Panel on Climate Change

IVC – In-vessel Composting

LARAC – Local Authority Recycling Advisory Committee

LCA – Life Cycle Analysis

MSW – municipal solid waste

NAEI – National Air Emissions Inventory

NPV – Net Present Value

PE – Population Equivalent

RAS – Returned Activated Sludge

ROC – Renewable Obligation Certificate

SOC – Soil Organic Carbon

SPC – Shadow Price of Carbon

STPR – Social Time Preference Rate

THP – Thermal Hydrolysis Process

TSS – Total Suspended Solids

UKWIR – UK Water Industry Research

WEEE – Waste Electrical and Electronic Equipment Regulations

WRAP – Waste and Resource Action Programme

WRATE – Waste and Resources Assessment Tool for the Environment

WwTW – Wastewater Treatment Works

Preface

Food waste disposal units

The need to meet landfill reduction targets for biodegradable municipal waste has become a major driver to gaining a better understanding of biodegradable waste streams, and of the alternative technical options available for the better management of these streams. Particular emphasis has been placed on the twin goals of both reducing the waste arising at source, and when further minimisation is not practicable, of identifying means to extract the greatest residual benefit from the material content in such streams and wherever possible converting any residue into a usable product.

Domestic food waste has been identified as an important and highly biodegradable stream which contributes significantly to the amount of municipal solid waste (MSW) requiring collection. Segregation and separate collection of this fraction could facilitate a reduction in the frequency of residual waste collection and the food waste itself is a valuable resource. Extensive research undertaken by the Waste and Resources Action Programme (WRAP) has addressed the minimisation of food waste (through, for example the Love Food Hate Waste campaign) the promotion of home composting solutions and the implementation of segregated collection, treatment and beneficial re-use approaches. Anaerobic digestion (AD) has been identified as a particularly suitable treatment option for food waste as it not only produces a stable residual product suitable for agricultural use but also biogas which can be used in either a local combined heat and power (CHP) system, or with further treatment, as a renewable source of natural gas (methane). The UK water industry is an experienced user of AD technology and was an early signatory to a commitment to maximise the benefits from AD (“Anaerobic Digestion – Shared Goals”, Defra 2009).

Segregated kerbside collection is not the only option for the management of domestic kitchen food waste. In some areas kerbside collection in combination with other biodegradable waste streams such as garden waste is offered whilst householders may alternatively prefer the use of home composting or home food waste digesters. A further option, which is the subject of this study, is the use of domestic food waste disposal (FWD) units. FWD units are small macerators or grinders which can be installed in the kitchen sink outlet to reduce food waste to fine particles which are then flushed to the sewer in a flow of cold water. As a biodegradable waste stream, the food waste would be expected to be effectively treated by the conventional wastewater treatment methods currently used. FWD units have been available for many years and manufacturers promote their use on the basis of their convenience, practicality and environmental merit. It has been reported that about 5% of UK households currently have FWD units. More widescale use of FWD units could divert a significantly larger proportion of domestic kitchen food waste to the sewer, reducing the need for kerbside collection but increasing the demand on the wastewater infrastructure.

The UK water industry has been concerned for some time that the increasing pressures to reduce household waste should not lead to increased misuse of the sewer system through inappropriate disposal of waste. The industry has a programme of sewer network abuse prevention and is actively working with manufacturers of products which are intended to be flushed into the sewer. Whilst FWD units have been in use in the UK for many years in relatively small numbers, the water industry has expressed strong reservations regarding the potential adverse impacts of their more widespread use and in particular the possible implications for the increased maintenance of sewers.

National Food Waste Programme

This report summarises work which was undertaken by WRc in early 2008 as the first stage of the proposed National Food Waste Programme. The Programme was jointly funded by Defra and the water industry, through the industries collaborative research body UK Water Industry Research (UKWIR) to investigate the potential impacts of more widespread use of domestic FWD units.

The purpose of this work was to undertake a desk-based modelling study, using information which was readily available to WRc at the time, which would highlight the financial and technical factors associated with potential widescale FWD use. The model which was built as part of the study provides a simple representation of the options for segregated kerbside collection or widescale FWD use and the resulting treatment and re-use routes. It is limited to considering only certain specific collection of treatment options which were selected prior to the commissioning of the study. The model does not seek to identify which is the ‘best option’ but instead to identify the relative magnitude of the key factors as a means of prioritising further research and data collection. It was intended that the model would provide a framework for the evaluation of data arising from future practical trials of FWD units and would be further developed within the course of the programme.

This report is primarily aimed at those directly involved in the work of the programme but has been more widely published as it may be of value to others interested in food waste treatment and disposal. It should be recognised that the study was not intended to inform more general food waste management policy making at the local authority level as this would require a much more detailed and specific assessment of the available options. The study has fulfilled its main purpose in assisting Defra and the water industry in the prioritisation of research in this area.

Since the initial desk study in early 2008, the programme itself has been unable to establish a collaborative trial with a local authority and water company due in part to the sharp decline in the property market and funding restrictions. The original desk study is, therefore, now being published as a stand-alone document. Since the initial draft report in 2008 a number of revisions have been made in response to detailed technical comment and peer review but the underlying model reflects the position as in 2008. Subsequently various studies of FWD units have been published and in particular the results of extended trials in Sweden (Evans *et al.* 2010). The report has not been updated to include consideration of these results or the more detailed information now becoming available on segregated food waste collection costs and on AD treatment of food waste. The parameter values adopted in this study, therefore, do not necessarily reflect the best available data which is now available.

Executive Summary

i Objective and purpose

To compare, using readily available data, the whole life environmental emissions and financial costs for the kerbside collection and treatment of segregated kitchen food waste, with an alternative approach using food waste disposal (FWD) units, transport in the sewer and co-treatment at a wastewater treatment works (WwTW). This study has been undertaken as a preliminary guide to identifying priorities for further work within the food waste programme.

Ii Conclusions

This assessment has been conducted by identifying and estimating the most significant greenhouse gas (GHG) releases and financial costs of three food waste management options, using a simple numerical modelling approach and is based on a hypothetical “model catchment”. To do this it has been necessary to make assumptions regarding both the most important mechanisms for GHG releases and the values for various parameters. Costs were estimated as the Net Present Value (NPV) over a 25 year assessment period and expressed as a cost per tonne (t) of food waste collected. It has been assumed that the active participation rate of food waste would be the same for FWD use as for kerbside collection. The modelling approach has not been undertaken as a life cycle assessment and has not sought to fully consider the impact of future recycling on material use and GHG emissions.

The differences observed between the options considered were within the range of uncertainty in these estimates. Within the recognised limitations of this modelling approach the following conclusions can, however, be drawn.

i) Kerbside collection of segregated domestic kitchen food waste was shown to have lower GHG emissions and overall financial costs when compared with the use of domestic FWD units followed by discharge to sewer, where no increase in blockages was assumed and both routes used a thermal hydrolysis process followed by anaerobic digestion (THP/AD) with energy recovery and biosolids reuse. For kerbside collection, operating costs were predominant but FWD use was more capital intensive.

ii) The overall GHG emissions and financial cost for kerbside collection with THP/AD were estimated to be 85.03 kg CO_2e/t and £97.01/t. The main financial items were the capital costs of caddies and bins (£6.14/t), treatment plant (£29.07/t), costs for caddy liners (£19.52/t) and collection labour (£44.72/t). These costs were partially offset by a credit for the sale of the electricity generated (£10.70/t) and the related renewable obligation certificates (£17.51/t).

iii) Where FWD units were used, with similar biosolids treatment, the estimated emissions were 104.80 kg CO_2e/t and the cost was £108.22/t. The main capital costs were for FWD units (£62.37/t) and treatment plant (£32.09) but the main operating costs related to water and electricity for FWD use (£10.22/t). The value of the credit for surplus electricity generated was slightly lower than that for segregated food waste (£8.48/t), but due to the lower renewable obligation certificates (ROC) banding for electricity generated from 'sewage gas' (SI 785, 2009), the ROC income was significantly less (£3.47/t).

iv) The use of in-vessel composting (IVC), as an alternative to THP/AD in the kerbside collection option, resulted in a significantly higher emission (167.04 kg CO_2e/t) and slightly higher financial cost (£103.08/t). The estimated process emissions for the IVC process were derived largely from IPCC emission factors and are significantly higher than other estimates for composting.

v) To examine the potential effect of increased sewer blockage it was assumed that the use of FWD units would increase blockages by 25%. Under this assumption the estimated emissions increased from 104.8 to 105.16 kg CO_2e/t and the financial costs from £108.22 to £121.19/t. A large part of the increased financial costs related to dealing with foul flooding of properties.

vi) Throughout the options considered, monetisation of GHG emissions using the shadow price of carbon had only a small impact on the estimated financial costs, contributing less than 5% to the total.

Iii Limitations

A desk-based modelling study has significant limitations, in particular it can only make use of the available data and provide a relatively simplistic representation of the real-world situation. Many of the factors considered contain uncertainty and these may influence the resulting comparison. Ideally, for factors which are included in the numerical analysis, the range of uncertainty should be identified for each and a quantitative estimate of the effect of this uncertainty estimated as a 'sensitivity analysis'. However, the interdependence of some factors can make this task more complex.

Careful consideration also has to be given to factors which are excluded from the numerical analysis. Factors may be excluded because they are expected to have only a minor impact on the result, because they are common to all options and so their impact would 'cancel out', or because a robust quantitative analysis is not possible within the scope of the study.

Attention is drawn to a number of specific assumptions and constraints.

i) It has been assumed that both the total quantity of food waste produced and the capture rate are the same for all options. In this respect it is assumed that the same number of households would install and use FWD units as would take advantage of kerbside collection. This assumption has been adopted as insufficient data were available to indicate if householders would prefer one option compared with another.

ii) There is some evidence that kerbside collection may encourage householders to recognise the quantity of food waste being produced and that this may encourage a reduction in that waste. However, there is as yet no long-term trials data to support an estimate of the magnitude of this and no comparable data were available for the effect of FWD unit use on waste. It has, therefore, been assumed that the quantity of food waste collected via each option remains the same over the assessment period.

iii) Two options have been considered for the treatment of segregated food waste; these being a thermal hydrolysis process followed by mesophilic anaerobic digestion (THP/AD) and aerobic in-vessel composting (IVC). In both cases the resulting treated biosolids are assumed to be beneficially used in agriculture.

iv) THP has been selected as representing good practice in terms of both achieving compliance with the Animal By-Products Regulations (ABPR) and maximising the recovery of energy value from the food waste stream.

v) The behaviour of food waste when received at a wastewater treatment works has been the subject of some uncertainty. In particular, it is not clear how much of the additional organic load is removed as particulate matter by conventional primary settlement (where this process is installed) how much results in additional organic load on the secondary treatment process resulting in additional operating costs and to what extent this may benefit the operation of the secondary process.

Iv Benefits

An assessment of the greenhouse gas emissions and financial costs associated with the use of FWD units, when compared to kerbside collection of segregated kitchen food waste, will assist in identifying and prioritising areas for future investigation.

1. Introduction

1.1 Background

It has been estimated that UK households produces approximately 6.7 million tonnes of food waste annually (WRAP 2008a). Most of this is discarded by householders with other components of municipal solid waste (MSW) collected from the kerbside and disposed of to landfill. The need to meet EU targets for the reduction in the use of biodegradable municipal waste sent to landfill has led to significant changes to the practices for the collection, treatment and disposal or re-use of this waste. In particular, in an increasing number of areas, householders are being encouraged to make use of schemes in which food waste is segregated and collected separately before being treated by composting or anaerobic digestion and the organic product used beneficially in agriculture. Such schemes are seen as a key element towards achieving landfill reduction targets for biodegradable municipal wastes. This route requires the development of a significant collection and treatment infrastructure and the wide-scale beneficial re-use of the resulting treated food waste will be subject to limits imposed on the amount of nitrogen-containing material recycled to land under the Nitrate Directive (EU 1991).

As an alternative to segregation and kerbside collection, the use of domestic food waste disposal (FWD) units offers an opportunity for the diversion of food waste to sewer for co-treatment with domestic sewage. Domestic FWD units are small macerators or grinders, which are usually installed in the kitchen sink outlet. Most foods are reduced to small particles and are flushed via the kitchen drain into the public sewer. FWD units have been used in the USA and some other countries for some time and this approach to food waste management justifies serious consideration. Whilst this route would make use of existing collection, treatment and organic products management infrastructure, widespread use of FWD units would lead to the need for significant investment in additional treatment capacity and would result in a change in the composition of domestic wastewater.

In the USA, domestic FWD units have been widely used for many years. In 1998, a life cycle investigation by the University of Wisconsin recommended that use of FWD units should be encouraged when “solids handling systems are adequate, methane is combusted to generate energy and … sludge are returned to the soil” (Diggelman and Ham, reproduced in Strutz 1998). A more recent environmental impact study in the UK by Evans (2007) concluded that FWD units provide a convenient and hygienic means to separate kitchen food waste at source. This study indicated that, although with FWD unit use the *per capita* costs associated with wastewater and sludge treatment would increase, there would be a greater saving in direct costs to the solid waste collection and disposal agencies.

Concern has been expressed within the UK that widescale use of FWD units may lead to an increase in operational problems associated with sewer systems (Water UK 2009a). These views are based in part on the age of many sections of the sewer systems in older towns and cities in the UK where blockages associated with fats, oil and grease (FOG) already present significant problems. Foul flooding arising from sewer blockage is thankfully rare but where it does occur it can be a source of significant distress and of financial loss. Water and wastewater services in the UK are provided by licensed operators who are subject to control by the water services regulator, Ofwat. Ofwat have set stringent performance standards with respect to the limitation and reduction of incidents of foul flooding and licensed operators are understandably concerned that proper controls should be in place to ensure that the potential impacts of any new or changed uses of the sewer system are fully evaluated before their widescale uptake.

In the UK some collection and disposal authorities have indicated that the use of FWD units could potentially reduce the overall cost of domestic food waste management by diverting biodegradable municipal wastes from landfill. The Local Authority Recycling Advisory Committee (LARAC) supports investigation of additional measures that will reduce the biodegradability of residual waste and which may include consideration of devices such as sink macerators (FWD units). The widescale use of FWD units would involve a shift of financial and environmental burdens from the solid waste sector to the wastewater sector. Before any such shift of resources is contemplated, a fuller assessment of the financial and environmental costs and implications would be required. If widescale use of FWD units were to result in any significant adverse impacts, such as an increase in sewer blockages and associated sewage flooding of property, then the potential benefits could easily be negated and the essential performance of the foul sewer system could be compromised.

Both Defra and the water industry (through UK Water Industry Research) have supported work to further investigate the potential impacts of more widespread FWD unit use through the National Food Waste Disposal research programme. This report describes the main findings of a preliminary desk study comparing various food waste collection and treatment options undertaken as part of that research programme. The study was not intended to provide a definitive view of the preferred option for food waste management but, through a simple modelling approach, to highlight the factors influencing option selection and to provide a framework for the future evaluation of data from any trials undertaken as part of the national research programme. To do this, it has been necessary to make a number of simplifying assumptions and to compare directly two alternative scenarios: kerbside collection or use of a FWD unit. It is assumed that both routes are equally effective in “capturing” food waste and that the quantities of food waste generated are identical in both i.e. that the different methods of food waste collection do not themselves influence domestic behaviour in food purchase, use or disposal.

1.2 Scope of Work and Objectives

The primary objective of this modelling study was to compare the GHG emissions and financial costs of two alternative options for the management of domestic food waste:

Option A	source-segregated food waste with kerbside collection, dedicated treatment and beneficial re-use in agriculture, or
Option B	maceration in the kitchen using a FWD unit, transport in the sewer and co-treatment with domestic sewage.

Two sub-options have been considered within Option A which adopt different methods of food waste treatment, using either in-vessel composting in combination with garden green waste (Option A1) or thermal hydrolysis followed by anaerobic digestion (Option A2). These sub-options have been compared with a single treatment route for Option B comprising thermal hydrolysis followed by anaerobic digestion. These options are described in more detail within the methodology (Section 2).

The scope of work and available timescale excluded a detailed literature review or the opportunity to directly collect additional data from operators. It was, therefore, agreed that the study should be based on information which was readily available to WRc at the time.

1.3 Limitations

A desk-based modelling study has significant limitations, in particular it can only make use of the available data and provide a relatively simplistic representation of the real-world situation. Many of the factors considered contain uncertainty and these may influence the resulting comparison. Ideally, for factors which are included in the numerical analysis, the range of uncertainty should be identified for each and a quantitative estimate of the effect of this uncertainty estimated as a ‘sensitivity analysis’. However, the interdependence of some factors can make this task more complex.

Careful consideration also has to be given to factors which are excluded from the numerical analysis. Factors may be excluded because they are expected to have only a minor impact on the result, because they are common to all options and so their impact would ‘cancel out’, or because a robust quantitative analysis is not possible within the scope of the study. An indication of the numerical factors considered in this study can be obtained by reference to the parameters listed in Appendix A. The assumed relationships between these parameters are generally described in the Methodology and Discussion, and in some cases are explicitly described by way of sample calculations in Appendix D. Some of the factors which are not included in the numerical analysis are discussed qualitatively in Table 5.

1.4 Key assumptions and constraints

In order to satisfy the initial limited timescale requirements of the study the broad range of options considered in the modelling was constrained to those set out in Section 1.2 above. Many of the key working assumptions were considered and parameter values selected at the outset of the work. The technical approach and values used were selected with the assistance of a project steering group representing both water industry and waste sector views.

For kerbside collection some UK performance data were becoming available at the time of the initial study in April 2008. However, the comprehensive report of the WRAP separate food waste collection trials (WRAP 2008b[1]) was not published until September 2008 and was, therefore, not available for the first phase of work. The model was partially updated to incorporate the WRAP data in Autumn 2008.

A further significant constraint for this study was the absence of robust independent data on the performance of FWD units under UK conditions. Widescale FWD unit use in the UK does not currently exist and a large number of significant assumptions relating to their possible deployment had to be made. It is usual when considering such 'new' approaches to give the benefit-of-doubt to technical performance claims unless there are sound, reasonable grounds on which to reject those claims and this approach has been adopted here.

Attention is drawn to a number of constraints and key assumptions which were made in order to facilitate the use of a simple modelling approach:

i) **Active participation rate** – Not all of the householders in any area will take an active role in recycling or reuse of materials. The report of the WRAP trials makes reference to two measures to quantify this; the "participation rate" and the "set-out rate". A household which set-out food waste for collection at least once during a three week monitoring period was considered to be participating whilst the number of households setting out food waste for any one collection gave the set-out rate. Typically the set-out rate is a little lower than the participation rate and the difference reflects occasions when participating households have no food waste, miss setting-out or may use some other disposal route. The set-out rate largely determines the amount of, and costs of food waste collection.

    However, for the purposes of this study a simple assumption was used that only a single fixed proportion of the population would contribute to kerbside collection or FWD unit use. This proportion has been termed here the "active participation rate" and is assumed to be the same for both kerbside collection and FWD unit use.

    Modelling has been conducted for two levels for the active participation rate (Case 1 = 60% for options A and B and Case 2 = 80% for options A and B) in order to compare the effect of this on costs. The lower rate (60%) has been selected as this represents the level of kerbside collection which can be readily achieved across relatively large urban areas. The higher rate (80%) has been selected as this represents the achievement of a good collection level. These active participation rates used have been selected based on the range of participation rates reported in trials conducted by WRAP (WRAP 2008b).

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[1] An updated version of this report was subsequently published by WRAP in June 2009.

FWD units are not widely used in the UK so there are no directly comparable data on which to select a corresponding "active participation rate" or range of rates. There are two steps limiting FWD unit use; firstly a unit must be physically installed and secondly the householder must then choose to use it. In formulating the assumptions for this study it has been recognised that the time taken to install sufficient FWD units to achieve the 60 and 80% active participation rates could be considerable. No attempt has been made to model this uptake period. It has, therefore, been assumed that the same proportion of the population would potentially install and use FWD units as would take advantage of kerbside food waste collection (i.e. 60% and 80%). This assumption has been made so that the costs of the two collection options can be directly compared.

Active participating households in the FWD option would need to have FWD units installed. It has been assumed that only the absolute minimum number of these FWD units would need to be installed. That is for Case 1 only 60% of households would install FWD units. As a result of this all of these units would be fully utilised throughout the assessment period. This assumption is favourable to the FWD unit option as in reality some additional FWD units would need to be installed to achieve the 60% active participation rate at all times.

i) **Quantity of food waste –** The amount of food waste produced by different households and the quantity of this food waste which can be collected at the kerbside or diverted to FWD units varies. Three UK studies (Biffaward 2002, WRAP 2008b & Harder & Woodard 2009) have been briefly reviewed and the results are discussed in Section 3.1. On the basis of the data presented in these studies it has been assumed here that the quantity of food waste collected or diverted to FWD units by each actively participating household would be 2.9 kg/week[2].

The model cannot be used to determine which option (kerbside collection of FWD unit) would be preferred by individual householders or which would be most effective in collecting food waste.

ii) **Timescale for roll-out of the FWD unit option –** Kerbside collection can be rolled out relatively rapidly across a collection area whilst the installation of FWD units could take considerably longer. If food waste collection were an approach used as a part of meeting meet landfill diversion targets, then it is possible that both approaches would have to operate in the same area in parallel until the level of FWD unit installation and use reached the necessary level. Many factors would affect the rate of FWD unit roll-out, particularly the use of any financial incentives or of collection service charges. The financial incentivisation of FWD units would only be considered if this option were

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[2] Subsequent experience from food waste collection trials would indicate that typical values may be a little higher at 3.3 kg/hhd/week.

considered to be favourable in the long-run. This study has not concerned with approaches to incentivisation of FWD units and so this intermediate stage has not been considered here. Instead the modelling considers only the end-point for FWD installation when the required level (60% or 80%) has already been achieved.

iii) **Transport of food waste in the sewer -** The behaviour of food waste when discharged to the sewer has been the subject of some debate. As a desk study the current work can shed little additional light on these issues but it is necessary to make some assumptions about this behaviour and the effects on the operation and maintenance of the existing infrastructure of sewers, pumping stations and storm overflows. In particular, it is not clear if the addition of food waste, which would be present primarily as particulate material, would aggravate blockage formation within the sewer.

In the absence of conclusive data for UK sewer networks it has been assumed in the base case used here that the addition of food waste would have no adverse effect on the sewer blockage rate. This assumption is favourable to the FWD option. To further investigate any possible effects, the additional costs associated with sewer blockages have been calculated for two further situations based on Case 1B(60% active participation): Case 1B.1 – as Case 1 but where the addition of food waste results in a 25% increase in sewer blockage rate and Case 4 – as Case 1 but where food waste results in a 50% increase.

Biological activity is known to occur within sewers and a further possibility is that food waste could be partially or completely biologically oxidised during the period of conveyance within the sewer. This would not occur to the same extent in all sewers as biological oxidation is dependent upon factors such as the retention time in the sewer, temperature, the availability of oxygen and the extent of biofilm formation within the sewer. In the absence of conclusive data it has been assumed in all cases considered here that no reduction in the organic content (as indicated by the BOD or COD values) occurs as a result of any processes occurring during conveyance within the sewer.

iv) **Treatment of food waste at the wastewater treatment works** – The addition of food waste will result in an increase in both the organic and particulate content of the domestic sewage. As the particulate matter is fine organic solids it has been assumed that none of this would be removed during the preliminary wastewater treatment processes of grit and screenings removal. The particle size distribution of the food waste is likely to differ from that of domestic sewage and consequently the removal of particulate matter achieved by primary settlement may differ from that of sewage. The assumptions used in the model for this process stage are discussed in Section 3.3. Not all of the organic material is removed by primary settlement and some additional organic load will pass to the secondary treatment process, resulting in additional operating costs. The additional operating cost has been estimated and included in the results produced. It has been proposed in some studies that the additional organic material may benefit the operation of the secondary process by, for example, enhancing biological nitrogen removal. There was insufficient information available on which to estimate any such general financial benefit and no allowance for this was included. The detailed process assumptions used in this modelling are set out in Section 3.3 and in Appendix A.

v) **WwTW sludge treatment -** There are a wide range of possible treatment options for food waste which is discharged to the sewer and enters the WwTW sludge stream. Currently about 60% of the sludge from UK WwTW is treated by AD with beneficial re-use in agriculture of the resulting stabilised biosolids. There is now a further trend to apply the thermal hydroloysis process (THP) as a pre-treatment process prior to anaerobic digestion to increase volatile solids destruction and improve the quality of the organic products. The combined THP/AD process route was selected on the basis of expert water industry advice as the basis for comparison with the segregated collection route in the modelling work as representing good practice in terms of both achieving compliance with the Animal By-Products Regulations and maximising the recovery of energy value from the food waste stream. The resulting treated organic product is then dewatered to facilitate storage and transportation and applied beneficially to agricultural land.

It should be noted that for WwTW sites where other sludge treatment options have been adopted (such as incineration) the effect of the addition of food waste may be to increase operating costs due to the increased solids mass but with little benefit to mitigate these increased costs. The option selected for the comparison here is, therefore, generally favourable to the use of FWD units.

vi) **Segregated food waste treatment -** Many options are available for the treatment of segregated food waste. It is important to have a similar degree of food waste treatment for all the options considered to avoid introducing any bias into the options assessment. Two options have been considered; these being a thermal hydrolysis process followed by mesophilic anaerobic digestion (THP/AD) and aerobic in-vessel composting (IVC). In both cases the resulting treated organic products are assumed to be Quality Protocol-compliant and therefore beneficially used in agriculture. Product from the THP/AD is a liquid digestate which is dewatered to facilitate storage, transportation and spreading.

2. Methodology

2.1 Summary

The approach used in this study has been to estimate the GHG emissions and financial costs associated with a simple "model catchment" for the three alternative food waste collection and treatment options as defined in the Scope of Work (Section 1.2) over a fixed period of time. The GHG emissions were then monetised using the shadow price of carbon (SPC) and combined with the financial costs to provide a total net present value (NPV) for each option over that time period. The results have then been compared to identify areas of similarity and difference. To facilitate comparison, as far as reasonably possible, factors common to all options have been excluded from the analysis. **The costs and emissions presented, therefore, do not represent the total for a particular option but focus on the areas of potentially significant difference (i.e. marginal cost analysis).**

Where possible, assumptions and parameter values for this model have been taken from recognised sources which were readily available to WRc at the time of the study. The values used have been selected on the basis of engineering judgement and the selection of particular values is not supported here by a detailed review of possible alternatives. In view of the large number of parameter values required within the model, sensitivity analyses have not been presented.

A general description of the methodology and key assumptions is given below and discussed in Section 5. More detailed assumptions are tabulated in Appendix A and the more significant calculations are illustrated in Appendix D. Some calculations also included illustrate individual factors which have been shown not to be significant.

Where appropriate, all costs and emissions have been expressed on a common basis as "per tonne" (/t) on a wet food waste weight basis to facilitate comparison. The dry solids content of food waste has been assumed to be 30.0% (Appendix A, Table A.6).

2.2 Greenhouse gas emissions

The emissions of three significant greenhouse gases have been considered; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Emissions of CH_4 and N_2O have been expressed as CO_2 equivalent (CO_2e) based on widely recognised conversion factors (IPCC 2006). Estimates include both operational and embedded GHG emissions.

Operational emissions arising from the transportation and delivery of any significant quantities of chemicals used were included together with the embodied carbon associated with the production of the chemicals themselves.

As far as practically possible, a common approach has been taken to the estimation of embedded emissions. The embodied carbon in any "new" capital assets required was estimated. For scenarios involving thermal hydrolysis and in-vessel composting, the material requirements (steel, concrete etc.) for a fixed plant size were derived from the "WRATE" LCA tool (Environment Agency 2008). Where necessary appropriate emission factors (EFs) were sourced from literature and applied (Hammond & Jones 2006, UKWIR 2008). To these were added a factor to account for the processing of the materials into components and the values were then summed. A factor was used to account for transportation of components to site for construction. A conversion factor was then applied to determine the embodied carbon in plants of differing size.

The CO_2 emissions arising from vehicle fuel associated with transport used in clearing sewer blockages were assessed. However, CH_4 and CO_2 emissions from within the sewer were not included because of the short residence time assumed in sewer transit.

Emissions and costs associated with the fuel used to transport the treated organic products were included in the estimates. Process emissions of CH_4 and/or N_2O from land (including during the storage phase), were also included. The embodied carbon in the vehicles used for transport was included.

Emissions from the use of tractors at the farm used for application of the organic products were excluded, as was the potential gain from long-term carbon sequestration into the soil from the deposited products.

No direct emissions are associated with the financial cost of labour.

Some further elaboration on the assumptions and calculation of GHG emissions is given in Appendix C.

2.3 Economic analysis

Whilst a financial cost analysis considers only the direct costs to companies, a full economic analysis considers these financial costs together with external costs to society. By their nature, external costs do not have revealed market prices and so require the use of economic valuation techniques. External costs are often intangible (e.g. change in welfare level) and, as a result, difficult to value.

The components of costs included in this economic analysis include the following.

- Capital Expenditure (Capex) – the cost incurred to acquire physical assets. These costs may be incurred by water companies, local authorities, waste collection contractors or individual householders.

- Operating Expenditure (Opex) – recurring costs associated with the operation of the asset base over the period of analysis. Again these costs may be incurred by the various participants within the schemes.

- External costs – costs resulting from a transaction/action that are not borne by the buyer of a good/service. The cost of carbon has been included in this analysis.

2.3.1 Period of analysis and asset lifetime

To enable comparison on a common basis this assessment has been conducted over a project lifetime of 25 years. All capital items (e.g. FWD units, bins, vehicles and treatment plant) have been assigned a nominal economic working lifetime and are assumed to be fully replaced at the end of that period. A straight-line depreciation has been assumed for each asset and no residual (scrap or waste) value has been given to assets at the end of their working lifetime. Where assets have been renewed and have a residual working life at the end of the 25 year assessment period, the discounted residual value of the asset has been calculated and subtracted from the total Capex NPV for that asset. This approach to asset costing is broadly consistent with the methodological framework proposed by Ofwat for "first cut analysis" of water companies business plan costs for medium lived non-infrastructure assets (Ofwat 2003).

Generally, within the water industry, treatment plants with a major civil works component would be expected to have an asset lifetime of 60 years, whilst mechanical assets and associated electrical plant would have shorter lifetimes of 16 to 30 years and instrumentation, control and automation elements would have still shorter lifetimes of 6 to 15 years (Utility Regulator 2010). These items would require renewal or refurbishment at occasional intervals over the lifetime of the civil assets. For water industry non-infrastructure (treatment plant) assets Ofwat suggest the use of a general asset life profile for medium lived assets of: 5% = 10 years, 80% = 20 years and 15% = 60 years (Ofwat 2003). However, there is insufficient experience of dedicated food waste treatment assets to make a reliable estimate for their asset lifetime. Anaerobic digestion plants constructed to date appear to favour the use of coated steel sheet construction for vessels, which may give much shorter operational lifetimes than corresponding concrete vessels. It would seem unlikely that the waste industry would anticipate asset lifetimes for such plants of up to 60 years as may be expected in the water sector.

To accommodate these differences all treatment plant assets have been given a single uniform economic lifetime of 25 years and, therefore, have no residual asset value at the end of the assessment period.

2.3.2 Discounting

Discounting is a technique used to convert future costs into present values, thus enabling the comparison of costs that occur in different time periods. Expenditure in Year 1 has been calculated at Q3 2007 prices. Expenditure in subsequent years has been discounted. Different discount rates should be applied to social and financial costs.

Financial costs (i.e. Capex and Opex) should be discounted using the cost of capital (also referred to as the ‘private discount rate’). This is the rate of return required for providers of capital to invest in a privately-owned company/asset base. The cost of capital calculated for each private company encompasses the company’s debt and cost of equity; hence, it reflects the level of risk involved in an investment. Private discount rates are commonly in the region of 5-6%, but there is no single standardised value for use in generic economic evaluation. In the latest water industry periodic review (PR04) individual water and sewerage companies submitted business plans based on rates ranging from 5.0 to 5.5%. For the generally smaller water only companies rates ranged from 5.7 to 6.5%. In the event the weighted average cost of capital for 2005-2009 was set at 5.1% (post tax) for the purposes of the final water industry price determination (Ofwat 2004). In this study, a private discount rate of 5.5% has been adopted, for consistency, across water industry and waste industry expenditure. The Social Time Preference Rate (STPR), commonly referred to as the ‘social discount rate’ should be applied to non-financial, external costs. This rate has two components embedded in it: assumed rate of time preference (i.e. the rate at which individuals discount future consumption over present consumption) and annual growth in real per capita consumption (reflecting that future consumption will be higher relative to the current position). The HM Treasury Green Book recommends a standard social discount rate of 3.5% (HM Treasury, 2003).

2.3.3 Capital expenditure (Capex)

Generally, capital costs of large items, such as treatment plant have been estimated using cost functions derived from available data for similar plants. Costs were built up, where appropriate, from the water industry cost database TR61 version 8.0 (WRc 2006). Where necessary, historical capital costs have been adjusted for price-cost inflation, using appropriate cost indices, to a common base value at Q3, 2007.

For wastewater assets only the marginal additional capacity required for the food waste component has been considered. This has been estimated by calculating the treatment plant requirements with and without the food waste component and then calculating the difference between these. No “headroom” in treatment capacity has been assumed and all treatment plant requirements have been costed on the assumption that they would be provided at the start of Year 1.

2.3.4 Operational expenditure (Opex)

Fuel and electricity used in the sludge treatment processes have been included. For anaerobic digestion all the available heat is considered to be used within the process itself, whereas excess electricity is exported and Renewable Obligation Certificates (ROCs) generated. Sale of ROCs provides a valuable source of income and a constant value of

£45/MWh has been assumed throughout the period. The energy required to generate a ROC is banded to provide different levels of support for differing technologies depending upon the maturity and risk associated with each technology. Under the current banding arrangements, electricity generation from landfill gas requires 4MWh/ROC but that from 'sewage gas' requires 2MWh/ROC. Emerging technologies, which include anaerobic digestion of food waste, require only 0.5MWh/ROC (Statutory Instrument No. 785, 2009).

It is assumed that the resulting treated organic products are made available free-of-charge to the agricultural or horticultural outlet.

No financial provision has been made for the purchase or development of land required for transport, storage or treatment facilities. Typically these factors are highly site specific depending upon land availability and the local infrastructure.

2.3.5 Shadow price of carbon

The adverse effects of greenhouse gas emissions have been "monetised" by calculating the shadow price of carbon (SPC) emitted following the approach proposed by Defra (2007). Briefly, the annual GHG emissions are estimated as the carbon dioxide equivalent and converted to a monetary value using an SPC conversion factor. Currently, Defra recommend that the SPC conversion factor is escalated at a rate of 2% per annum to reflect the increasing harm caused by such emissions. This monetised cost is then discounted using the social time preference rate of 3.5% per annum over the project lifetime to produce a net present value. The SPC NPV can then be directly added to the NPV derived for other financial elements of the project to give the total NPV. For clarity, the three components are shown separately in results tables; that is the GHG emissions (as CO_2e), the monetised GHG emissions (as SPC NPV) and the total financial costs (as total NPV).

3. Modelling of Alternative Options

3.1 Model catchment, food waste arisings and food waste properties

A model catchment of some 400,000 people has been used in this study to represent an urban area typical of the situation in which food waste management is an emerging issue. The main parameters describing this catchment are summarised in Table 3.1 and Appendix A, Table A.2. Quantities have been calculated on the basis of the collection of Case 1 60% and Case 2 80% of the total collectable food waste. Selection of these various parameter values is briefly discussed below.

Table 3.1 Model catchment parameters

Parameter	Value	Unit	Comment
Total population	400,256	people	Assumed value
Average size of household	2.36	people /hhd	UK average
Total number of households	169,600	households (hhd)	Calculated value (400256 / 2.36)
Average food waste available for collection	2.90	kg/hhd/wk (as wet food weight)	Assumed value based on UK trials data (Biffaward 2002, WRAP 2008b and Harder & Woodard 2009)
Total collectable food waste in model catchment	25,575	tonnes/year	Calculated value (169,600 * 2.9 * 52 / 1000)
Proportion of households supplied with kitchen caddies and bins	100	%	-
Proportion of households setting out food waste for kerbside collection (active participation rate)	Case 1: 60 Case 2: 80	%	Assumed values
Proportion of households with FWD units installed (active participation rate)	Case 1: 60 Case 2: 80	%	Assumed market penetration selected to correspond with kerbside collection rates used (see also New York City DEP 1997, Galil & Yaacov 2001

Parameter	Value	Unit	Comment
			and Marashlian & El-Fadel 2005)
Proportion of collectable kitchen waste diverted via FWD units in households where FWD units are installed	100 %		Assumed FWD unit use (see for example Karlberg & Norm 1999, de Koning & van der Graaf 1996 and Lundie & Peters 2005)
Total number of actively participating households	Case 1: 101,760 Case 2: 135,680	hhd	Calculated
Total collectable food waste from participating households	Case 1: 15,345 Case 2: 20,461	tonnes/year	Calculated
Dry solids content of wet food waste	30	%	de Koning (2004)
Total dry solids of collectable food waste	Case 1: 4,604 Case 2: 6,138	tonnes/year	Calculated

The model catchment size has been selected to be representative of the larger urban areas in the UK (e.g. Bristol - c 450,000 population). Numerically there are many smaller towns in the region of 50,000 to 250,000 population and modelling these would be a very similar process although they would be less likely to support a dedicated treatment facility and therefore transportation assumptions would be more complex. The average household size is typical of the UK.

The quantity of “collectable” food waste has been more difficult to select. In a study conducted in 2001/02 by the University of Southampton and the anaerobic digestion plant operator Greenfinch Ltd., the kerbside collection of segregated food waste from 80 to 120 households resulted in an overall average yield of food waste of 2.94 kg/household per week (Biffaward 2002). Although the average household size was not reported, the residents were described as typically “retired” with household size of 1 or 2 persons. The contamination level of the food waste was reported to be low (<2.5%). Extensive kerbside collection trials for food waste were conducted by 19 local authorities in 2007/08 supported by funding from WRAP. The evaluation of these data demonstrated that the food waste collected was variable and was influenced by a variety of factors including housing type, socio-economic characteristics and the waste collection regime. Most effective collection was achieved with weekly food waste collection and fortnightly residual refuse collection (WRAP 2008b). Using data from areas with fortnightly refuse collection, the average food waste collected by a kerbside food waste collection service was 1.74 kg/hhd/week, with an average participation rate of 65.8% of households. Based on these values the average quantity of food waste set out by each participating household would have been 2.64 kg/hhd/week (1.74 * 100 / 65.8). More recently

Harder and Woodard (2009) have investigated the effect of home food waste digesters (“Green Cone” device) on the composition of residual waste from 153 households. The average yield of “GC-desirable” material for the control period was reported to be 3.0 kg/household per week.

Studies conducted by WRAP indicate that kerbside collection does not capture all of the household food waste produced. Some of this other food waste is discarded to the residual waste (e.g. as unopened packaged food or as food residues on discarded packaging materials) whilst a further quantity (mainly fluids) is disposed of to the sewer via the kitchen sink. This material has been excluded from this analysis.

The composition of domestic kitchen food waste is variable, and as a material stream, it is not well defined. There is no widely recognised classification scheme for food waste components and the reported studies are more difficult to compare directly. Composition data from three studies were briefly examined (Biffaward 2002, Bolzonella *et al.* 2003 and WRAP 2008c). These studies indicate that cooked and un-cooked fruit and vegetables form the bulk of the waste (typically 60 to 70%), followed by a group variously comprising bread, pasta, rice and cereals (7 to 30%), with smaller amounts of meat and fish (5 to 13%). Few data were available on the content of bones and other dense materials, e.g. seeds, nuts, which may be expected to be more problematic for the sewer disposal route.

To provide a simple comparable basis for this study the average “collectable” food waste has been assumed to be 2.90 kg/household per week (as wet weight of food waste - wfw) or 150.8 kg/hhd/year on average. It has been assumed that, over the long-term, 60% of households would actively participate in weekly food waste collection (Case 1). All of the collectable food waste from the participating households is assumed to be diverted via the specified food waste collection route. It is assumed that these parameters do not change over the 25 year assessment period. It is assumed that the method of collection (kerbside or FWD unit) does not change the total quantity of food waste or the quantities passing to other disposal routes (e.g. residual waste or home composting) and so consideration of these has been excluded from the scope of this assessment.

Recognising that participation in food waste collection may increase over time the modelling has been repeated for a 80% actively participating households (Case 2) to establish to what extent the two main collection routes are sensitive to this factor.

Within this simplified catchment no differentiation has been made between type of household dwelling (e.g. between flats or houses) or the socio-economic distribution of the population. For the purposes of collection-round calculations all dwellings have been assumed to be geographically uniformly distributed within the catchment and no additional time allowance has been made for collection from flats.

Segregated kerbside collection

In Option A, where kerbside collection is used, caddies and kerbside bins are assumed to be provided at the outset (start of Year 1) to all households. These items are each assumed to have a typical lifetime of 7 years and are replaced for all households at the start of years 8, 15 and 22. The residual value of caddies and bins remaining in use at the end of Year 25 has been included in the economic analysis. No routine maintenance costs are assumed. This approach differs to that often used for kerbside collection in which all properties are supplied initially and then an annual replacement rate is assumed for subsequent years. The two approaches give similar overall costs providing that the average lifetime bins and caddies is the same in both analyses[3].

It is assumed that participating households make use of biodegradable bin liners and that average weekly use is 2 liners per participating household. Estimates of the cost of such liners has been found to vary widely from about 2 pence to 10 pence each. The lower cost relates to bulk purchase by collection authorities where these are then supplied free-of-charge to residents and the higher to individual purchases from local shops or internet suppliers. A mid-range cost of 5 pence has been assumed here. In practice not all households would purchase liners (some may use newspaper or not use a liner) but, of those that do, many would purchase these at a retail price nearer to 10 pence each.

Costs have also been calculated for water used for occasional washing of the caddies or bins. A value of 6 litres per household per year has been assumed based on a value provided in the Waste and Resources Assessment Tool for the Environment (WRATE) database.

FWD unit use

In Option B, where FWD units are installed, it is assumed that these are used in a similar way to kerbside collection. It is assumed that FWD units are installed in 60% (Case 1) of all households (the actively participating households) and that FWD units are not installed in the remaining 40% of “non-participating” households. In participating households, the average throughput of each FWD unit is assumed to be the same as the collectable food waste (2.90 kg of grindable food waste per household per week as wet food waste). These two assumptions have been adopted to ensure that both Option A and Option B divert similar amounts of food waste from other disposal routes.

Market penetration of FWD units in the USA has been described as reaching 50% over a period of 60 years of marketing (de Koning & Graaf, van der 1996) whilst a study by Shpiner (cited in Galil & Yaacov 2001) estimated that FWD use in residential areas in Israel would not

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[3] Subsequent experience from food waste collection trials would indicate that a typical bin/caddy replacement rate might be 5% per year, indicating a lifetime of c 20 years.

exceed 60% in the near future. Marashlian and El-Fadel (2005) considered a range of possible market penetration cases in a study for the Greater Beirut Area ranging from 25 to 75%. The market penetration values of 60% and 80% for FWD units assumed in this study are, therefore, high expectations but are similar to the range of values which have been considered in similar impact assessment studies.

It is also evident that FWD units are not suitable for the disposal of all types of food waste. However, estimates of the quantity of food waste produced and of the proportion of this which is “grindable” both vary widely. In discussing possible food waste diversion in a Dutch study, de Koning & van der Graaf (1996) assumed that the annual quantity of “grindable” food waste was 44 kg/person whilst Karlberg & Norm (1999) assumed 50 kg/person based on data from two Swedish studies. Assumptions given by Galil and Shpiner (2001) correspond to an estimate for Israel of 63.2 to 79.0 kg/person per year. A later desk study by Lundie & Peters (2005) assumed the equivalent of 86.7 kg/person per year based on data for the Waverley Council area of Sydney. For the University of Wisconsin study, the assumed food waste production was 100 kg in a little over a year for an average US family of 2.63 giving a lower value of 38 kg/person (reported in Strutz 1998).

The assumptions used here for FWD units are the same as those for kerbside collection and are based on the three recent UK studies discussed above in relation to “collectable” food waste (Biffaward 2002, WRAP 2008b and Harder & Woodard 2009). This equates to 150.8 kg/hhd/year for an average household of 2.36 persons or 63.9 kg/person per year. Since the main components of this comprise vegetables, fruit, bread, pasta, meat and fish it has been further assumed that all of this would potentially be “grindable”.

Manufacturers recommend the use of a flow of cold water (supplied from the kitchen tap) during FWD unit operation but estimates of the total quantity of water used vary widely. In practice, operation of the FWD unit is dependent on householder behaviour and habits. It may coincide with other routine water use (such as sink cleaning following food preparation) and so the FWD unit water-use itself may not necessarily be entirely additional to the normal kitchen water use. De Koning & van der Graaf (1996) assumed an additional water use of 4.5 l/person/day equating to 10.7 l/hhd/day (based on 2.36 persons per hhd) equivalent to a 3.3% increase in average daily water use. Galil and Shpiner (2001) collated water use values from eight other studies giving a range of FWD unit water use from 0.8 to 6.6 l/person/day.

The value used in this report, 7.38 l/FWD unit/day that equates to a *per capita* water use of 3.1 l/person/day, is based on a recent study for the Market Transformation Programme. It is derived from estimates of average frequency and duration of FWD unit use and average kitchen tap flow rates (Defra 2008). The average parameters presented in the study are summarised in Table A.3 of the Appendix A.

Using de Koning’s assumptions of 120 g food waste per person per day (44 kg/person/year) and 4.5 l/person/day, water use would be equivalent to 37.5 l/kg food waste. Lundie and Peters (2005) adopted a significantly lower estimate of 12.4 l/kg. The assumptions used here equate to an annual water use of 2694 l/FWD unit (7.38 * 365) for the disposal of 150.8 kg food waste. This gives a specific water use of 17.9 l/kg of food waste processed.

FWD units are assumed to have a lifetime of 12 years (Lundie and Peters 2005) and are installed at the start of Year 1 and renewed at the start of years 13 and 25. No residual value is attached to the units which are replaced at the end of their working lifetimes. However, because the final replacement occurs close to the end of the assessment period a credit is given for the residual value of the FWD units still in service of 11/12 of the discounted installed capital value. The FWD units are assumed to have no maintenance costs above the cost of replacement (Lundie and Peters 2005). Operating costs are calculated for the water and electricity used in typical operation. (These values are summarised in Appendix A, Table A.2.)

3.2 Collection and transport of food waste

It is assumed that food waste is either collected and conveyed by road vehicle (segregated kerbside collection options) or transported by gravity flow in the sewer (FWD unit options). In both cases the same total amount of food waste material is transported but the method and distances travelled differ.

Segregated kerbside collection

WRAP have published the results of trials of several approaches for the collection of food waste (WRAP 2008b). Various collection options exist (e.g. alternate weekly collection, use of single manned vehicles, co-collection with garden green waste in large refuse collection vehicles and co-collection with dry recyclables). The WRAP trials demonstrated that effective food waste collection could be achieved by collecting segregated food waste on a weekly basis using relatively small (7.5 tonnes gross vehicle weight) vehicles operating with a two-man crew and that approach has been adopted here. The published data provides a breakdown of the time spent in various collection stages and this has been used in the calculation of a typical collection “round”.

The collection area considered here results in a total collected food waste load of 15,345 t/year (Case 1) or 20,461 t/year (Case 2). Although these quantities could be treated in a small dedicated facility, recent indications are that larger units are likely to be favoured, probably serving several population centres. Dedicated food waste treatment plants have typically been reported to have capacities in the range of 45,000 to 60,000 t/year. The use of small collection vehicles becomes relatively uneconomic if the vehicle has to travel a large distance to such a treatment centre. To accommodate this, the model used assumes that the collection vehicles discharge at a local waste transfer station and that a further stage of transport to a treatment centre is then provided using larger bulk waste vehicles. It is assumed that no significant emissions or costs will arise from the waste transfer station itself as this station will provide only space for the temporary storage of collected food waste prior to onward transfer to the treatment plant, although the transfer station would require a permit (including annual subsistence fees) from the Environment Agency, and would be required to meet minimum engineering standards.

No provision has been made in the modelling for washing or sanitisation of the small collection vehicles. It is assumed that the larger bulk vehicles (or the transit skips used by them) would be cleaned at the treatment plant reception area.

The financial costs and emissions from road transport have been included for four main components: labour, vehicles, road fuel and tyre wear. Vehicle and tyre life have been based on mileage assumptions. These have been calculated as annualised costs and emissions based on the collection and transport distances required.

Vehicle’s maintenance costs (excluding tyres replacement) were omitted in this assessment.

FWD unit use

Transportation of food waste within the sewer is assumed to occur under gravity with the normal domestic wastewater flow together with the small additional flow due to FWD use (see Appendix D Table D.8). The inclusion of food waste to the extent considered in this model catchment would result in a substantial increase in the concentration of several wastewater pollutant parameters, particularly chemical oxygen demand (COD), biological oxygen demand (BOD) and suspended solids.

Occasional blockages occur in sewer systems and these can have significant financial and social impacts. The preferred good practice approach for clearing such blockages is to use high pressure jetting to break up the accumulated material, to extract this together with the water used for jetting and to deposit the material at the treatment works. For simple blockages clearance costs are relatively low but a small number of these blockages will result in more widespread flooding with increased clean-up costs. In a few cases internal foul sewage flooding of properties can occur, resulting in substantial remedial costs and distress to householders.

Characteristics of the sewer system considered, typical blockage rates and cost impacts are summarised in Appendix A, Table A.4. It is uncertain to what extent the use of FWD units would affect blockage rates. With this in mind a sensitivity analysis has been undertaken, with FWD units having different influences on blockages occurrence, as follows.

- FWD units will not alter the blockage rate (base case).
- FWD units will result in a 25% (Case 1B.1) and a 50% (Case 1B.2) increase in the incidence of blockages. There will be a similar increase in sewage related flooding caused by blockages, both external and inside property.

The results of this sensitivity analysis are given in section 4.2

Where sewers may include surface water run-off, provisions may be made for a direct, consented, overflow to a controlled surface water. Typically, such an overflow would require screening as a minimum degree of treatment but the screen aperture required (6 mm) is significantly greater than the particle size generated by FWD units. Overflow screening is, therefore, unlikely to significantly reduce any overflow of food waste. However, the extent to which storm overflows occur, and the resulting impact on surface water quality, are considered to be highly specific to the characteristics of an individual catchment and have not been considered further here.

The degree of wastewater pumping which occurs is widely variable, there is no pumping in some catchments but in others it may be necessary to pump the wastewater over relatively long distances. The model used includes provision for pumping all of the wastewater flow at the inlet of the wastewater treatment works.

3.3 Treatment of food waste organic products

The main purpose of the treatment of the food waste organic products is to render them suitable for disposal or beneficial re-use. Disposal options usually include some form of dewatering or drying followed by incineration (ideally with energy recovery) before landfilling of the resulting ash.

The primary beneficial re-use option for food waste is in agriculture or horticulture provided the food waste has undergone adequate treatment.

Segregated kerbside collection

In order that the residual material from kerbside collection can be safely applied to land the treatment process used needs to comply with the appropriate Animal By-Products Regulations (ABPR) (Statutory Instruments No. 2347 & 1293, 2005 & 2006) (Scottish statutory Instrument 411, 2003). Two main methods of treatment are specifically described in the regulations - composting and 'biogas digestion'. To be compliant, both require that the waste is protected from contact with any animal until it has been processed using the specified minimum heat treatment regime (70^{o}C for a minimum of 1 hour). For the purposes of this study two main ABPR-compliant options have been considered:

- Option A1 - in-vessel composting (IVC) and,
- Option A2 – a thermal hydrolysis process followed by anaerobic digestion (THP/AD) with energy recovery using a combined heat and power plant (CHP).

Other treatment options (such as steam pasteurisation followed by AD) may be ABPR-compliant but have not been included here.

In the IVC process option it is assumed that shredded domestic green waste is used as a bulking agent and that this is provided free of charge. The treatment and final disposal costs for this green waste are included in the food waste costs as this is a necessary element in the IVC option for food waste. The required mass ratio assumed is adjusted to give a combined dry solids basis content of 50%. The capital and operating costs of IVC treatment relate to the total mass composted (green waste plus food waste). The resulting compost is transported for beneficial use in agriculture. The fertiliser displacement value is calculated together with the emissions resulting from the added compost.

The corresponding value of ROCs can be claimed where renewable energy (heat or electrical power) are generated. For food waste treatment by anaerobic digestion this value equals to 0.5MWh per ROC.

FWD unit use

A number of studies were reviewed regarding the physical and treatment properties of ground or macerated food waste, particularly Bolzonella (2003), de Koning (2004) and a recent unpublished UK investigation (Thomas 2008). The studies were broadly consistent indicating that food waste is readily biodegradable (BOD_5/COD ratio 0.5 to 0.70), that a significant proportion of the total dry solids are particulate (c. 70%) with the remainder being either soluble or colloidal and that the particulate solids are readily settleable in primary treatment. The parameter values adopted here are summarised in Table 3.2.

Table 3.2 Assumed Food Waste Properties

Parameter	Value	Unit	Comment
Ratio of Food waste COD to food waste dry solids	1.5	-	Based on typical food waste composition of 50.5% C, 6.72% H, 39.6% O, 2.74% N and 0.44% S taken from de Koning 2004
Proportion of food waste volatile solids to total food waste solids	0.95	-	Estimated value derived from food waste study (Thomas 2008)
Proportion of total COD which is soluble	0.40	-	Derived from Bolzonella 2003 for organic waste
Ratio of BOD_5 to total COD	0.50	-	Derived from Bolzonella 2003 for organic waste
Removal of suspended solids in primary settlement	90	% of TSS	Taken from de Koning 2004 (see also Appendix D)
Removal of soluble COD in primary settlement	0	% of soluble COD	Assumed to be dissolved material

Parameter	Value	Unit	Comment
Removal of particulate COD in primary settlement	90	% of particulate COD	Follows from TSS removal assumption

Where FWD units are used the resulting food waste biosolids will be conveyed and co-treated together with domestic sewage. Readily settleable particulate material will be removed in the first stage of treatment (primary settlement) while less settleable, colloidal or dissolved matter will pass through to a secondary, biological treatment stage. At some treatment works a further tertiary treatment stage may be involved. Solids separated in the primary treatment stage are then treated further before disposal or re-use.

There are many possible process options for the various WwTW treatment stages and within the scope of this study it has not been possible to consider all of these. In practice, selection of the route of treatment for the resulting organic products will be driven primarily by the need to ensure a secure, long-term management option for the sewage organic products component. Option selection is strongly influenced by the local availability of suitable agricultural land, population density and the presence of trade waste.

The option considered here (Option B) comprises the following treatment process:

- primary treatment – assumes conventional gravity settlement only;
- secondary treatment – assumes nitrifying activated sludge process only;
- organic products treatment – assumes thickening followed by thermal hydrolysis process (THP) and anaerobic digestion (AD) with combined heat and power (CHP). Organic products are thickened before transport to agricultural land.

Anaerobic digestion is applied to approximately 60% of the sewage organic products produced in the UK but pre-treatment using THP is relatively new and is currently applied to a far smaller proportion.

The impact of food waste on secondary treatment will be dependent upon the removal in primary settlement. It is assumed here that 60% of sewage sludge solids are removed in primary settlement and that 90% of the food waste that is solid is removed in primary settlement. The soluble solids fraction of both sewage and food waste has been set at 30% and these are not removed in primary treatment. The additional electricity required for aeration and for pumping returned activated sludge (RAS) to treat this soluble load has been estimated together with the additional production of secondary sludge.

Appendix B provides mass flow diagrams for the COD and total suspended solids (TSS) of sewage and food waste that have been used in the model.

3.4 Transport and beneficial re-use of treated organic products

The resulting treated organic products from the segregated kerbside collection (IVC and THP/AD) and FWD unit option (THP/AD) are assumed to be dewatered and transported for beneficial use on agricultural land.

The use on land of treated organic products arising from food waste or sewage sludge will displace manufactured fertilisers that would otherwise be required. The key nutrients present in these organic products that could replace manufactured fertiliser requirements include nitrogen, phosphorus, potassium, sulphate, and lime. Application of the organic products will have other benefits such as improving the soil structure, microbial biomass and soil respiration, which are less easy to quantify. The concentrations of nutrients in the treated organic products used as the basis for the calculation of fertiliser offset are provided in Tables A.15 and A.16 in Appendix A. The application rate of sludge to land is taken to be 250 kg/ha based on total Nitrogen (total N). This is the limit set by the Nitrate Pollution Prevention Regulations 2008 (Statutory Instrument No. 2349, 2008) for spreading of organic manures in designated nitrate vulnerable zones, which apply to most arable land in England. Top-up of manufactured fertiliser may or may not be required depending on the concentration of key nutrients in the organic products, applied based on an application of 250 kg total N/ha, relative to the crop requirements for those nutrients. The avoided fertiliser use is the difference between what would have been used and what has been supplied by the organic products.

Nutrients from manufactured fertilisers will have an associated embodied carbon from their manufacture, packaging and transport to site of use which should be considered in this study. The embodied carbon values, and corresponding application requirements based on the needs of a winter wheat crop, are provided in Table 3.3 (Water UK 2009).

Table 3.3 Total GHG emissions (CO_2e) following the production, packaging and transport of manufactured fertiliser products required to supply a winter wheat crop at typical nutrient requirement levels (Water UK 2009)

Manufactured fertiliser product	CO_2e (kgCO2e/kg product)	Field application rate (kg/ha)	CO_2e (kg/ha)
N as ammonium nitrate	7.11	193	1370
P_2O_5 as triple super phosphate	1.85	62	115
K_2O as muriate of potash	1.76	76	135

Manufactured fertiliser product	CO_2e (kgCO2e/kg product)	Field application rate (kg/ha)	CO_2e (kg/ha)
SO_3 as ammonium sulphate	1.05	51	55
CaO as ground limestone	0.15	1360	205

3.5 Overview of main options considered

An overview of the three main options considered is shown diagrammatically in Figures 3.1, 3.2 and 3.3. The main inputs considered for each process stage are illustrated in the lower (yellow) callout shapes and the main GHG emissions considered are shown in the upper (blue) cloud shapes.

Figure 3.1 Option A1 – Segregated kerbside collection with IVC treatment and agricultural re-use

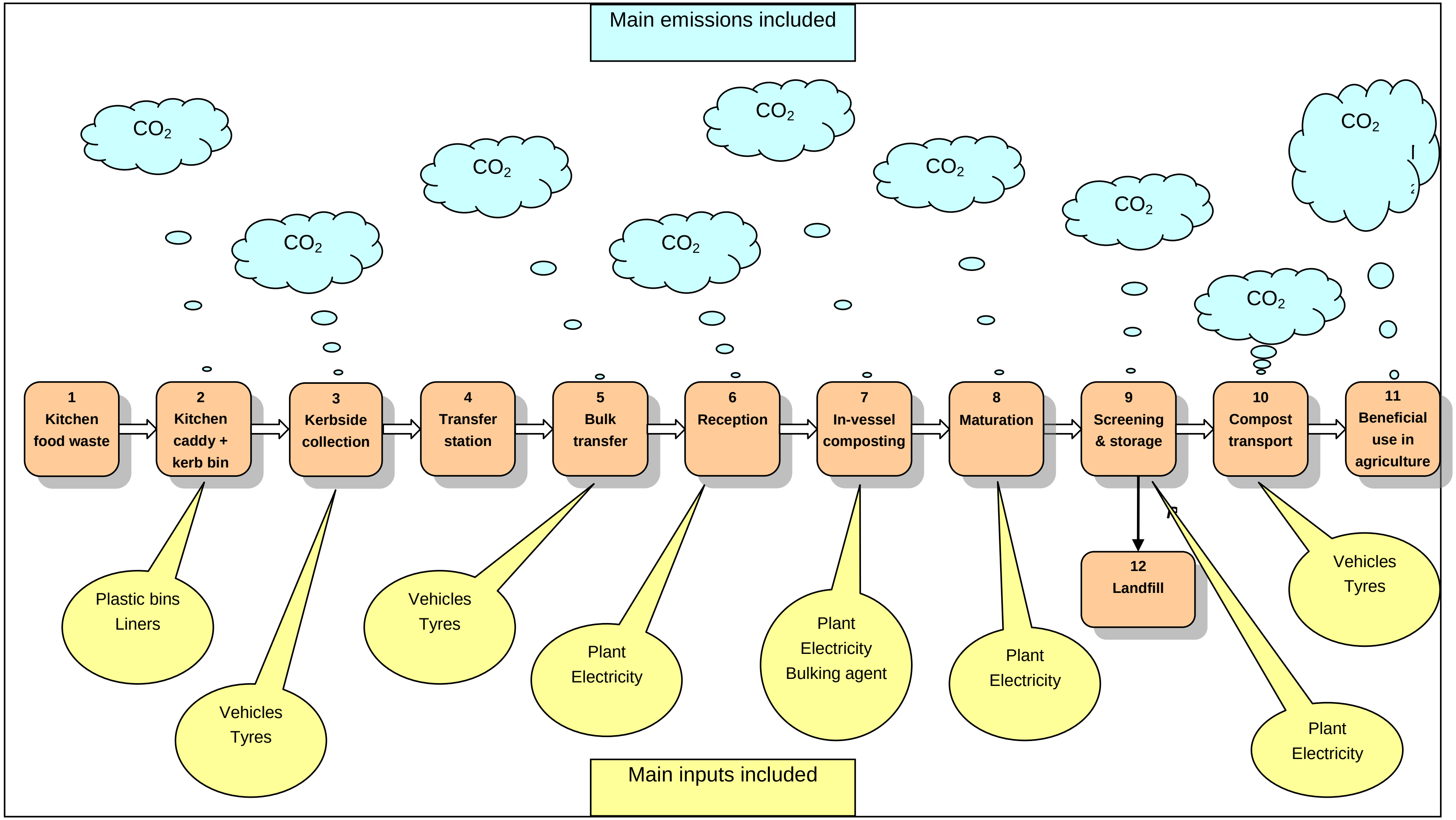


Figure 3.2 Option A2 – Segregated kerbside collection with THP/AD treatment and agricultural re-use

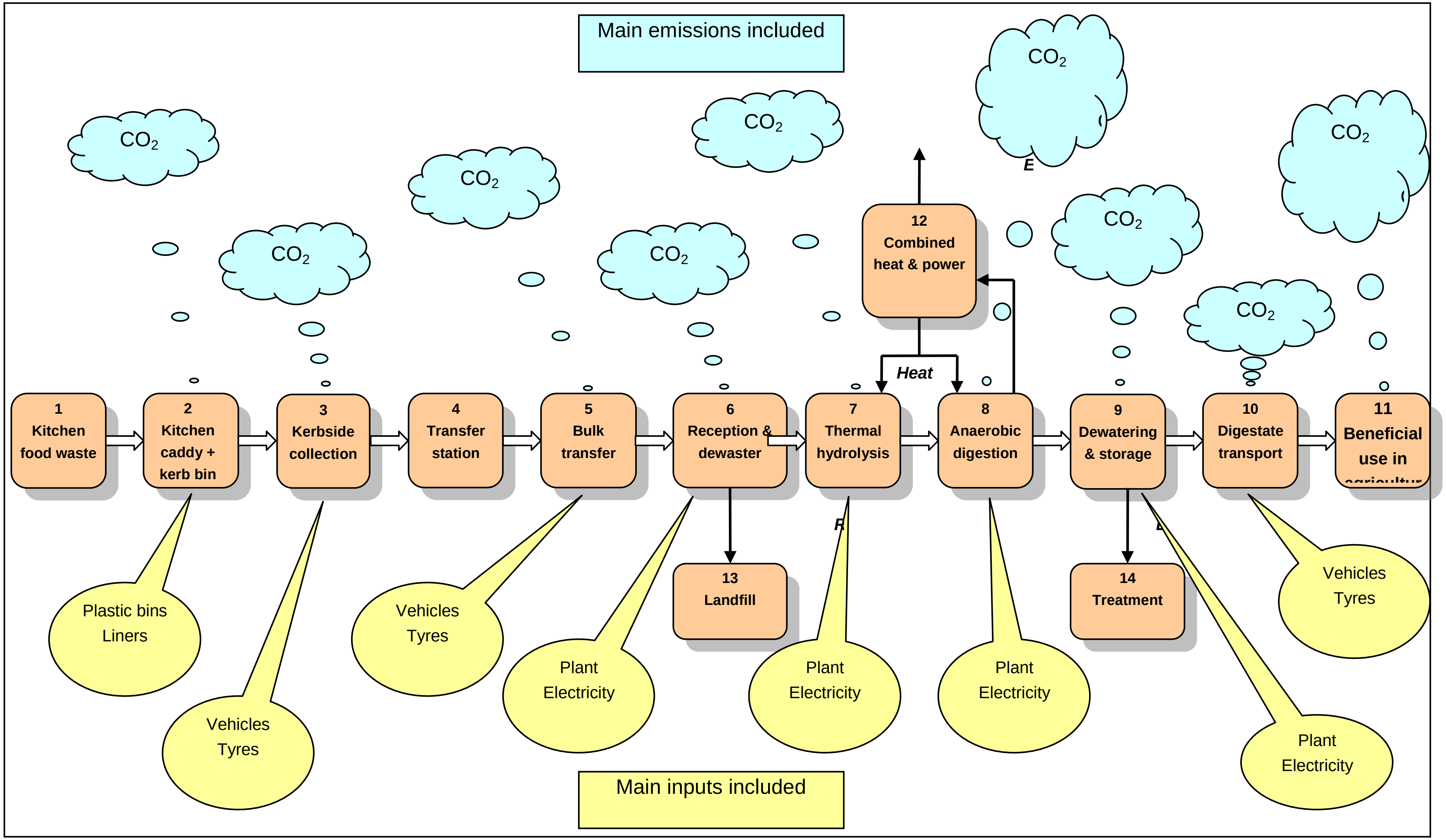
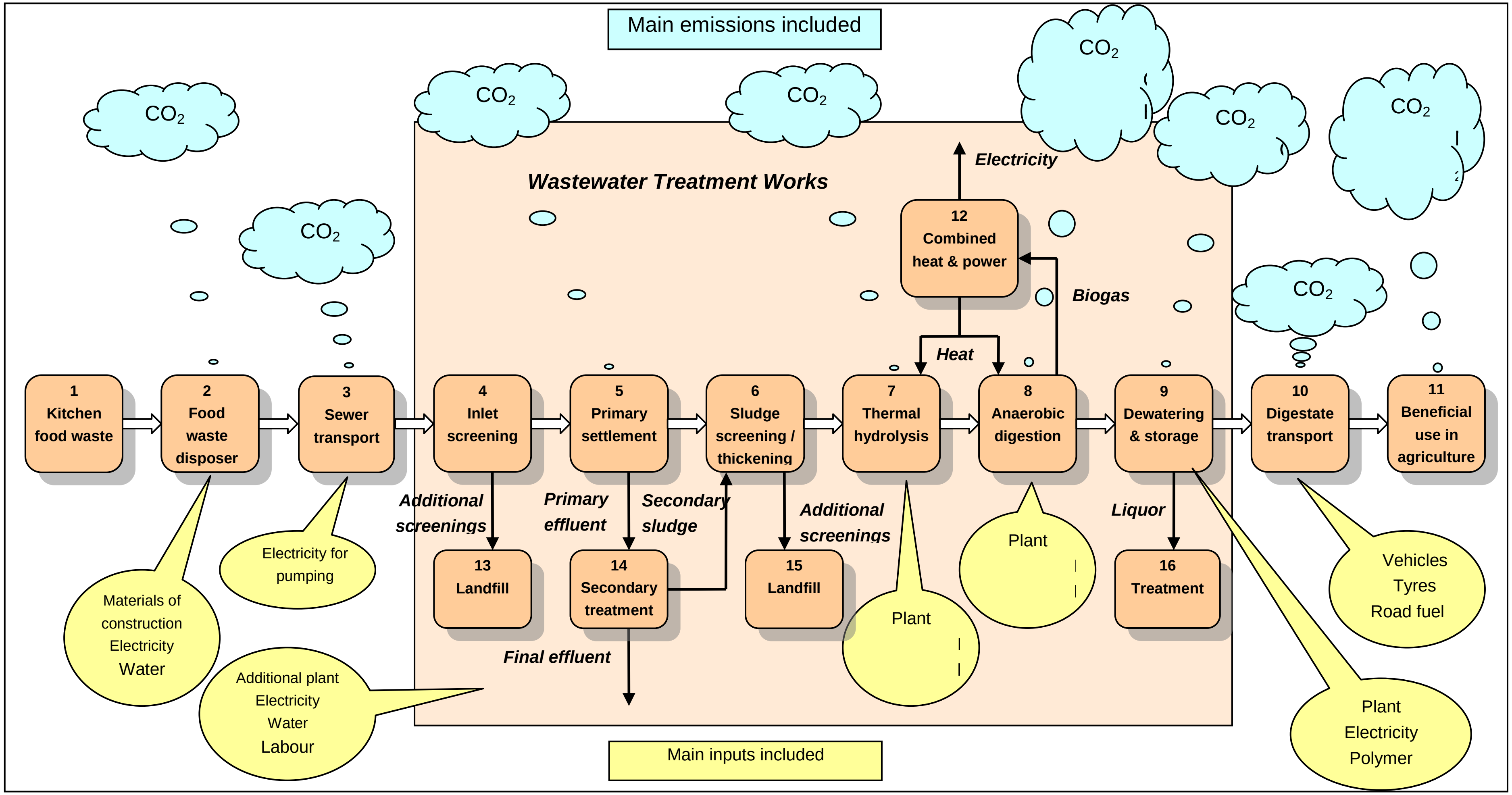


Figure 3.3 Option B – Use of FWD units and transport in sewer with THP/AD treatment and re-use in agriculture



4. Results

4.1 Process emissions and costs

The GHG emissions, shadow price of carbon (SPC) and overall financial NPV for the three main options considered (Options A1, A2 and B) were calculated for a number of relevant items. These were summarised into three main areas for each option:

i. collection and transport of food waste:

   a. options A1 and A2 - caddies, bins, bin liners, water for washing caddies and bins, kerbside and bulk collection vehicles, tyres, vehicle fuel and labour;

   b. option B - supply and installation of FWD units, electricity and water for FWD operation and electricity for wastewater pumping;

ii. treatment:

   a. option A1 - capital cost of IVC plant, electricity and fuel use in the IVC, labour, maintenance, emissions from bulking agent and from food waste composting;

   b. option A2 - capital cost of THP/AD plant, labour, maintenance, water used for process water, emissions from liquor treatment, digester, CHP and credits from sale of surplus electricity and ROCs;

   c. option B - capital cost of THP/AD plant and additional secondary treatment plant, electricity for additional secondary treatment plant, labour, maintenance, emissions from additional secondary treatment, liquor treatment, digester and CHP, credits from sale of surplus electricity and ROCs;

iii. beneficial use in agriculture:

   a. option A1 - vehicles, tyres, vehicle fuel, labour for transport and emissions associated with land use;

   b. option A2 and B - dewatering of digestate and emissions from storage, vehicles, tyres, vehicle fuel and labour for cake transport and emissions associated with land use.

The intent of the model was only to indicate the relative magnitude of the various emissions and costs. The results should not be considered to show the 'best option' as the outcome is strongly influenced by the various assumptions and estimates used in construction of the model itself. The results are summarised in Table 4.1 for Case 1 (60% active participation rate) and Table 4.2 for Case 2 (80% active participation rate), showing the GHG emissions, NPV of the emissions based on the shadow price of carbon and the overall financial NPV. All values are expressed **per tonne of wet food waste** and calculated for the 25 year assessment period.

Table 4.1 Summary of GHG emissions, SPC values and financial costs for main options (Case 1: 60% collection)

A1

Item	Total GHG emissions kgCO2e/tonne (wfw)	Discounted cost of GHG emissions (as SPC) £/tonne (wfw)	Financial cost (as NPV , inc. SPC) £/tonne (wfw)
Segregated kerbside collection			
Kitchen collection			
Supply of kitchen caddies	2.45	0.06	1.61
Supply of kerbside waste bin	8.52	0.20	4.53
Supply of biodegradable liners (1)	0.00	0.00	19.52
Wash water for caddies	0.01	0.00	0.02
Transport (dedicated kerbside collection and bulk transfer vehicles)			
Vehicles	0.64	0.02	5.20
Tyres	0.03	0.00	0.14
Vehicle fuel	17.78	0.45	5.48
Labour	N/A	N/A	44.72
Sub total	29.43	0.73	81.23
In-vessel composting with green waste			
Capital cost of IVC plant	1.68	0.04	9.62
Landfill of screenings	not included	not included	not included
Electricity use - composting	8.27	0.18	0.66
Diesel use	3.74	0.08	3.01
Labour	N/A	N/A	3.04
Maintenance			
Bulking agent (3)	1.01	0.02	0.02
N2O emission - returned liquor	None	N/A	N/A
CH4 & N2O - composting stage	128.64	2.87	2.87
Credit from sale of electricity	N/A	N/A	N/A
Credit from sale of ROCs	N/A	N/A	N/A
Sub total	143.34	3.21	19.24
Beneficial use in agriculture			
Compost transport			
Vehicles	0.03	0.00	0.48
Tyres	0.00	0.00	0.01
Vehicle fuel	1.86	0.04	0.50
Labour	N/A	N/A	1.79
Spreading & land emissions	-7.63	-0.17	-0.17
Sub total	-5.74	-0.13	2.61
Total	**167.04**	**3.81**	**103.08**

A2

Item	Total GHG emissions kgCO2e/tonne (wfw)	Discounted cost of GHG emissions (as SPC) £/tonne (wfw)	Financial cost (as NPV , inc. SPC) £/tonne (wfw)
Segregated kerbside collection			
Supply of kitchen caddies	2.45	0.06	1.61
Supply of kerbside waste bin	8.52	0.20	4.53
Supply of biodegradable liners (1)	0.00	0.00	19.52
Wash water for caddies	0.01	0.00	0.02
Vehicles	0.64	0.02	5.20
Tyres	0.03	0.00	0.14
Vehicle fuel	17.78	0.45	5.48
Labour	N/A	N/A	44.72
Sub total	29.43	0.73	81.23
Thermophilic hydrolysis & anaerobic digestion with energy recovery			
Segregated food waste only			
Capital cost of THP/AD plant	5.13	0.00	29.07
Landfill of screenings	not included	not included	not included
Electricity use (aeration,digestion de-waster)(4)	N/A	N/A	N/A
Diesel use	N/A	N/A	N/A
Labour	N/A	N/A	3.04
Maintenance	N/A	N/A	8.00
Water	0.01	0.00	1.13
N2O emission - returned liquor	0.82	0.02	0.02
CH4 emission - digester & CHP	51.00	1.14	1.14
Credit from sale of electricity	N/A	N/A	-10.70
Financial credit from sale of ROCs	N/A	N/A	-17.51
Sub total	56.96	1.16	14.19
Beneficial use in agriculture			
Digestate dewatering & transport			
Dewatering & cake storage	3.67	0.08	0.49
Vehicles	0.01	0.00	0.21
Tyres	0.00	0.00	0.00
Vehicle fuel	0.83	0.02	0.22
Labour	N/A	N/A	0.80
Spreading & land emissions	-5.88	-0.13	-0.13
Sub total	-1.36	-0.03	1.60
	85.03	**1.86**	**97.01**

B

Item	Total GHG emissions kgCO2e/tonne (wfw)	Discounted cost of GHG emissions (as SPC) £/tonne (wfw)	Financial cost (as NPV , inc. SPC) £/tonne (wfw)
Domestic food waste disposal unit			
Kitchen disposal			
Supply and installation of FWD units	8.77	0.21	62.37
Electricity for FWD operation	13.32	0.30	1.07
Water for FWD operation	4.93	0.11	10.22
Transport			
Electricity - sewer pumping	0.42	0.01	0.03
Blockages removal (2)	0.00	0.00	0.00
Sub total	27.44	0.63	73.70
Thermophilic hydrolysis & anaerobic digestion with energy recovery			
Marginal additional cost emissions for food waste component			
Capital cost of THP/AD plant	3.90	0.10	23.46
Capital cost of secondary treatment	0.87	0.02	8.63
Landfill of screenings	not included		not included
Electricity for secondary treatment	32.24	0.72	2.59
Electricity use (aeration,digestion de-waster)(4)	N/A	N/A	N/A
Diesel use	N/A	N/A	N/A
Labour	N/A	N/A	1.94
Maintenance	N/A	N/A	6.88
N2O emission - sewage treatment	5.26	0.12	0.12
N2O emission - returned liquor	0.86	0.02	0.02
CH4 emission - digester & CHP	36.93	0.83	0.83
Credit from sale of electricity	N/A	N/A	-8.48
Financial credit from sale of ROCs	N/A	N/A	-3.47
Sub total	80.06	1.81	32.51
Beneficial use in agriculture			
Digestate dewatering & transport			
Dewatering & cake storage	9.35	0.21	1.24
Vehicle	0.01	0.00	0.18
Tyres	0.00	0.00	0.00
Vehicle fuel	0.72	0.02	0.19
Labour	N/A	N/A	0.69
Spreading & land emissions	-12.77	-0.29	-0.29
Sub total	-2.70	-0.06	2.02
	104.80	**2.38**	**108.22**

Table 4.2 Summary of GHG emissions, SPC values and financial costs for main options (Case 2: 80% collection)

A1

Item	Total GHG emissions kgCO2e/tonne (wfw)	Discounted cost of GHG emissions (as SPC) £/tonne (wfw)	Financial cost (as NPV , inc. SPC) £/tonne (wfw)
Segregated kerbside collection			
Kitchen collection			
Supply of kitchen caddies	1.84	0.04	1.20
Supply of kerbside waste bin	6.39	0.15	3.40
Supply of biodegradable liners (1)	0.00	0.00	19.52
Wash water for caddies	0.01	0.00	0.02
Transport (dedicated kerbside collection and bulk transfer vehicles)			
Vehicles	0.64	0.02	5.17
Tyres	0.03	0.00	0.14
Vehicle fuel	17.78	0.45	5.48
Labour	N/A	N/A	44.72
Sub total	26.69	0.66	79.67
In-vessel composting with green waste			
Capital cost of IVC plant	1.26	0.03	7.67
Landfill of screenings	not included	not included	not included
Electricity use - composting	8.27	0.18	0.66
Diesel use	3.74	0.08	3.01
Labour	N/A	N/A	2.28
Maintenance			
Bulking agent (3)	1.01	0.02	0.02
N2O emission - returned liquor	None	N/A	N/A
CH4 & N2O - composting stage	128.64	2.87	2.87
Credit from sale of electricity	N/A	N/A	N/A
Credit from sale of ROCs	N/A	N/A	N/A
Sub total	142.93	3.20	16.53
Compost transport			
Vehicles	0.03	0.00	0.48
Tyres	0.00	0.00	0.01
Vehicle fuel	1.86	0.04	0.50
Labour	N/A	N/A	1.79
Spreading & land emissions	-7.63	-0.17	-0.17
Sub total	-5.74	-0.13	2.61
Total	**163.87**	**3.73**	**98.81**

A2

Item	Total GHG emissions kgCO2e/tonne (wfw)	Discounted cost of GHG emissions (as SPC) £/tonne (wfw)	Financial cost (as NPV , inc. SPC) £/tonne (wfw)
Segregated kerbside collection			
Supply of kitchen caddies	1.84	0.04	1.20
Supply of kerbside waste bin	6.39	0.15	3.40
Supply of biodegradable liners (1)	0.00	0.00	19.52
Wash water for caddies	0.01	0.00	0.02
Vehicles	0.64	0.02	5.17
Tyres	0.03	0.00	0.14
Vehicle fuel	17.78	0.45	5.48
Labour	N/A	N/A	44.72
Sub total	26.69	0.66	79.67
Thermophilic hydrolysis & anaerobic digestion with energy recovery			
Segregated food waste only			
Capital cost of THP/AD plant	3.85	0.00	26.37
Landfill of screenings	not included	not included	not included
Electricity use (aeration,digestion de-waster)(4)	N/A	N/A	N/A
Diesel use	N/A	N/A	N/A
Labour	N/A	N/A	2.28
Maintenance	N/A	N/A	7.18
Water	0.01	0.00	1.13
N2O emission - returned liquor	0.82	0.02	0.02
CH4 emission - digester & CHP	51.00	1.14	1.14
Credit from sale of electricity	N/A	N/A	-10.70
Financial credit from sale of ROCs	N/A	N/A	-17.51
Sub total	55.68	1.16	9.90
Beneficial use in agriculture			
Digestate dewatering & transport			
Dewatering & cake storage	3.67	0.08	0.49
Vehicles	0.01	0.00	0.21
Tyres	0.00	0.00	0.00
Vehicle fuel	0.83	0.02	0.22
Labour	N/A	N/A	0.80
Spreading & land emissions	-5.88	-0.13	-0.13
Sub total	-1.36	-0.03	1.60
	81.00	**1.79**	**91.17**

B

Item	Total GHG emissions kgCO2e/tonne (wfw)	Discounted cost of GHG emissions (as SPC) £/tonne (wfw)	Financial cost (as NPV , inc. SPC) £/tonne (wfw)
Domestic food waste disposal unit			
Kitchen disposal			
Supply and installation of FWD units	8.77	0.21	62.37
Electricity for FWD operation	13.32	0.30	1.07
Water for FWD operation	4.93	0.11	10.22
Transport			
Electricity - sewer pumping	0.42	0.01	0.03
Blockages removal (2)	0.00	0.00	0.00
Sub total	27.44	0.63	73.70
Thermophilic hydrolysis & anaerobic digestion with energy recovery			
Marginal additional cost emissions for food waste component			
Capital cost of THP/AD plant	2.92	0.08	21.30
Capital cost of secondary treatment	0.79	0.02	7.89
Landfill of screenings	not included		not included
Electricity for secondary treatment	32.24	0.72	2.59
Electricity use (aeration,digestion de-waster)(4)	N/A	N/A	N/A
Diesel use	N/A	N/A	N/A
Labour	N/A	N/A	1.45
Maintenance	N/A	N/A	6.26
N2O emission - sewage treatment	5.26	0.12	0.12
N2O emission - returned liquor	0.86	0.02	0.02
CH4 emission - digester & CHP	37.95	0.85	0.85
Credit from sale of electricity	N/A	N/A	-8.48
Financial credit from sale of ROCs	N/A	N/A	-3.47
Sub total	80.02	1.80	28.53
Beneficial use in agriculture			
Digestate dewatering & transport			
Dewatering & cake storage	9.35	0.21	1.24
Vehicle	0.01	0.00	0.18
Tyres	-0.02	0.00	0.00
Vehicle fuel	0.72	0.02	0.19
Labour	N/A	N/A	0.69
Spreading & land emissions	-12.15	-0.27	-0.27
Sub total	-2.10	-0.05	2.04
	105.37	**2.39**	**104.26**

Notes to Tables 4.1 and 4.2:

1. The embodied carbon (EC) emission value for the biodegradable caddy liners has not been included. WRATE does not have a value for this and calculated weight of liners is insignificant in comparison to the total weight of food waste. Calculations illustrating this can be found in Appendix D.

2. It has been assumed that the food waste will not contribute to any additional sewer blockages or maintenance costs (base case).

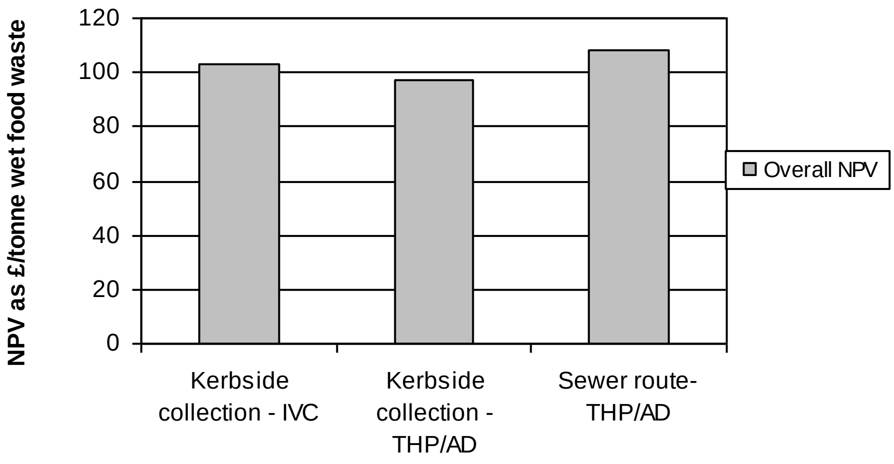
3. It is assumed that the food waste is co-composted with green waste as a bulking agent which is provided in a shredded form, free of charge at the IVC plant. The GHG emissions associated with the transport to site are included.

4. The electricity consumed as part of the THP/AD/CHP process is assumed to be a parasitic load which would be met by power generated by the CHP unit. It has therefore been treated as having no direct additional purchase cost and contributing no additional GHG emissions. The power consumed has been deducted from the electrical power available for export.

Comparison of Tables 4.1 and 4.2 indicate that the effectiveness of active participation rate of food waste collection (i.e. Case 1: 60% and Case 2: 80%) has little impact on either the emissions or costs expressed on a wet food waste basis. These results are discussed more extensively in Section 6.1.

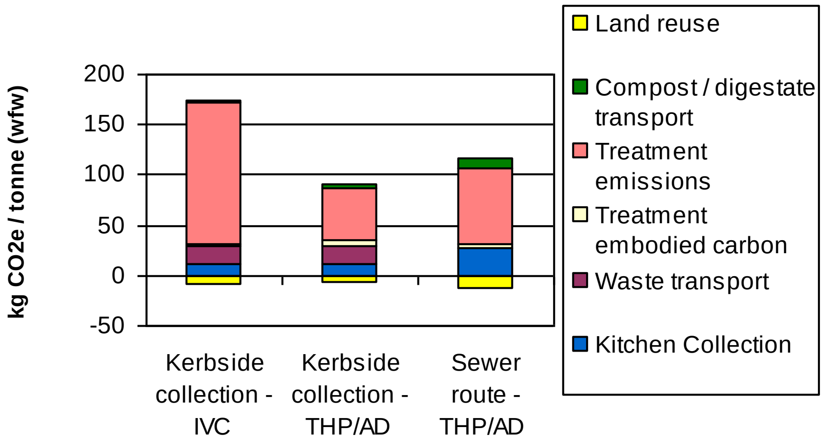
The overall financial costs for each option were obtained by deducting the income from the sale of electricity and ROCs from the total costs. These overall costs are compared in Figure 4.1 for Case 1 (60%).

Figure 4.1 Overall financial costs for Case 1 (active participation rate 60%)



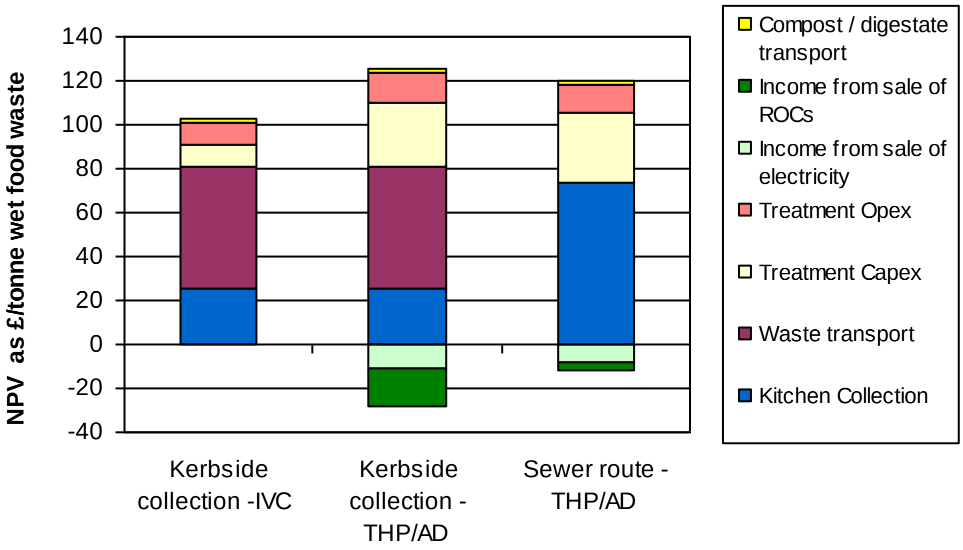
The GHG emissions are summarised and shown graphically in Figure 4.2.

Figure 4.2 Individual GHG emissions for Case 1 (active participation rate 60%)



The individual financial costs are shown graphically in Figure 4.3 (expressed as the NPV per tonne of wet food waste). Income values are shown as negative cost values.

Figure 4.3 Individual financial costs for Case 1 (active participation rate 60%)



It is evident from Table 4.3 that the value of ROC sales is a significant factor in the observed differences between the three main options. Calculation of the NPV, based on the ROC banding for options A2 and B, is shown in Table 4.3 based on the estimated surplus electricity produced (after deducting the process power consumption for operation of the THP, AD and CHP units). The lower surplus electricity for Option B arises from the assumption that a proportion of the incoming food waste passes to secondary treatment where it is partially oxidised and therefore results in a net lower production of biogas. The electricity demand for this additional secondary treatment has been treated as being outside the boundary of the THP/AD/CHP stage and so is identified and costed separately.

Table 4.3 Effect of ROC banding on NPV (active participation rate 60%)

Value	Option A2	Option B	Unit
Annual food waste treated	15,345	15,345	t (wfw)/year
Net electricity surplus	5,274	4,181	MWh/year
Surplus electricity	344	272	kWh/t (wfw)
ROC ratio	0.5	2.0	MWh/ROC
Assumed ROC value	45	45	£/ROC
Annual financial value of ROCs	474,703	94,065	£/year
Proportional value of ROC	30.93	6.13	£/t (wfw)
NPV value of ROC (25 years at 5.5%)	-17.51	-3.47	£/t (wfw)

4.2 Blockages

It is uncertain to what extent, if any, the use of FWD units will have on the number of sewer blockages. To examine this three scenarios have been considered, as follows.

- FWD units will not alter the blockage rate (base case).
- FWD units will result in a 25% (Case 1B.1) and 50% (Case 1B.2) increase in the incidence of blockages.

Table 4.4 Effect of blockages (active participation rate 60%)

Item	Total GHG emissions	Discounted cost of GHG emissions (as SPC)	Financial cost (as NPV, inc. SPC)
	$kgCO_2e$/tonne (wfw)	£/tonne (wfw)	£/tonne (wfw)
Base case	*104.80*	*2.38*	*108.22*
Case 1B.1	105.16	2.39	121.19
Case 1B.2	105.52	2.39	134.16

The assessment shows that an increase in the blockage rate and associated flooding would increase the cost of the FWD use option significantly. This would increase from £108.22/tonne of food waste to £121.19/tonne of food waste in Case 1B.1 (25%) and up to £134.16/tonne of food waste in Case 1B.2 (50%).

5. Other, Non-Quantified, Impacts

There are numerous potential environmental, social, public health and financial issues associated with the storage, collection, treatment and disposal of food waste, either at kerbside or *via* the sewer. The main concern of this study has been to estimate and evaluate these two waste management approaches with respect to GHG emissions and direct financial costs. However, a number of other impacts and issues have been identified which, although largely outside the scope of this study, are also relevant to the evaluation of the various food waste management options. These impacts are considered briefly in Table 5.1 in relation to the two broad alternatives of kerbside collection and sewer transport.

Table 5.1 Non-quantified impacts

Issue	Kerbside collection	Sewer transport
Collection vehicle movements and their impacts on traffic growth and congestion, and associated noise and air quality (other than GHG emissions). (Environmental/Social/Public Health)	There may be some traffic increase as a result of separate food waste collection but the corresponding residual MSW collection frequency may be reduced depending on corresponding changes to the overall waste collection strategy employed. If segregation gives rise to a greater general awareness of the issue of food waste then the total quantity of food waste requiring collection may be reduced. To some extent compensation for traffic-related social costs has been incorporated into the financial analysis through the inclusion of the cost of road fuel duty.	No impact.
Ammonia, odour and pest issues associated with the storage, transport and treatment of putrescible organic waste. (Environmental/Social/Public Health)	An appropriate storage container fitted with odour control lid should mitigate odours and pest issues, however, it can still be a concern when storing putrescible organic waste within/outside homes.	No impact.
Householder convenience (Social)	Likely to be differences in householder effort required between the two approaches but this has not been investigated in this study.	

Issue	Kerbside collection	Sewer transport
Householder awareness of waste minimisation (Environmental/Social)	Directly involves householders in recycling activity. Collected food waste may help to monitor the amount of food waste being produced at regular time intervals and act as a prompt to help identify items which are frequently over-purchased. This can help to adopt a responsible attitude of food waste minimisation.	Risk that convenient disposal will encourage the householder to adopt an out-of-sight/out-of-mind attitude and would not allow to control the amount of food waste being flushed down the sink. True level of waste is effectively “hidden”.
Mixing (in effect) of digested sludge derived from food waste with digested sewage sludge containing anthropogenic contaminants derived from industry, road-runoff and non-food domestic sources. (Environmental/Public Health)	No applicable.	Contravenes the general principle that wastes are better kept segregated to enable optimal recycling/disposal. Constraints which are now (or may in the future) be applied to treated products derived from sewage sludge (due for instance to the presence of anthropogenic contaminants) would reduce the beneficial use of treated organic product derived from food waste.
Benefits of soil conditioning and carbon sequestration within soils. (Environmental)	No impact.	Could be impaired if mixing of wastes reduces disposability to agricultural land of treated organic product derived from food waste (as above).
Competition between food waste and sewage sludge for agricultural outlets, and long-term security of land disposal outlets. (Environmental)	The relative lack of anthropogenic contamination in food waste might enable it to displace agricultural outlets for sewage sludge.	No impact.
Risk of misuse. (Environmental)	Risk of misuse of caddies and bins by disposing of other household wastes inappropriately.	Direct risk of misuse likely to be small as FWDs will jam if fed inappropriate waste materials, and householders will not wish to damage them. Potential risk that use of FWDs will negate the benefits of campaigns to dissuade householders from disposing of

Issue	Kerbside collection	Sewer transport
		other household wastes inappropriately to sewer (e.g. nappies, cotton wool buds and sanitary items).
Effects of long term water use reduction on flow in sewers. (Environmental/Social/Public Health)	No impact.	Any tendency of food waste to increase frequency and/or severity of sewer blockages should be seen in the context of likely future reduced water use and consequent sewer flows, which may itself increase the risk of blockages.
Effects on sewer overflows and storm-water discharges. (Environmental)	No impact.	The strength of untreated sewage will increase, and this could increase the undesirable environmental impacts of sewer overflows and storm water discharges.

On the basis of current knowledge WRc considers that, of the above, the main issues of concern are likely to be:

1. the convenience to householders of the sewer route, in contrast to the kerbside collection route which might requires more effort on the part of householders to segregate and manage putrescible food waste;

2. the importance to society of involving householders in the sound management of their domestic waste, including food waste;

3. concerns of householders about the health, odour and pest issues potentially **perceived** to be associated with the segregation and storage of putrescible food waste, taken in conjunction with 1 above;

4. the potential undesirability, in principle and in relation to several specific potential concerns, of mixing (in effect) digested sludge derived from food waste with digested sewage sludge containing higher levels of anthropogenic contaminants.

Although 1 and 3 tend to favour the sewer route, 2 and 4 tend to favour the kerbside collection route. These four issues *in particular* should be considered (along with the other matters addressed in Table 5.1 above) in any further examination beyond this work, of the two disposal routes and their impacts and sustainability.

6. Discussion

6.1 Effect of active participation rate

As discussed in Section 1.4 the model used does not consider the timescale required to achieve the necessary minimum level of FWD unit use within the study catchment (60%) nor does it consider the time required for this to be increased to the higher level which has also been considered (80%). Instead it is assumed *a priori* that all actively participating households would have such a unit available. The results obtained, therefore, only illustrate the difference in emissions and costs once that level of kerbside collection or FWD use has been achieved,

Comparison of Table 4.1 and 4.2 show the effect of increasing the active participation rate from 60% to 80%. The overall effect on financial cost is very small. For Option A the cost of kerbside collection is marginally reduced primarily due to the greater utilisation of the caddies and bins provided. Similarly the cost of food waste treatment for both segregated kerbside collection (Option A) and FWD unit use (Option B) are both reduced due to the economy of scale in treating the larger quantity of food waste.

In view of these small differences observed between Case 1 and Case 2 the subsequent discussion is restricted to the results from Case 1 (60% active participation) only.

6.2 Collection and transportation of food waste

Segregated kerbside collection

It is apparent from Table 4.1 that the GHG emissions are primarily due to the estimated embedded carbon in the caddies and bins (10.97kg CO_2e/t (wfw)) and those from use of vehicle fuel (17.78 kg CO_2e/t (wfw)). Together they contribute c. 34% of the total positive GHG emissions for option A2. The estimated contribution from these could be reduced if it were assumed that replacement were based only on demand from the householder (e.g. as a result of breakage or loss). Replacement would then not be expected for the 40% of households which do not participate in food waste collection. A further significant reduction would occur if it were assumed that at the end of the working lifetime the materials were recovered and the plastic recycled. The road fuel emissions are an inherent characteristic of kerbside collection. Although optimisation of the collection and transport regime could reduce these emissions it is likely to remain a dominant factor using current vehicle technology. In this application there is potential for the use of low emission vehicles such as electric or diesel/electric, however, this has not been considered further in this study.

From Table 4.1, the financial costs of kerbside food waste collection are dominated by the caddy liners and the labour for collection. There is a significant uncertainty in both of these values. The liner cost is based on the average use of two liners per week (104 per year) purchased at 5p each giving an annual cost to participating households in this analysis of

£5.20. Reported values for the cost of supplying caddy liners vary widely. WRAP suggest a cost of approximately £3.00 per participating household per year (WRAP 2008d) whilst one internet vendor (The Bin Company UK 2009) charges £11.85 for 100 bags (11.85p each) which would give an annual cost of £12.32 per year. The labour cost for food waste collection is based on the productivity of collection achieved in the WRAP trials. These trials typically used two-man vehicle operation and this contributes significantly to the calculated labour cost. Alternative approaches to collection, such as single manning or co-collection with other biodegradable streams may result in significantly lower labour costs.

These costs are also influenced by the assumptions made regarding the collection round and the distance travelled to the waste transfer station. These were based on the average values reported by WRAP for their collection trials and so are considered to be reasonably typical. However, for areas where properties are more geographically dispersed or where access is difficult and time-consuming, costs (and emissions) would increase significantly.

No emissions or costs have been included for the waste transfer station.

FWD unit use

The GHG emissions of the FWD option for the base case (i.e. no effect on sewer blockages) are primarily due to the embedded carbon in the FWD units (8.77 kg CO_2e/t (wfw)) and the electricity used in their operation (13.32 kg CO_2e/t wfw). The embedded carbon emission of the FWD units has been calculated with an allowance for the use of recycled materials.

The assessment shows an increase in the blockage rate and associated flooding would increase the cost of the FWD use option significantly. This would increase from £108.22/tonne of food waste to £121.19/ tonne of food waste in Case 1B.1 (25%) and up to £134.16/tonne of food waste in Case 1B.2 (50%).

Whilst there is no evidence that there will be an increase in blockage rate resulting from FWD use, it is known that:

- sewers deteriorate with age, for example the pipes move slightly and joints deteriorate;
- there is an increased incidence of blockages in drains/sewers in less than perfect condition, for example by sewer solids snagging on poor joints.

Thus, it is reasonable to assume that, should FWD use become more widespread, there could be an increase in blockage rates, especially in residential areas that were constructed 50 years ago or earlier. In this respect data from the English House Condition Survey shows that typically 60% of domestic property was built before 1964. Hence there is the potential for an increased likelihood of blockages.

Additionally, a proportion of sewer blockages will not be able to be cleared before sewage has spilled from the backed up system. Consequently there could also be an associated increase in sewage flooding, both externally and inside property. The latter is regarded as by far the most serious failure that can occur in a sewer system. For example, people who have been flooded with sewage can be affected for many years. It is not simply the cost of cleaning up and repair, which can be significant, there can also be psychological effects.

In the assessment it has been assumed that 2.78% of blockages result in internal flooding. This has been derived from blockage and flooding data held by Ofwat, the water industry regulator.

Sewage flooding caused by blockages is referred to by Ofwat as “other causes flooding”: For many years the majority of sewage flooding was caused by the sewer systems not being able to cope with the runoff from extremely heavy rainfall. The water industry has significantly reduced this problem and ‘other causes’ flooding has become the main concern. The water industry now regards reducing ‘other causes’ flooding as very important.

An increase in sewer blockage rates and flooding has indirect financial impacts:

- a significant adverse impact on the measures used to assess the operational performance of a companies sewage collection business, as assessed by Ofwat;

- increased levels of public complaint;

- reduced confidence amongst a water and sewerage company shareholders and investors.

In the assessment it has been assumed that the cost of an internal flooding caused by blockage is £3,900. This cost has been derived after considering the cost borne by the water and sewerage company in attending the incident and the subsequent claims made by householders on their insurance.

Whilst there is a high confidence regarding the cost of sewer blockage clearance, the cost of clean up following internal sewage flooding is less clear. Some clean ups and associated costs (hotel accommodation whilst out of the house etc.) cost upwards of £70,000, although the majority a less significant and cost considerably less. The value used of £3,900 represents a best conservative estimate.

Overall, for the collection and transport stage, FWD units, on the assumptions used, give lower GHG emissions and financial costs than kerbside collection. If, in practice, it was established that the presence of ground domestic food waste increased the rate of occurrence of sewer blockages then operational costs for FWD unit use increase and may exceed those of kerbside collection.

6.3 Treatment

For both options A2 and B the largest GHG emission arises from the assumption made regarding fugitive losses of methane from the digesters and CHP unit. The basis of these assumptions is discussed in Appendix C, Section C4.3. For option A2 this emission (51.00 kg CO_2e/t) represents 60% of all positive GHG emissions (i.e. emissions excluding the GHG credit from surplus electricity). The assumption used is based on a loss equivalent to about 3% of the total methane produced and is derived from measurements conducted in the water industry some years ago. At that time the industry still made use of some floating roof digesters and these were particularly prone to methane losses. Newer installations achieve higher standards of gas containment and so the floating roof component has been excluded (see Appendix C, Table C4.3). The estimated process emissions for the IVC process were derived largely from IPCC emission factors and are significantly higher than other estimates for composting (Defra 2006). The substantially higher GHG emission value for option A1 (167.04 kg CO_2e/t) primarily reflects fugitive emissions from the composting process.

The current value of both the SPC (£26.50/t CO_2e at 2008) and the SPC escalator (2% per annum) are considered to be relatively low. Consequently, despite the relatively high GHG emissions of option A1 (167.04 kg CO_2e/t) this component contributes less than 5% to the overall financial cost. Option A1 is, therefore, particularly sensitive to any future change in the value of SPC or the SPC escalator. It has been suggested that the current SPC value used to price carbon emissions may significantly undervalue the true cost of the harm caused and the House of Commons Select Committee on Environmental Audit has indicated that the SPC calculation should be reformed (House of Commons Select Committee on Environmental Audit, 2008). In view of the short period over which carbon cost data are available and the rapidly changing perception of climate change, it is extremely difficult to predict the future financial cost for such emissions.

The capital cost of the treatment process is the largest single component of the overall NPV for each option. IVC has a significantly lower cost than THP/AD. Option B has the highest total capital cost due to the need for some additional secondary treatment plant to accommodate the soluble and non-settleable food waste component. These secondary treatment costs are entirely dependent upon the assumption made regarding the settleability of the food waste. The capital cost of the THP/AD stage for Option B is slightly lower than Option A2 because some of the food waste will be oxidised in secondary treatment.

Labour and maintenance costs have been assumed to be related to the total capital investment and so they reflect the changes in capital costs.

The overall treatment cost for Option A2 is lower than A1 due to the income from the surplus electricity generated. No allowance has been made for the value of surplus heat energy which is also available in Option A2. Where this can be utilised (e.g. either in drying the digestate product or in integrated horticultural applications) the financial benefit would be greater.

Option B has the highest financial cost, primarily due to the lower value of ROCs generated. In this assessment it has been assumed that the banded values of the ROC would remain throughout the 25 year assessment period but this assumption may be challenged. The stated justification for the differential banded values is to offer a positive incentive for the development of a technology which is relatively new. This implies that, when proven and when commercial risks are better understood (as with the generation of biogas from sewage sludge), this differential incentive should be reduced or removed altogether. At such a time the economics of treatment Options A2 and B would become very similar. The cost difference would then depend entirely on the assumptions made regarding the settlement of food waste and the organic and nitrogenous load passing forward to secondary treatment. The evidence to support the assumed settlement is relatively weak, resting primarily on unpublished work within the UK water industry. Other studies have reported that the non-settleable load is small.

Surplus electricity generated in options A2 and B is potentially available for use by others. In the longer-term, a reduction in the average grid emission factor should be expected as a result of reduced coal-fired generation, application of carbon capture and storage (CCS) and the increased use of nuclear and renewable sources. If the average grid emission factor were reduced the relative GHG benefit of AD options would be reduced relative to the IVC process.

6.4 Beneficial use in agriculture

The emissions and costs associated with the storage, transport and use of the treated organic products are a relatively small part of the totals for each option. The estimated emissions make allowance for the displacement of mineral fertilisers through the use of treated organic products. The negative emission values represent a credit for the avoided emissions associated with the manufacture, packaging and transport of inorganic fertilisers (N, P_2O_5, K_2O and SO_4) and lime. A greater credit is obtained for the mixed food waste with sewage treated organic products as the relatively high potassium content of the food waste offsets the mineral potassium requirements for some of the sewage biosolids. A similar quantity of potassium is present in the segregated food waste digestate but, as this is applied alone, the full benefit of this potassium addition is not realised in this calculation.

6.5 Overall comparison

Option A2 – Option A2 has both the lowest GHG emissions (85.03 CO_2kg/t) and the lowest financial cost (£97.01/t). The financial result for the treatment element is strongly influenced by the favourable banded value for ROCs (0.5MWh/ROC) and the assumption, applied here, that this incentive will remain in place over the 25 year assessment period.

Option A1 – Option A1 has higher financial cost than option A2 due to substantially higher GHG emissions and zero credit from ROCs.

Option B – Option B has the second highest GHG emission and the highest estimated financial cost. Although FWD units offers the lowest cost for food waste collection. This depends on an assumption that the food waste does not significantly increase the cost of sewer operation. This study has also not considered the costs or impact of sewer overflow as this is seen as a highly site-specific factor. GHG and financial costs for option B could be reduced if an effective recycling mechanism were available so that value could be recovered from FWD units at the end of their operational lifetime.

7. Conclusions

This assessment has been conducted by identifying and estimating the most significant greenhouse gas (GHG) releases and financial costs of three food waste management options, using a simple numerical modelling approach, and is based on a hypothetical “model catchment”. To do this it has been necessary to make assumptions regarding both the most important mechanisms for GHG releases and the values for various parameters. Costs were estimated as the Net Present Value (NPV) over a 25 year assessment period and expressed as a cost per tonne (t) of food waste collected. It has been assumed that the active participation rate of food waste would be the same for FWD use as for kerbside collection. The modelling approach has not been undertaken as a life cycle assessment and has not sought to fully consider the impact of future recycling on material use and GHG emissions.

The differences observed between the options considered were within the range of uncertainty in these estimates. Within the recognised limitations of this modelling approach the following conclusions can, however, be drawn.

i) Kerbside collection of segregated domestic kitchen food waste was shown to have lower GHG emissions and overall financial costs when compared with the use of domestic FWD units followed by discharge to sewer, where no increase in blockages was assumed and both routes used a thermal hydrolysis process followed by anaerobic digestion (THP/AD) with energy recovery and biosolids reuse. For kerbside collection, operating costs were predominant but FWD use was more capital intensive.

ii) The overall GHG emissions and financial cost for kerbside collection with THP/AD were estimated to be 85.03kg CO_2e/t and £97.01/t. The main financial items were the capital costs of caddies and bins (£6.14/t), treatment plant (£29.07/t), operating costs for caddy liners (£19.52/t) and collection labour (£44.72/t). These costs were partially offset by a credit for the sale of the electricity generated (£10.70/t) and the related renewable obligation certificates (£17.51/t).

iii) Where FWD units were used, with similar biosolids treatment, the estimated emissions were 104.80kg CO_2e/t and the cost was £108.22/t. The main capital costs were for FWD units (£62.37/t) and treatment plant (£32.09) but the main operating costs related to water and electricity for FWD use (£10.22/t). The value of the credit for surplus electricity generated was slightly lower than that for segregated food waste (£8.48/t), but due to the lower renewable obligation certificates (ROC) banding for ‘sewage gas’, the ROC income was significantly less (£3.47/t).

iv) The use of in-vessel composting (IVC), as an alternative to THP/AD in the kerbside collection option, resulted in a significantly higher emission (167.04kg CO_2e/t) and slightly higher financial cost (£103.08/t). The estimated process emissions for the IVC process were derived largely from IPCC emission factors and are significantly higher than other estimates for composting.

v) If it was assumed that the use of FWD increased blockages by 25% then the estimated emissions and financial costs were 105.16kg CO_2e/t and £123.56/t. A large part of the increased costs related to dealing with flooding of properties.

vi) Monetisation of GHG emissions using the shadow price of carbon had only a small impact on the estimated financial costs, contributing less than 5% to the total.

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Appendix A Assumptions and Variable Parameter Values used in the Modelling Study

A1 Emission factors

Aspect	Value	Units	Comments
Grid electricity emission factor	0.53702	kg CO_2/kWh	2008 Guidance to Defra GHG conversion factors for company reporting, Annex 3, Table 2. Grid rolling average
GWP CH_4	25	kg CO_2e/kg	IPCC Fourth Assessment Report. Working Group I Report "The Physical Science Basis". See: http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch02.pdf
GWP N_2O	298	kg CO_2e/kg	IPCC Fourth Assessment Report. Working Group I Report "The Physical Science Basis". See: http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch02.pdf

A2 Model catchment demographics

Aspect	Value	Units	Comments
Catchment population	400,256	people	Chosen to ensure that the waste processing facility was large enough for reasonable mass flows. The size chosen is close to that of Bristol.
Average number of people in household (houses and flats)	2.36	people	UK average for households – DEFRA website
Total number of households	169,600		Calculated (400256 / 2.36)
Proportion of households with kitchen caddies and bins	100	%	Based on WRAP Food Waste collection trials
Proportion of households actively participating in food waste collection	Case 1: 60 Case 2: 80	%	Based on WRAP Food Waste collection trials
Total number of participating households	101,760		Calculated (169600 * 60 / 100)

A3 Food waste disposal units

Aspect	Value	Units	Comments
Embodied CO_2 in FWD unit	15.87	kg CO_2e / FWD unit	Derived from typical emission factors and FWD composition data (for calculation see Appendix F6)
Lifetime of FWD unit	12	Years	Taken from Lundie and Peters 2005. For other estimates see www.nettally.com/palmk/GDwarranties.html and values in www.getprice.com.au/Food-Waste-Disposal-Unit-Buying-Guide___arts_147
Proportion of households with FWD units installed	Case 1: 60 Case 2: 80	%	Assumed market penetration (see for example New York City DEP 1997, Galil & Yaacov 2001 and Marashlian & El-Fadel 2005)
Proportion of collectable food waste diverted via FWD units in households where FWD units are installed	100	%	Assumed FWD unit use (see for example Karlberg & Norm 1999, de Koning & van der Graaf 1996 and Lundie & Peters 2005)
Frequency of use	3	Uses/day	Defra Market Transformation Programme (Defra 2008)
Duration of use	30	Seconds/ use	Defra Market Transformation Programme (Defra 2008)
Power	0.41	kW	Defra Market Transformation Programme (Defra 2008)
Electricity usage per unit	3.74	kWh/FWD /year	Calculated from values in Defra 2008.
FWD water use – flow rate	4.92	l/min	Defra Market Transformation Programme (Defra 2008)
Increase in water use per unit	7.38	l/FWD/ day	Calculated from values in Defra 2008.
Increase in water use per person (PE) per day.	3.13	l/PE/day	Calculated from values in Defra 2008.
Average water consumption	150	l/PE/day	DEFRA website. Value not used in assessment; included in this table only to provide an indicative value for comparison with the estimate additional water usage from FWD.

A4 Sewerage Assumptions

Aspect	Value	Units	Comments
Length of private drains in England and Wales per property	9.22	m/property	UKWIR 2009
Length of lateral drains in England and Wales per property	1.60	m/property	UKWIR 2009
Length of private sewers in England and Wales per property	8.20	m/property	UKWIR 2009
Length of public sewer in England and Wales per property	13.81	m/property	UKWIR 2009
Current blockage rate in drains	1.5	blockages/km/ year	UKWIR 2009
Current blockage rate in private sewers	1.0	blockages/km/ year	UKWIR 2009
Current blockage rate in public sewers	0.49	blockages/km/ year	Derived from June Return 07/08 company average. www.ofwat.gov
Serious pollution events from public sewers	0.0003	Events /km/year	Calculated from EA data divided by length of public sewer
Percent of blockages that develop into external flooding	23.05	%	Derived from June Return 07/08 company average. www.ofwat.gov
Percent of blockages that develop into internal flooding	2.78	%	Derived from June Return 07/08 company average. www.ofwat.gov
Cost of blockage removal	100	£	Rounded value taken from typical values on Dyno Rod website.
Cost of sewage flooding (external)	200	£	WRc assumption
Cost of sewage flooding (internal) - includes initial investigation, initial clean-up, CCTV, solicitors, GSS payments, overhead costs etc.	3,900	£	Association of British Insurers, as quoted to the Councils and Local Government
Cost of sewage flooding (internal) - average for ex-gratia payments to cover for uninsured losses = £4000 for 1 in 20 incidents)	200	£	WRc assumption. Water companies are limited to £1,000, £200 chosen as a value that may reflect typical payouts.
Cost of serious pollution event (clean-up, court costs, fines)	25000	£	WRc assumption. The maximum fine is £20,000. WRc have added £5,000 for legal costs. See www.utilityweek.co.uk/news/uk/water/united-utilities-given-maximum.php
Average travel distance to a blockage (rural)	20	miles	WRc assumption

Aspect	Value	Units	Comments
Average travel distance to a blockage (urban)	10	miles	WRc assumption
Sewer pumping head	8	m	WRc assumption
Sewer pumping efficiency	50	%	Typical value for open-faced impellers (also described as uncloggable pumps). www.mwponline.co.uk/Features/impeller_importance www.zoeller.com/Zep/Techbrief/JF1article.htm

A5 Wastewater Preliminary and Primary Treatment

Aspect	Value	Units	Comments
Per capita flow plus an allowance for infiltration	200	l/PE/day	WRc assumption
Screenings average moisture content	61.3	%	UKWIR 2009
Screenings production by population	0.007	m^3 day/1000 population	UKWIR 2009
Percentage increase in screenings	0	%	WRc assumption
Screenings density	0.5	t/m^3	UKWIR 2009
TSS after grit removal	0.08	kg /PE/day	WRc assumption
TSS removed in primary treatment	60	%	Typical value (CIWEM 1973)
Sludge thickness	3	%	Typical value (CIWEM 1973)
BOD to COD ratio	0.5	g BOD/g COD	Typical UK value.
Raw influent BOD	0.060	kg /PE/day	EU Urban Waster Treatment Directive
Raw influent COD	0.120	kg /PE/day	From BOD:COD ratio 0.5
Raw influent NH_3-N	0.007	kg /PE/day	Produces ammonia in crude sewage of 35 mg/l, in line with CIRIA recommendations for wastewater modelling.
Raw influent COD that is rapidly biodegradable (soluble)	25	%	Typical value (IWA 2000)
Raw influent COD that is slowly biodegradable (particulate)	60	%	Typical value (IWA 2000)
Raw influent COD that is non-biodegradable (soluble)	5	%	Typical value (IWA 2000)
Raw influent COD that is non-biodegradable (particulate)	10	%	Typical value (IWA 2000)
Particulate COD removed in primary treatment	55	%	Typical value (WRc experience)
BOD removed in primary treatment	38.5	%	Set to keep BOD:COD ratio as 0.5
NH_3-N removed in primary treatment	0	%	Since ammonia is soluble

A6 Food waste properties

Aspect	Value	Units	Comments
TSS from food waste that is removed in primary treatment	90	%	de Koning, J. (2004)
COD of food waste (on dry solids basis)	1.5	g COD/g DS	de Koning, J. (2004)
Percent of FW COD that is rapidly biodegradable (soluble)	25	%	Equivalence with domestic wastewater[1]
Percent of FW COD that is slowly biodegradable (part)	60	%	-"-
Percent of FW COD that is non-biodegradable (soluble)	5	%	-"-
Percent of FW COD that is non-biodegradable (particulate)	10	%	-"-
BOD of food waste (on dry solids basis)	0.75	g BOD/g DS	To keep BOD:COD ratio of 0.5
Nitrogen content of raw and digested food waste	0.028	g N/g DS	Within range quoted by Bolzonella *et al.*, (2003)
NH_3-N percent of FW removed in primary treatment	0	%	Since ammonia is soluble
BOD percent of FW removed in primary treatment	70	%	Set so ratio BOD:COD on secondary treatment is 0.5
Particulate COD percent of food waste removed in primary treatment	90	%	Typical value. (de Koning, 2004)

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[1] Bolzonella *et al*. (2003) quote that their ground food waste had similar soluble/particulate COD ratios to their domestic wastewater, and used the IWA Activated Sludge Model No. 2 to simulate the effects of food waste on sewage treatment. They observed much higher levels of soluble COD in their domestic sewage (50%) than is regarded as typical (30 -40% - IWA, 2000) but this could be explained by higher temperatures (Italy). Their use of ASm2 for modelling does reinforce the assumption of using standard domestic sewage characterisation in the absence of other data.

A7 Secondary Treatment - Activated Sludge

Aspect	Value	Units	Comments
Process influent: BOD per PE per day	40	g/d	UKWIR, 2008
Process influent: COD per PE per day	80	g/d	UKWIR, 2008
Process influent: Ammoniacal nitrogen per PE per day	7	g/d	UKWIR, 2008
Process effluent: BOD	15	mg/l	UKWIR, 2008
Process effluent: COD	60	mg/l	UKWIR, 2008
Process effluent: ammoniacal nitrogen	5	mg/l	UKWIR, 2008
Percentage of ammoniacal nitrogen that is denitrified	65	%	UKWIR, 2008
Percentage of ammoniacal nitrogen that is converted to N_2O	0.21	%	UKWIR, 2008
Sludge yield from BOD	0.8	kg/kg BOD	UKWIR, 2008
COD content of sludge	1.2	kg/kg	UKWIR, 2008
Sludge thickness	3	%	UKWIR, 2008
RAS recycle ratio	2		UKWIR, 2008
RAS recycle pump head	3	m	UKWIR, 2008
RAS recycle pump efficiency	66	%	UKWIR, 2008
Oxygenation efficiency	1.5	kg/kWh	UKWIR, 2008
F:M ratio	0.1	/d	UKWIR, 2008
MLSS	3000	mg/l	UKWIR, 2008
Number of aeration tanks	4		UKWIR, 2008

A8 Supply chain - Operational

Aspect	Value	Units	Comments
Roundtrip distance for delivery of polyelectrolyte	50	km	UKWIR 2008
Capacity of vehicle delivering polymer	20	tonnes	Typical size of a bulk transport vehicle.
Roundtrip distance for delivery of lime	50	km	UKWIR 2008
Capacity of vehicle delivering lime	20	tonnes	Typical size of a chemical transport vehicle.
Roundtrip distance for delivery of bulking agent	30	km	WRc assumption, that green waste providers should be more widely available (and therefore closer) than chemical providers.
Capacity of vehicle delivering bulking agent	20	tonnes	Typical size of a bulk transport vehicle.
Roundtrip distance for delivery of NaOH for gas cleaning	50	km	UKWIR 2008
Capacity of vehicle delivering NaOH for gas cleaning	20	tonnes	Typical size of a chemical transport vehicle.

A9 Segregated food waste collection

Aspect	Value	Units	Comments
Mass of food waste available for segregated collection	2.90	kg /household /week	Derived from data provided by WRAP. Discussed directly with WRAP representative as a reasonable basis for the study.
Mass of inorganic contamination in segregated food waste collection	0	kg /household /year	WRc assumption
Cost of purchasing a dedicated collection vehicle (7.5 t mgw). The vehicle is used during the food waste collection and is collecting food waste from householders and delivering it to transfer station.	38,000	£	Reigate and Banstead Borough Council
Life expectancy of dedicated collection vehicle	200,000	km	WRATE (EA 2008) The vehicles were assumed to be replaced at the end of their commercial ‘life’.
Cost of purchasing a bulk transportation vehicle. The vehicle transports food wastes from transfer station to treatment facility.	130,000	£	Reigate and Banstead Borough Council
Life expectancy of bulk vehicle	750,000	km	Telephone conversation (MAN Trucks typical lifetime). The vehicles were assumed to be replaced at the end of their commercial ‘life’.

A10 Bulk densities

Aspect	Value	Units	Comments
Water density	1000	kg /m^3	Standard value
Bulk density of raw sludge (<5%DS)	1020	kg /m^3	MASTAR (WRc 2001)
Bulk density of dewatered sludge (20-28%DS)	1070	kg /m^3	MASTAR (WRc 2001) (Calculated from assumptions)
Bulk density of dewatered sludge (28-35%DS)	1090	kg /m^3	MASTAR (WRc 2001) (Calculated from assumptions)
Bulk density compost	0.6	t/m^3	Stoffella and Kahn (2001)
Bulk density of food waste	470	kg /m^3	WRAP 2008b

A11 Embodied carbon (operational)

Aspect	Value	Units	Comments
Food waste kitchen caddies	1.55	kg CO_2e/ caddy	Calculated based on the information provided by STRAIGHT (http://www.straight.co.uk/)
Food waste bins	5.39	kg CO_2e/ bin	Calculated based on the information provided by STRAIGHT (http://www.straight.co.uk/)
Embodied carbon in lime	0.73	kg CO_2e/kg	UKWIR, 2008 Carbon Accounting In the UK Water Industry: Guidelines for dealing with 'Embodied Carbon' and whole life carbon accounting, Report Ref. No. 08/CL/01/6
Embodied carbon in polymer	8.21	kg CO_2e/kg	UKWIR (2008), Water Framework Directive: Sustainable Treatment Solutions for achieving good ecological status, Report Ref. No. 08/WW/20/3,
Embodied carbon in NaOH	0.989	kg CO_2e/kg	UKWIR, 2008 Carbon Accounting In the UK Water Industry: Guidelines for dealing with 'Embodied Carbon' and whole life carbon accounting, Report Ref. No. 08/CL/01/6
Greenhouse gases emitted in supplying 1Ml of water	0.276	tonnes CO_2e/ Ml	Water UK 2008

A12 Sludge Treatment – Thermal Hydrolysis (THP) and Anaerobic Digestion

Aspect	Value	Units	Comments
Volatile solids content of raw sludge	0.75	fraction	Lindquist *et al.* 2007
VS converted during AD after THP pretreatment	62	%	Pickworth.*et.al.* 2006.
Biogas yield from VS converted	1000	m^3/tonne	Lindquist *et al.* 2007
% methane in biogas	65	%	Lindquist *et al.* 2007
Dry solids of thickened raw sludge for thermal hydrolysis	16	%	WRc assumption
Digester feed dry solids (%)	10	%	WRc assumption, to allow for hydrolysis through the CAMBI process.
Digester output dry solids (%)	8	%	Vendor claims typically 60% VS removal between CAMBI inlet and digester outlet. 8% DS follows from this claim.
Cake dry solids (with THP, after AD)	34	%	Pickworth.*et.al*. 2006.
% biogas to thermal oxidisers	5	%	Pickworth.*et.al.* 2006.
% biogas to flare stack	5	%	Pickworth.*et.al.* 2006.
% biogas to produce steam	13	%	Pickworth.*et.al.* 2006.
Efficiency of CHP for electricity production	30	%	See, for example, www.building.co.uk/story.asp?storycode=3123114 www.esru.strath.ac.uk/EandE/Web_sites/97-8/chp_sizing_case/chp.html
Efficiency of CHP for heat production	50	%	See, for example, www.building.co.uk/story.asp?storycode=3123114 www.esru.strath.ac.uk/EandE/Web_sites/97-8/chp_sizing_case/chp.html
Hydraulic Retention Time (HRT) in anaerobic digester	15	days	Typical value. DoE Sludge to agricultural guidelines require a minimum HRT of 12 days; a higher value is used to provide a safety margin, and promote operational stability
Fraction of boiler heat requirement met by biogas	1	fraction	Pickworth.*et.al*. 2006.
Electricity requirements for anaerobic digestion	20.6	kWh/tonne material	WRATE (EA 2008)
Fuel (diesel) requirements for anaerobic digestion	1.3	kg/tonne material	WRATE (EA 2008)
Unit capacity /batch volume of Cambi heating vessel	730	m^3	MASTAR (WRc 2001)
Daily number of batches per heating vessel	6	batches	MASTAR (WRc 2001)
Specific electrical power required for anaerobic digestion	0.0041	kW/m^3	MASTAR (WRc 2001)
Electrical power required for Cambi process (for 730m^3 volume)	108	kW	Calculated pro-rata from Kepp *et al.* 2000

A13 Food Waste Treatment – Thermal Hydrolysis (THP) and Anaerobic Digestion

Aspect	Value	Units	Comments
Volatile solids content of raw food waste	0.965	fraction	de Koning, J. (2004)
Fraction of VS converted during AD after THP pretreatment	0.65	dimensionless	Sargalski *et al.* (2007)
Biogas yield from VS converted	1000	m^3/tonne	Lindquist *et al.* (2007)
% methane in biogas from food waste	67	%	EPA 2008
Dry solids of raw food waste	30	%	de Koning (2004)
Reject (overall)	0	%	WRc assumption
Reject rate in reception hall	0	%	WRc assumption
Reject rate in dewaster	0	%	WRc assumption
Dewaster energy use	14	kWh/tonne feed	Evans *et al.* 2007
Number of days of delivery (working week only)	260		5days/wk, 52 wks/year
Delivery hours (10:00 till 16:00)	6		WRc assumption
Dewaster maximum flow rate	4	m^3/h	WRc assumption
Dewaster operational hours per day	10		WRc assumption
Reception hall number days storage capacity	3	days	Evans *et al.* 2007

A14 Food Waste Treatment – In-vessel composting

Aspect	Value	Units	Comments
Fraction of VS converted during food waste composting	57	%	Chynoweth *et al.* 2003
Electricity requirements	9.0	kWh/tonne material	WRATE (EA 2008)
Diesel requirements	1.63	l/tonne wet compost	MASTAR (WRc 2001)
Bulking agent (green waste) required – food waste	0.5	Wet tonnes/tDS	WRc assumption
Moisture content of compost	65	%	WRc assumption. Typically values of 60% or greater are required to ensure that the composting process progresses. (Taha, 1978)
Garden waste moisture concentration	58	%	WRATE (EA, 2008)

A15 Nutrient concentrations of treated sludge organic products

Aspect	Value	Units	Reference
Total Nitrogen of raw and digested sludge	0.043	g N/g sludge DS	Water UK 2009b
Total Nitrogen of advanced digested sludge	0.044	g N/g sludge DS	WRc assumption – use the dried sludge value as the best approximation.
Total Nitrogen content of composted sludge	0.018	g N/g sludge DS	Water UK 2009b
Percentage TN available to next crop - raw & digested sludge	15	%	Water UK 2009b
Percentage TN available to next crop - composted sludge	15	%	Water UK 2009b
Phosphorus content of raw sludge	0.012	g P_2O_5/g sludge DS	From a mass balance on the digested sludge
Phosphorus content of digested sludge	0.072	g P_2O_5/g sludge DS	Water UK 2009b
Phosphorus content of THP digested sludge	0.075	g P_2O_5/g sludge DS	Intermediate between digested and thermally treated
Phosphorus content of composted sludge	0.010	g P_2O_5/g sludge DS	Water UK 2009b
Percentage TP available to next crop - raw sludge	50	%	MAFF 2000
Percentage TP available to next crop - digested sludge	50	%	MAFF 2000
Percentage TP available to next crop - THP digested sludge	50	%	MAFF 2000
Percentage TP available to next crop - composted sludge	50	%	MAFF 2000
K_2O content of raw sludge	0.0025	kg K_2O/kg DS	MAFF 2000 describes this as 'trace'
K_2O content of digested sludge	0.0025	kg K_2O/kg DS	MAFF 2000 describes this as 'trace'
K_2O content of THP digested sludge	0.0025	kg K_2O/kg DS	Water UK 2009b
K_2O content of composted sludge	0.005	kg K_2O/kg DS	Water UK 2009b
SO_3 content of raw sludge	0.018	kg SO_3/kg DS	Banks *et al.* 2008
SO_{34} content of digested sludge	0.018	kg SO_3/kg DS	Pro-rata on sewage sludge values
SO_3 content of THP digested sludge	0.018	kg SO_3/kg DS	-"-
SO_3 content of composted sludge	0.003	kg SO_3/kg DS	-"-
Percentage SO_4 available to next crop - raw sludge	50	%	MAFF 2000
Percentage SO_4 available to next crop - digested sludge	50	%	MAFF 2000
Percentage SO_4 available to next crop - THP digested sludge	50	%	MAFF 2000
Percentage SO_4 available to next crop - composted sludge	50	%	MAFF 2000
CaO content of raw sludge	0	kg CaO/kg DS	Water UK 2009b
CaO content of digested sludge	0	kg CaO/kg DS	Water UK 2009b
CaO content of THP digested sludge	0	kg CaO/kg DS	Water UK 2009b
CaO content of composted sludge	0	kg CaO/kg DS	Water UK 2009b

A16 Nutrient concentrations of treated food waste organic products

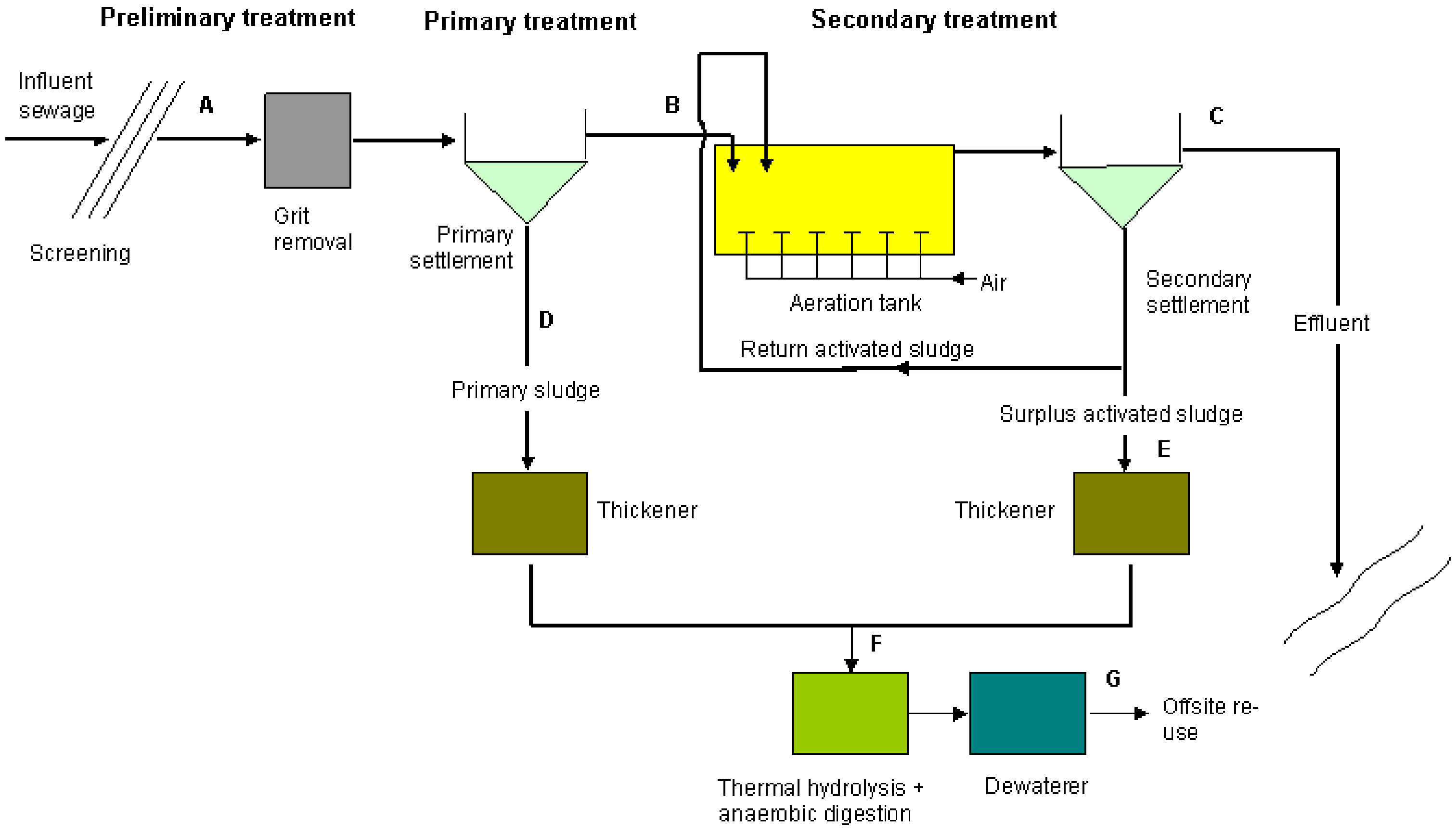
Aspect	Value	Units	Reference
Nitrogen content of raw and digested food waste	0.028	g N/g DS	Within range of Bolzonella *et al. date*
Nitrogen content of THP digested food waste	0.028	g N/g DS	Pro-rata on sewage sludge values
Nitrogen content of composted food waste	0.011938	g N/g sludge DS	-“-
Percentage TN available to next crop - raw & digested food waste	15	%	Assuming sludge values from Water UK 2009b apply
Percentage TN available to next crop - composted food waste	15	%	-“-
Phosphorus content of raw food waste	0.001	g P_2O_5/g sludge DS	Wang et al. 2004
Phosphorus content of digested food waste	0.00625	g P_2O_5/g sludge DS	Pro-rata on sewage sludge values
Phosphorus content of THP digested food waste	0.00625	g P_2O_5/g sludge DS	-“-
Phosphorus content of composted food waste	0.000833	g P_2O_5/g sludge DS	-“-
Percentage TP available to next crop - raw food waste	50	%	Assuming values from MAFF 2000 apply
Percentage TP available to next crop - digested food waste	50	%	-“-
Percentage TP available to next crop - THP digested food waste	50	%	-“-
Percentage TP available to next crop - composted food waste	50	%	-“-
K_2O content of raw food waste	0.045	kg K_2O/kg DS	Wang *et al.* 2004
K_2O content of digested food waste	0.045	kg K_2O/kg DS	-“-
K_2O content of THP digested food waste	0.045	kg K_2O/kg DS	-“-
K_2O content of composted food waste	0.09	kg K_2O/kg DS	-“-
SO_3 content of raw food waste	0.025	kg SO_3/kg DS	WRc assumption
SO_3 content of digested food waste	0.025	kg SO_3/kg DS	Pro-rata on sewage sludge values
SO_3 content of THP digested food waste	0.025	kg SO_3/kg DS	-“-
SO_3 content of composted food waste	0.004333	kg SO_3/kg DS	-“-
Percentage SO_4 available to next crop - raw food waste	50	%	Assuming values from MAFF 2000 apply
Percentage SO_4 available to next crop - digested food waste	50	%	-“-
Percentage SO_4 available to next crop - THP digested food waste	50	%	-“-
Percentage SO_4 available to next crop - composted food waste	50	%	-“-
CaO content of raw food waste	0	kg CaO/kg DS	No lime added
CaO content of digested food waste	0	kg CaO/kg DS	-“-
CaO content of THP digested food waste	0	kg CaO/kg DS	-“-
CaO content of composted food waste	0	kg CaO/kg DS	-“-

A17 Economic Parameters and costs

Aspect	Value	Units	Comments
Financial discount rate	5.5	%	WRc assumption
Social discount rate	3.5	%	HM Treasury, 2003
Water cost	0.001	£/litre	www.stwater.co.uk/upload/pdf/Indicative_Wholesale_Access_Prices_for_publication.pdf
FWD unit cost	150	£	Includes installation cost
Electricity cost	0.055	£/kWh	www.theyworkforyou.com/wrans/?id=2006-03-13c.57431.h
Diesel cost	1.15	£/litre	www.whatgas.com/petrol-prices/diesel-prices.aspx
Natural gas cost	0.02	£/kWh	www.greenbuildingforum.co.uk/newforum/comments.php?DiscussionID=1539
Polymer cost	1.6	£/kg	www.slaterservices.co.uk/triall_results.htm
NaOH cost	266	£/t	http://ed.icheme.org/costchem.html - inflated from 2002 price given
Lime (CaO) cost	80	£/t	http://ed.icheme.org/costchem.html - inflated from 2002 price given
Bulking agent cost	0	£/t	WRc assumption
FW Kitchen caddy volume	7	l	STRAIGHT (http://www.straight.co.uk/)
FW kitchen caddy cost	1.50	£	Bristol City Council 2009
FW bin volume	21	l	STRAIGHT (http://www.straight.co.uk/)
FW bin cost	4.20	£	Bristol City Council 2009

Appendix B Mass Flow Diagrams for COD and TSS both with and without Food Waste

B1 Sewage treatment flow diagram



B2 Wastewater solids and COD balance for Case 1 (per pe)

Stream	**Stream Id (See flow diagram)**	**Solids**			**COD**		
		Sewage	**FW**	**Sewage+FW**	**Sewage**	**FW**	**Sewage+FW**
Wastewater (gTSS/pe.d):							
Influent	A	80	19	99	120	46	166
Settled effluent	B	32	1.9	34	73.8	16.9	91
Treated effluent	C	2	-	2	12	-	12
Sludge (gTS/pe.d):							
Primary solids	D	48	17	65	46	29	75
Secondary solids	E	27	6.8	33.9	49	16.3	66
Mixed primary/sec solids	F	75	24	99	96	45	141
THP/AD solids	G	40	9	49	58	12.9	71

Derived from the spreadsheet using the default values in Appendix A.

B3 Wastewater solids and COD balance for Case 1 (per tonne of wet food waste)

Stream	**Stream Id (See flow diagram)**	**Solids**			**COD**		
		Sewage	**FW**	**Sewage+FW**	**Sewage**	**FW**	**Sewage+FW**
Wastewater (kgTSS/tonne wet FW):							
Influent	A	760	180	940	1139	434	1574
Settled effluent	B	304	18	322	701	161	861
Treated effluent	C	19	-	19	114	-	114
Sludge (kgTS/tonne wet FW):							
Primary solids	D	456	162	618	439	274	712
Secondary solids	E	257	64	322	469	155	624
Mixed primary/sec solids	F	713	226	939	908	429	1337
THP/AD solids	G	382	84	466	552	122	674

Derived from the spreadsheet using the default values in Appendix A.

Appendix C Notes on Calculation of Greenhouse Gas Emissions

C1 Introduction

Suitable emission factors (EFs) were determined for greenhouse gases (GHG) from the different stages of each process. These were chosen based on the source material available. Where country specific data is not well established the EFs have been derived from the published Intergovernmental Panel on Climate Change (IPCC) factors (IPCC 2006). The IPCC guidance, designed for country wide emissions, recommends a tiered system approach where each tier represents different levels of methodological complexity. Tier 1 being a basic method using default IPCC factors and Tiers 2 and 3 more complex EFs based on country specific data. Where extensive UK data are available and published these have been used e.g. from the National Air Emissions Inventory (NAEI).

Short-cycle CO_2 emissions are excluded from the calculations. Fossil fuel derived emissions of CO_2 are assessed, as are process related emissions of CH_4 and N_2O. Global Warming Potentials (GWP) used for CO_2, CH_4 and N_2O are from the IPCC Fourth Assessment Report i.e. 25 kg CO_2e/kg CH_4 and 298kg CO_2e/kg N_2O.

C2 Emissions from sewers

GHG emissions from sewers were not considered in this project. This is unlikely to be a significant source due to short residence times and would be unlikely to change unless there was significantly greater deposition of solids in the sewer. Solids are assumed to be broken up and flushed through the sewer so no emissions would be associated with these. The fuel needed for a crew to reach each sewer blockage has been included.

C3 Emissions from sewage treatment

C3.1 Methane

The EF for CH_4 from wastewater treatment, which includes a factor for mechanical treatment and short term storage of sludge, is 2.7 kg CH_4 per tonne DS, based on the approach taken in the UKWIR Carbon Accounting Methodology (UKWIR 2008).

C3.2 Nitrous oxide

The EF for N_2O from wastewater treatment is provided in Equation 1:

$$N_2O \text{ emitted during treatment} = 0.002 \times N \text{ load on secondary treatment} \times 44/28 \qquad [1]$$

The N load may be affected by the proportion of food waste and therefore the EF may also change.

C4 Emissions from sludge and food waste treatment

C4.1 Maximum methane generation potential (B_o)

Under the IPCC methodology, emissions of methane from many processes can be derived based on the maximum methane generation potential of the material, referred to as B_O (Table C4.1).

Table C4.1 Derivation of the maximum methane generation potential (B_O) of sewage sludge and food waste

	kg VS/t	%VS destruction	%CH_4	Conversion factor [1]	kg CH_4/tonne raw DS (B_O)	Source
Sewage Sludge	750	65	(60)	0.67	195	DoE, 1996
Domestic food waste	800	(82.5)	75	0.67	330	Monnet, 2003

Values in brackets assumed from data

1 Conversion factor assumes 1 m^3 biogas/kg VSS destroyed, MW for methane = 16 and volume 22.4 l/mole.

Food waste is likely to have a higher yield of methane than sewage sludge which has been partly degraded already.

C4.2 Methane generation by anaerobic digestion

1. Methane

Generation of CH_4 from the anaerobic digestion of sewage sludge or food waste is dependent upon factors such as composition, volatile solids destruction or digester residence time. Methane generated in this way may be collected and energy recovered via combined heat and power (CHP) units. Typical CH_4 yields are provided (Table C4.2).

Table C4.1 CH_4 generation from anaerobic digestion

	kg VS/t	%VS destruction	%CH_4	Conversion factor [1]	kg CH_4/tonne raw DS	Source
Sewage sludge primary digestion	750	45	60	0.67	135	Watt Committee, 1994
Sewage sludge secondary digestion					8	UKWIR, 2008
Sewage sludge advanced digestion	750	62	65	0.67	202	From values in Appendix A
Domestic food waste anaerobic digestion[2]	907	75	58	0.67	264	From values in Appendix A

1 Conversion factor assumes 1 m^3 biogas/kg VSS destroyed, MW for methane = 16 and volume 22.4 l/mole.

2. For an equal comparison anaerobically digested food waste is considered to be stored on site in a similar manner to sewage sludge with secondary digestion and may also be stored after transport to land.

Nitrous oxide

The anaerobic digestion process is not considered to be an important source of N_2O emissions.

C4.3 Methane emissions from anaerobic digestion

The EF for CH_4 from the anaerobic digestion of sewage sludge is an adaptation of that used in the UKWIR Carbon Accounting Methodology (UKWIR 2008). This was a compound EF built up from several parts of the process. Similar sources of emissions will occur from dedicated food waste digesters. The same EFs have been applied to food waste digesters for the purposes of equal comparison (Table C4.3).

Table C4.1 GHG emissions from the anaerobic digestion process

Source	Loss (kg CH_4/ tonne DS)	EF used – sewage sludge (kg CH_4/ tonne DS)	EF used – food waste (kg CH_4/ tonne DS)
Losses via annular space of floating roofed digesters	3.3		
Venting due to ignition failure and downtime at flare stacks	0.29	0.29	0.29
Incomplete combustion	1.45	1.45	1.45
Fugitive emissions	5.1	5.1	5.1
Secondary digestion	8		
Total	18.1	6.8 (14.8 with 2ary digestion)	6.8 (14.8 with 2ary digestion)

The EF value used in this study (6.8 kg CH_4/tonne DS) assumes that newer installations would use fixed roof digester construction and would not use a secondary (cold) digestion stage. These values are being further reviewed as part of two on-going studies. ADAS and WRc in a report for Water UK (Water UK 2009) have recently recommended a lower values of 5.1 kg CH_4/tonne DS based on the assumptions that fugitive releases from new plant would be reduced from 5.1 to 1.3 kg CH_4/tonne DS offset to some extent by an allowance of 2.0 kg CH_4/tonne DS for emissions due to buffer storage. As these proposed lower values have not yet been fully accepted by Water UK the current assumed emission factor of 6.8 kg CH_4/tonne DS has been retained.

C4.4 Emissions from composting

1. Methane

IPCC (2006, Volume 4, Chapter 10) provides a ‘Tier 2’ derived EF for composting manure equal to 0.5% of the maximum methane-producing capacity (B_o) in a cool climate. This has been used for sewage sludge, with the assumption that it behaves like an animal manure and where B_o is 195kg CH_4/tonne raw DS (Table C4.1).

IPCC (2006, Volume 5, Chapter 4) provides a ‘Tier 1’ derived EF for the composting of organic waste, which includes food waste. The EF for food waste is significantly higher than that for sewage sludge which may be a reflection of compositional differences, the different approaches to estimation used and the uncertainty in the estimates.

Co-composting of sewage sludge and food waste is not considered. This is likely to require in-vessel composting and would therefore result in an increase in the costs for treating sewage sludge.

Table C4.1 Emission Factors for CH_4 from composting process

	Sewage sludge kg CH_4/tonne raw DS	Food waste[a] kg CH_4/t waste treated	
		Dry weight	Wet weight
Composted	0.98	10 (0.08 – 20)	4 (0.03 – 8)

a. Assumptions: waste 25-50% DOC in dry matter, 2% N in dry matter, 60% moisture content.

Other sources in the literature have made assessment of the methane emissions from composting (Table C4.5).

Table C4.2 Other literature values for CH_4 emissions from composting

Source	Type of composting	Emission Factor kg CH_4 per tonne waste	Notes
Schleiss, (1999). *(in WRAP, 2007)*	Fully automated composting	5.4	
Schleiss, (1999). *(in WRAP, 2007)*	Open air covered boxes	11.1	
Eunomia (2007) (in WRAP, 2007)		0.983	
Grontmij and IVAM (in WRAP, 2007)		0.195	
WRAP, 2007		Various scenarios. 0 (low emission case) 5.4 (high case) or, 0.983 (with biofilter)	
EA, 2008	In-Vessel composting	0.018kg CH_4/tonne material throughput	Derived from WRATE database.

Nitrous oxide

IPCC (2006, Volume 5) proposes default emission factors for N_2O emission arising from the biological treatment of waste.

Table C4.1 IPCC emission factors for N_2O from waste composting

	N_2O Emission Factors (g N_2O/kg waste treated)	
	Dry weight basis	**Wet weight basis**
Composting	0.6 (0.2 – 1.6)	0.3 (0.06 – 0.6)

Assumptions: waste 25-50% DOC in dry matter, 2% N in dry matter, 60% moisture content.

Default EFs for manures are also provided with a breakdown according to the composting system employed (IPCC, 2006, Volume 4). These EFs, as well as those obtained from other authors is provided in Table C4.7 (IPCC, 2006; UKWIR, 2008).

The EF used in Carbon Accounting Methodology tool (UKWIR, 2008) for sewage sludge, is based on a 2% conversion of the N in the feed sludge, and, when using the N_2O-N to N conversion factor, corresponds to a value of 31 kg/tonne sludge-N (where sludge-N is 0.043 kg N/kg DS). This is considered an average figure for the industry. The EF used for the in-vessel composting of food waste is 0.6 g N_2O/kg DS waste treated (Table C4.6).

Table C4.2 Other literature values for N_2O emissions from composting

Source	Type of composting	Emission Factor kg N_2O-N (kg N excreted)$^{-}$	Notes
IPCC 2006 (Vol 4)	Intensive windrow	0.1 (0.05 – 0.2)	
IPCC 2006 (Vol 4)	In-vessel	0.006 (0.003 – 0.012)	
IPCC 2006 (Vol 4)	Static pile with forced aeration	0.006 (0.003 – 0.012)	
IPCC 2006 (Vol 4)	Passive windrow	0.01 (0.005 – 0.02)	
Szanto *et.al*. 2007	Occasional turned pile	0.025	
Szanto *et.al.* 2007	Static pile, non-aerated	0.098	Increases as zones run out of degradable carbon
-		0.015	A maximum figure

Source	Type of composting	Emission Factor kg N_2O-N (kg N excreted)$^{-}$	Notes
Food waste study:			
Hellmann 1995		0.001 – 0.008 kg N_2O-N/ kg N	
Ballestero and Douglas 1996		0.0219 kg N_2O-N/kg N	Composting of manure
Ballestero and Douglas 1996		0.0118 kg N_2O-N/kg N	Composting of green waste
WRAP 2007		0.01 kg N_2O-N/kg N	
		Emission Factor kg N_2O/t	
Eunomia 2002 in WRAP 2007		0.011	
Gronauer 1997 in WRAP 2007		0.15	
EA 2008	In-Vessel	0.0099	Derived from WRATE database

C4.5 Emissions from incineration

Emissions of CH_4 from incineration are considered small and are therefore not included in the assessment. IPCC 2006, Vol. 5 contains a value for nitrous oxide emissions, specifically for sewage sludge, of 0.99 kg N_2O per tonne dry solids incinerated. This large value presumably reflects the high concentration of nitrogen in wastewater sludge compared to most other incinerator feedstocks.

C5 Emissions from transportation

Emissions of only CO_2 from the use of fuels in transportation are considered. These are primarily based on emission factors published in the Defra Guidelines (Defra, 2007). Waste collection vehicles have been given EFs due to the nature of the activity. These do not represent full "life cycle" emission factors but represent appropriate estimates for the more significant emissions (i.e. fuel use, tyre wear and embodied emissions from vehicle materials).

C6 Carbon sequestered

A benefit that has not been quantified in this project is the potential for sequestration of part of the carbon through an increase in the soil organic carbon (SOC) value. Methodologies to determine amounts of carbon sequestration are subject to a high degree of uncertainty particularly when considering land applications. An approach to estimating SOC values for biosolids has recently been proposed (Water UK, 2009) but has not yet been adopted. Use of this methodology would give rise to similar emission “credits” for both THP/AD options and a larger credit for IVC (due to the higher carbon application rate used).

Appendix D Calculation of some GHG Emissions, Process Parameters and Financial Costs

Sample calculations are presented below to illustrate the calculation procedure for several of the more significant emissions, costs or process parameters. Financial discount factors are based on a discount rate of 5.5% per year. The values used have been rounded-off for the convenience of presentation and so results may differ slightly from calculated values presented in the main text which are taken from the source spreadsheet model.

D1 Kitchen food waste caddies

Item	Value
Number of kitchen caddies required	169,600
Cost of single kitchen caddy	£1.50
Cost of caddies at each replacement	169,600*£1.50 = £254,400
Kitchen caddies lifetime	7 years
NPV of caddies (year 1)	£254,400 = £254,400
NPV of caddies (year 8)	£254,400*0.69 = £174,884
NPV of caddies (year 15)	£254,400*0.47 = £120,222
NPV of caddies (year 22)	£254,000*0.32–(4/7*£254,000*0.26)= £82,645-£38,121=£44,523
NPV of caddies over 25 years	£254,400+£174,884+£120,222+£44,523 = £594,029
Annual quantity of FW collected	15,345 tonnes/y
Cost of caddies expressed as NPV over 25 years/tonnes(wfw).	£594,029/(15,345tonnes/y * 25years) = **£1.55/tonnes(wfw)**

Capital costs of these items may differ significantly depending upon the number purchased and the supplier. Costs for bulk supply of caddies and bins for this study were obtained from Bristol City Council (BCC pers com., 2009).

D2 Kerbside Food Waste Bins

Item	Value
Number of bins required	169,600
Cost of single bin[1]	£4.20
Cost of bins at each replacement	169,600*£4.20 = £712,320
Bin lifetime	7 years
NPV of bins (year 1)	£712,320= £712,320
NPV of bins (year 8)	£712,320*0.69 = £489,675
NPV of bins (year 15)	£712,320*0.47 = £336,621
NPV of bins (year 22)	£712,320*0.32-(4/7*£712,320*0.26)= £231,405-£106,740=£124,665
NPV of bins over 25 years	£712,320+£489,675+£336,621+£124,665= £1,663,281
Annual quantity of FW collected	15,345 tonnes/y
Cost of bins expressed as NPV over 25 years /tonnes(wfw)	£1,663,281/(15,345tonnes/y * 25years) = **£4.34/tonnes(wfw)**

D3 Labour cost

Item	Value
Dedicated kerbside collection vehicle	
Maximum usable vehicle loading	2,800 kg /vehicle/round
Set out rate (taken as the same as the participation rate of 60% of all households)	0.6
Average collectable food waste per participating household	2.90 kg (wfw) per week
Average food waste collected per household	2.9 kg/hh/wk*0.6 = 1.74kg/hh/wk
Pass rate required per round (as hh)	2800 kg/vh/rd /1.74kg/hh/wk = 1,609.2hh
Number of households	169,600
Working days per week	5
Number of rounds required for weekly collection	169,600/(1,609.2 * 5) = 21.08

Item	Value
On cost factor (NI, pension etc.)	1.22
Holidays/sick leave per year per crew member (driver and crew member)	9 weeks
Number of drivers	1
Salary of driver	£22,000/year
Cost of dedicated vehicle driver	(£22,000/y*1.22)+((£22,000/y*1.22)*(9w/ 52w)=£26,840+£4,645=£31,485/year
Number of crew members	1
Salary of crew member	£16,000/year
Cost of dedicated vehicle crew	(£16,000/y*1.22)+((£16,000/y*1.22)*(9w/ 52w))=£19,520+£3,378=£22,898/year
Total cost of dedicated vehicle staff	(£26,840/year+£4,645+£19,520+£3,378/ year) * 21.08 = £1,146,349/year
Bulk food waste transfer vehicle	
On cost factor (NI, pension etc.)	1.22
Bulk vehicle driver salary	£22,000/year
Number of bulk vehicle required	2.1
Cost of bulk vehicle driver salary	(1,22*£22,000/y)+((1,22*£22,000/y)*(9/52) =£31,485/year
Total cost of bulk vehicle driver salary	£31,485/year*2.1=£66,072.6/year
Total labour costs for collection and transport	
Total cost of labour in year one	£1,146,349/year+£66,072.6/year=£1,212,421.95/year
NPV of labour over 25 years	£1,212,421.95/year *14.1517 = £17,157,831.7
Annual quantity of FW collected	15,345 tonnes/y
Cost of labour expressed as NPV over 25 years / tonnes (wfw).	£17,157,831.7/(15,345tonnes*25years) = **£44.72/tonnes (wfw)**

D4 Food waste disposal units

Item	Value
Number of installed units based on 60% participation	101,760
Installed cost of single FWD unit	£150
Cost of FWD units at each replacement	101,760*£150 = £15,264,000
FWD units lifetime	12 years
NPV of FWD units (year 1)	£15,264,000*1.0 = £15,264,000
NPV of FWD units (year 13)	£15,264,000*0.53 = £8,028,582
NPV of FWD units for final year	(£15,264,000*0.28)-(11/12*£15,264,000*0.26)= £4,222,886-3,669,174=£553,712
NPV of FWD units over 25 years	£15,264,000+£8,028,582+£553,712= £23, 846,294
Annual quantity of FW processed	15,345 tonnes/y
Cost of FWD units expressed as NPV over 25 years / tonne (wfw).	£23,846,294/(15,345tonnes/y*25years) = **£62.16/tonnes (wfw)**

FWD units are replaced at the start of year 25 but would retain a significant residual value at the end of the assessment period. Allowance for this has been made by including only 1/12 of the Year 25 NPV of the installation cost.

D5 Water for FWD units operation

Item	Value
Number of FWD unit uses per day	3 /d
Duration of each FWD unit use	30 seconds
Assumed tap flow rate during use	4.92 litre/min
Increase in water consumption per FWD unit	(3*30secs*4,92l/min)/60=7.38litre/unit/day
Number of FWD units installed	101,706
Annual water consumption by all FWD units.	101,760*7,38l/unit/d*365d= 274 Ml/year
Cost of water as supplied	£0,001 /litre
Cost of additional water use	274Ml/l * 1,000,000 * £0.001 = £274,111/year

Item	Value
NPV of additional water over 25 years	£274,111/year * 14.1517 = £3,879,137
Quantity of FW collected per year	15,345 tonnes
NPV of additional water expressed as NPV over 25 years /tonnes(wfw).	£3,879,137/(15,345tonnes*25years) = **£10.11/tonnes (wfw)**

D6 Embodied carbon in FWD units

Item	Value
Weight of the FWD unit	**9.3kg**
Steel	50%
Stainless steel	9%
Iron	20%
Copper	8.5%
Aluminium	5%
Rubber	7.5%
Percentage of recycled steel, iron, copper and aluminium	92.5%
Emission factor - primary steel	2.75 kg CO_2/kg
Emission factor - secondary steel	0.43 kg CO_2/kg
Weight of steel per FWD unit (weight of recycled steel)	4.65kg (4.30kg)
Emission factor – general stainless steel	6.15 kg CO_2/kg
Weight of stainless steel per FWD unit	0.837kg
Emission factor –general iron	1.91 kg CO_2/kg
Weight of iron per FWD unit	1.86kg CO_2/kg
Emission factor – primary copper	3.83 kg CO_2/kg
Emission factor – secondary copper	0.96 kg CO_2/kg
Weight of copper per FWD unit (weight of recycled copper)	0.7905kg (0.73kg)
Emission factor – primary aluminium	11.5kg CO_2/kg
Emission factor – secondary aluminium	1.69 CO_2/kg

Item	**Value**
Weight of the FWD unit	**9.3kg**
Weight of aluminium per FWD unit (weight of recycled aluminium)	0.465kg (0.93kg)
Weight of rubber per FWD unit	0.6975
Emission factor – general rubber	3.18/ kg/ CO_2
Calculation of embodied carbon per FWD unit	=((4.30kg secondary steel x0.43kgCO_2/kg)+0.35kg primary steel x2.75kg CO_2/kg))+((0.73kg secondary copper x 0.96kgCO_2/kg)+(0.06kg primary copper x3.83kgCO_2/kg)) + (0.84kg stainless steel x6.15kgCO_2/kg) + (1.86kg iron x1.91kgCO_2/kg) + ((0.43kg secondary aluminium x1.69kgCO_2 /kg+0.04kg primary aluminium x 11.5kgCO_2/kg))+(0.7kg copper x3.18kgCO_2/kg)=**15.87kg CO_2e/ FWD unit**

D7 Weight of liners per tonne

Item	Value
Weight per liner	0.007kg
Number of liners per household per week	2
Weight of liners per household per week	0.007kg * 2 = 0.014kg
Number of households	101,760
Weeks in a year	52
Weight of liners per year assuming use by all participating households	0.014kg * 101,760 * 52 = 74,081.28kg = 74tonnes
Total food waste collected per year	15,345 tonnes
Contribution of liners to collection weight as %	100 * 74tonnes*/15,345tonnes = **+ 0.5%**

D8 Increase in wastewater flow due to FWD water use

Item	Value
Additional water use due to FWD unit	7.38 l/day per FWD unit
Average household size	2.36
Additional water use due to FWD unit on a user *per capita* basis	7.38 /2.36 = 3.13 l/day per person
Assumed FWD use within catchment	60%
Additional water use due to FWD unit on an average *per capita* basis	3.13 * 60 /100 = 1.88 l/day per person
Assumed wastewater flow	200 l/day per person
Increase in wastewater flow as %	100 * 1.88 /200 = **+ 0.94%**

D9 Settling fraction of food waste

Stokes law defines the settling velocity of a sphere as:

$$v_S = \frac{(\rho - \rho_W) \cdot g \cdot d^2}{18 \cdot \mu}$$

Where

v_s Settling velocity, m/s
ρ Density of solid, kg/m^3
ρ_W Density of Water, kg/m^3
g Gravitational acceleration, m/s^2
μ viscosity, Pa.s
d Particle diameter, m

Assuming:

- organic material density 1.013 g/cm^3
- typical settling tank rise velocity 24 m/h (CIWEM 1973)
- 98% of food waste is less than 2 mm diameter (Kegebin *et al.* 2001)

Particle diameter would need to be <0.2 mm for incomplete removal. (i.e. settling velocity less than 24 m/h).

Consequently, the assumption that 90% of the particulate food waste solids are settleable during primary sedimentation is reasonable.