SEVENTH FRAMEWORK PROGRAMME
THEME ENERGY.2009.3.2.2
Biowaste as feedstock for 2nd generation

VALORGAS

Project acronym: **VALORGAS**
Project full title: **Valorisation of food waste to biogas**
Grant agreement no.: 241334

D2.5 – Institutional and community food waste generation rates and appropriateness of scale for on-site utilisation for second generation biofuel production by AD

Due date of deliverable: Month 28
Actual submission date: Month 30

Project start date: 01/03/2010 Duration: 42 months

Lead contractor for this deliverable
Foundation for Innovation and Technology Transfer (IIT)

Revision [1]

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Revisions
Changes since version [0] of this deliverable mainly consist of the addition of case study 8 (port of Dover), and the correction of minor typographical errors

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D2.5 – Institutional and community food waste generation rates and appropriateness of scale for on-site utilisation for second generation biofuel production by AD

1 Introduction

This deliverable report presents the results of case studies on the food waste generation rates, real or potential, and on the corresponding scale of anaerobic digestion facilities needed to provide on-site renewable energy production. The report includes one theoretical and ten actual case studies, covering a range of institutions: a hospital, a prison, three army bases, a small community digester, a port[1], two universities, a waste collection depot, a town and a county. With the exception of one of the universities, all of the sites selected were in the UK, to facilitate comparison between the studies in terms of feasible operating scales.

2 Methods

2.1 The Waste Digestion energy modelling tool

Energy balances and greenhouse gas (GHG) savings were calculated using a simplified version of a spreadsheet-based tool developed at the University of Southampton (Salter, (2011), based on Salter & Banks (2009) and Salter *et al.* (2011)). The energy balance is calculated based on the input and output energies to the system as shown in Figure 2.1.

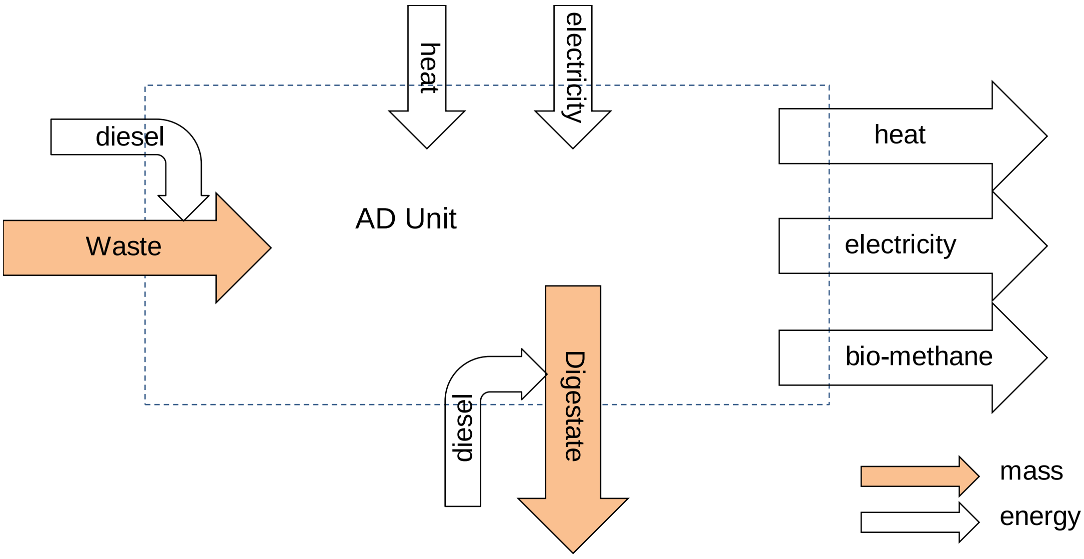

Figure 2.1. Input and output energy sources

The task of determining the energy requirements is conducted in a number of stages.

Input materials. This section defines the amount of waste to be digested. This includes waste characteristics (total and volatile solids content, methane potential, N, P and K content), the amount collected and distance the waste is to be transported to the digester from the

[1] Currently not available due to issues of confidentiality of data, but may be included in a later version of this deliverable report.

collection point. Default values for a number of pre-characterised waste streams are available, or the waste characteristics can be specified by the user. The tool also allows input of up to 10 multiple waste streams e.g. food waste, garden waste and animal manure. Energy requirements associated with the waste input are in the form of diesel used for collection and transport of the waste to the digester. The vehicle used in transport is be selected from a range of options including rigid and articulated lorries with associated fuel consumption and GHG emissions based on standard values (AEA, 2010).

Digester. This section calculates the required digester capacity, based on the amount of material to be digested and a user-specified loading rate or retention time. It is assumed that the biogas is stored in the digester and an additional 10% of the working volume is allowed for this purpose. A maximum digester size is assumed (of 3500 m^3 in the current work) and above this the required capacity is distributed between a number of equal-sized digesters. Parasitic energy requirements are considered in two parts. The total parasitic heat requirement is calculated from the digester size, based on heat loss through the walls, roof and floor and on the energy required to heat the feedstock to the user-specified digester operating temperature. Ambient temperatures for heat loss calculations are user-specified in the form of average monthly air and soil temperatures. Parasitic electrical requirement is calculated based on the amount and nature of the feedstock. For unprocessed food waste (i.e. as collected) this is taken as 40 kWh $tonne^{-1}$.

Digestate. The amount of digestate is calculated by subtracting the mass of biogas produced from mass of feedstock, assuming no losses. The nutrient composition of the digestate is based on the N, P, and K values of the feedstock, also assuming no losses. Digestate transport is calculated based on a user-specified distance from the digester to the location in which the digestate is to be spread. The vehicle used for digestate transport is selected from a range of vehicle options linked to the associated fuel consumption and GHG emissions (AEA, 2010). Unless specified, the energy required for transport of the digestate to the fields and application in the field is not included: this is assumed to be part of the farm energy balance.

Biogas use. Various options for biogas use are available, including boiler and CHP. The boiler provides heat at an assumed efficiency of 85%; the overall efficiency of the CHP plant is assumed to be 85% and the user can specify the electrical conversion. These options can be combined with upgrading to bio-methane if required. The parasitic energy requirement of the plant is assumed to be supplied by on-site CHP where available. Where a CHP unit is not selected or the output is insufficient it is assumed that the electricity required is imported from the national grid, and heat is provided by a user-specified range of fuel sources including natural gas, petrol or diesel oil.

2.2 Energy balances and GHG offsets

The energy balances are calculated solely in terms of direct energy, i.e. energy used in the form of fossil fuels or to replace energy produced from fossil fuels, and do not include the indirect or embodied energy in vehicles and plant.

Once the energy requirements for collection and processing of the waste and the potential energy outputs have been determined, energy balances can be calculated. The energy output of the system is taken as the energy contained in the electricity, heat or enhanced bio-methane available for export. The energy input is taken as the energy required to collect and transport the waste to the digester and to transport the digestate to the disposal point. Parasitic energy is not included here unless it is provided by external sources i.e. grid-based electricity or gas for heat. The energy balance can then be determined from:

Energy balance = energy out (heat, electricity, bio-methane) – energy in (transport, parasitic)

This can be expressed as a total value, per person or per tonne of waste collected.

As the energy considered is restricted to that for the use/replacement of fossil fuels, so the GHG emissions/savings are also based on the use/replacement of fossil fuels. GHG emissions from the CHP are not taken into account as it is assumed that these are part of the short-term carbon cycle. Sources of GHGs therefore include the diesel consumed in transport and any electricity or heat provided from grid sources. Emissions savings are from the use of the biogas as an energy source to replace energy derived using fossil fuels. For example, electricity produced and exported 'saves' 126 kg CO_2eq GJ^{-1} (DECC, 2011) compared to UK national grid-based production. If the heat exported replaces heat produced using natural gas, the saving is 57 kg CO_2eq GJ^{-1} (AEA, 2010). GHG emissions produced from the use of diesel in transport can therefore be off-set against emissions saved through the replacement of fossil fuel derived energy sources.

2.3 Parameters and assumptions made in modelling

Unless otherwise noted the following assumptions were applied in the case studies:

- CHP plant electrical efficiency 35%, heat efficiency 50%.
- The specific heat capacity of the waste is 4.19 kJ kg^{-1} K^{-1}, equal to that of water.
- Process losses are estimated at 1% of biogas produced.
- A digester loading rate of 3 kg VS m^{-3} day^{-1} is used.

2.3 References

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Salter, A. M., Jain, S. & Banks, C. J. (2011) Modelling the Mitigation of GHG Emissions and Nutrient Requirements for Dairy Farming Through the Use of Anaerobic Digestion. In Bochmann, G. (Ed.) *International Symposium on Anaerobic Digestion of Solid Wastes and Energy Crops.* Vienna.

3 Theoretical case study for institutional and community AD

3.1 Introduction

In order to provide an overall framework and context for the case studies of individual institutions and communities, a simple theoretical scoping study was carried out to assess the effects of the quantity and location of generated food waste on the required scale of anaerobic digestion plant and on the net energy produced. The study looked both at distributed sources, corresponding to communities which generate food waste over a dispersed geographical area; and at point sources, representing food waste arising at individual institutions or single sites such as canteens. To achieve this, the AD model described above was used to calculate the net energy output for a range of population sizes, population densities and collection areas.

3.2 Assumptions

3.2.1 Distributed source - communities

For the purposes of this exercise, the average capture rate for food waste from a source segregated collection was taken as 50 kg person^{-1} year^{-1}. The yield from a particular geographical area can thus be determined by multiplying this rate by the area in km^2 and the population density in person km^{-2}.

It is assumed that the food waste is taken to a single central point (e.g. transfer station or depot), with a fuel consumption for collection of 10.9 l diesel tonne^{-1} based on typical values obtained from modelling urban collections (see VALORGAS deliverable D2.7). From this point there are two options, depending on the location of the digester. In the first, the digester is located at the centre of the area used for digestate application (i.e. a farm-based AD plant), and in this case the food waste is transported to the digester in a rigid lorry of greater than 17 tonnes gross at a fuel consumption of 0.076 l diesel tonne^{-1} km^{-1} (AEA, 2010). In the second case the digester is located at the centre of the collection area (city-based AD plant), and the digestate is transported to the distribution area in the same type of vehicle.

The area required for distribution of the digestate is calculated based on the amount of digestate, using an application rate of 200 kg N ha^{-1} and a nitrogen content of 8 kg N tonne^{-1} digestate. It is assumed that collection and digestate distribution areas are circular and homogenous (Figure 1), with the digestate distribution area assumed to be 30% unusable for this purpose (i.e. occupied by roads, buildings etc). The transport distance for food waste from the collection point to the digester (farm-based) or for digestate from the digester to the application area (city-based) is therefore the radius of the collection area plus the radius of the digestate distribution area.

The energy required for spreading digestate on land can be omitted from the balance as it is at least partially offset by the reduced requirement for fertiliser: it therefore forms part of the farm energy balance and is outside the current system boundaries. Where the energy for digestate application is taken into account, it is assumed that digestate is transported to the fields using a tractor and trailer with an energy consumption of 1.91 MJ tonne^{-1} km^{-1} and applied in two separate applications using a trailed hose system at a rate of 3.6 l diesel ha^{-1}.

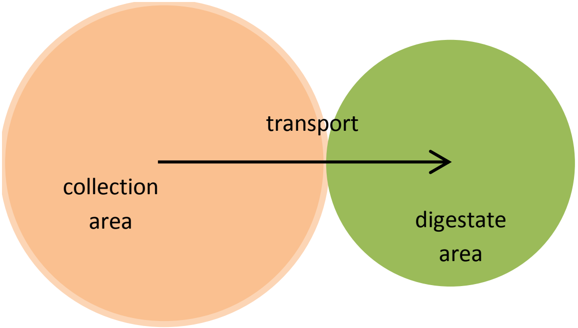


Figure 3.1. Collection and digestate distribution

The required digestion capacity is calculated based on a loading rate of 3 kg VS m^{-3} day^{-1}. The maximum volume for a single digester is set at 3500 m^3, and the number of digesters needed is determined by dividing the total waste available until the individual digesters are less than this. Parasitic electrical requirement is based on a value of 40 kWh $tonne^{-1}$ of food waste (personal communication Michael Chesshire, 2012) and was initially assumed to be the same at all scales of digestion. Parasitic heat requirement is determined according to average monthly temperatures (taken at Southampton, UK) the operating temperature of the digester (37 °C); and the digester construction (in this case insulated concrete). Heat requirement is determined from the heat needed to bring the feedstock up to digester temperature and the heat loss through the walls of the digester. It is assumed that the feedstock is pre-pasteurised at 70 °C for 1 hour. The size of the pre-pasteuriser is determined by dividing the daily amount of feedstock by 12, allowing 1 hour for heating and cooling. Heat loss is calculated as for the digester.

The biogas produced is used to provide the energy input to a CHP unit. This unit has an electrical efficiency of 35% and heat is captured at 50% of the input energy. Both the parasitic electricity and heat for the digester and pasteuriser are provided by the CHP unit.

The net energy balance is calculated by subtracting the energy inputs (waste collection, transport to the AD plant, and digestate transport to the application area with / without digestate spreading) from the energy available for export produced in the form of electricity and heat (total energy produced in the CHP less that required for parasitic uses). The reported energy balances do not include allowances for embodied energy for the digester or any ancillary plant. They thus represent the net operating energy balance for the scheme from collection to application.

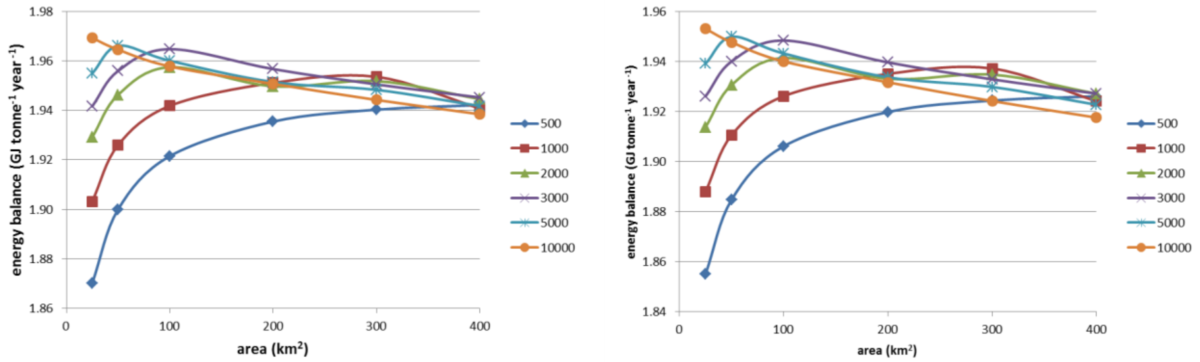
3.2.2 Point sources - individual institutions

Point sources were chosen to represent institutions with populations from 200 to 20000 whose waste is generated in one small area (e.g. one or more canteens or restaurants). These were modelled using the same tool as for distributed sources, with the collection area fixed at 1 hectare and population densities ranging from 20000 to 2000000 persons km^{-2}. The collection energy was assumed to be zero. Two options were considered for the location of the digester: in the first the digester was assumed to be located on site (equivalent to city-based), with the digestate transported 15 km for disposal; while in the second it was assumed that the food waste was transported 15 km off site for digestion, with digestate disposal centred around the digester (i.e. farm-based). Other assumptions were the same as for distributed sources.

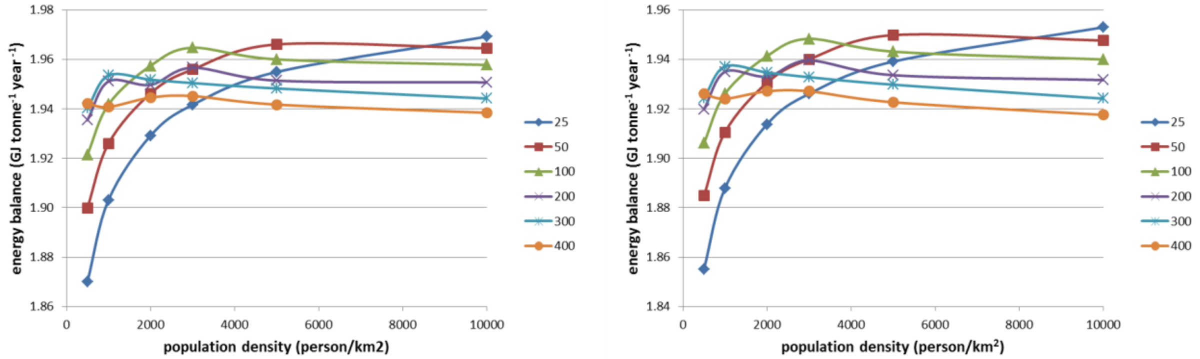
3.3 Results

3.3.1 Distributed source - communities

Overall net energy balances for a range of population densities from 500 to 10000 person km^{-2} and collection areas from 25 to 400 km^2 are shown in Figure 2, expressed in GJ tonne^{-1}. At low population densities an increase in collection area gives an improved energy balance, whereas at higher population densities this trend is reversed. For population densities over 500 persons km^{-2} the energy balance shows a maximum in the range of collection areas from 25 - 400 km^2.



a) Energy balance versus collection area for different population densities (persons km^{-2})
i) without spreading ii) with spreading



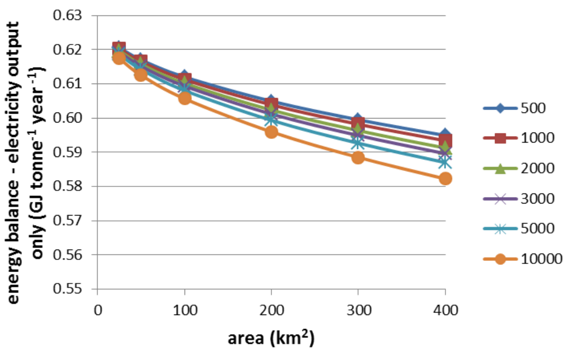
a) Energy balance versus population density for different collection areas (km^2)
i) without spreading ii) with spreading

Figure 2. Energy balance for farm-based digestion with area and population densities - total net energy

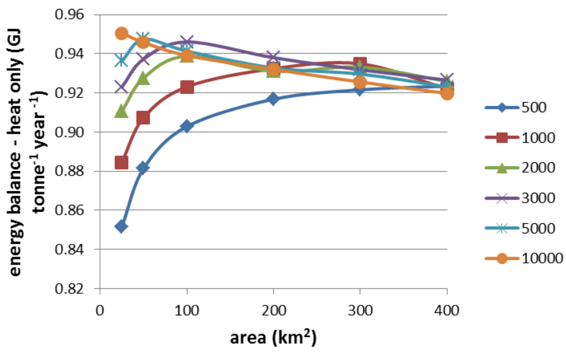
This behaviour is explained by considering the components for electricity only, heat and transport. The energy balance if electricity only is exported, and the surplus generated heat is wasted, is shown in Figure 3a: in practice this situation is quite common, as economic uses for the heat are often difficult to find, although this varies by country and region. The electricity generated and the parasitic energy demand are both directly proportional to the amount of waste. The energy balance for heat only is more complex, as shown in Figure 3b. Here, digester size has an impact as the volume to surface area ratio increases with size, reducing the amount of heat loss per m^3 of digester. This accounts for the improving energy balance especially at population densities until the waste collected is enough to fill a 3500 m^3

digester. For a given collection area, a higher population density produces more food waste and more digestate which in turn requires a bigger area for spreading and therefore increases the transport distance to the digester. Inclusion of digestate spreading energy makes only a slight difference to the overall total. The energy required for digestate application is approximately 30 times that for digestate transport and up to twice the energy requirement for waste transport, but is a fixed quantity per tonne so varies linearly with the amount of waste.

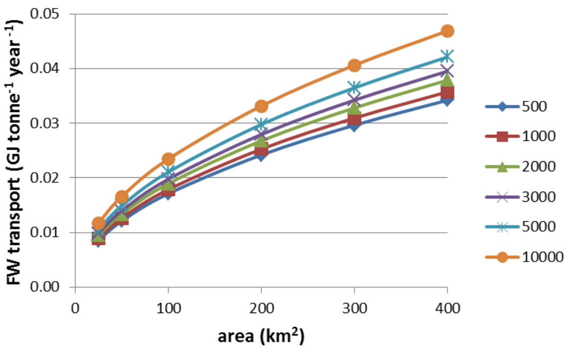
In the current example the energy balances are calculated for a plant producing electricity and heat in a CHP process. The results could be expressed in terms of raw biogas by increasing the energy produced by 15%, as this is the assumed loss in CHP generation. Modification to upgraded methane would be more complex as the upgrading process itself has an energy demand which varies with the quantity of gas to be upgraded.



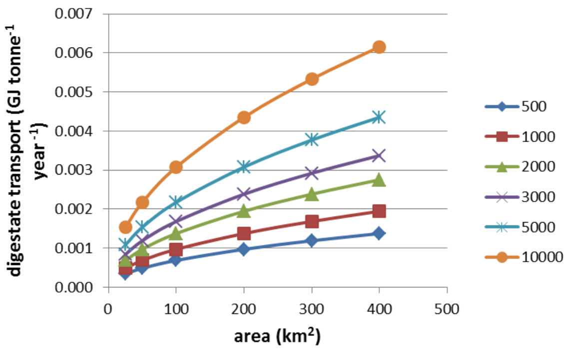
a) Electrical energy only



b) Heat energy only



c) Energy used in FW collection



d) Energy used in digestate transport

Figure 3. Net electrical and heat energy components of energy balance and energy used in transport versus collection area at different population densities (person km^{-2}) (Farm-based, without digestate spreading)

Multiple centres. The above scenarios are based on a single centre of digestion. An alternative approach is to divide the collected waste and distribute it to a number of digestion centres around the collection area, as shown in Figure 4. This reduces the transport distance and thus the fuel requirement. Embodied energy values are not included in the current analysis but the effect of these will vary: the number of digesters is unchanged but additional ancillary plant will be required and in some cases this may mean duplication of facilities such as shredders and pasteurisers without full use of their capacity.

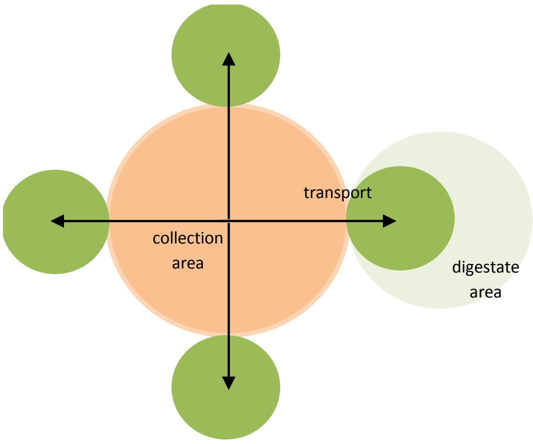
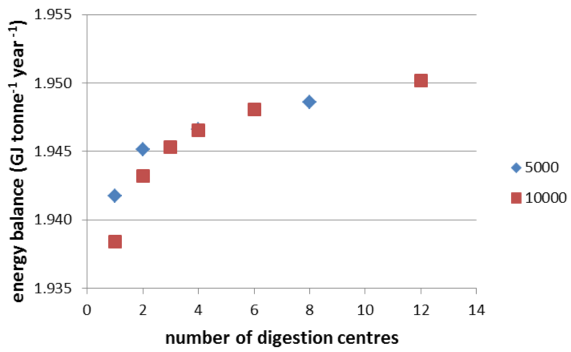


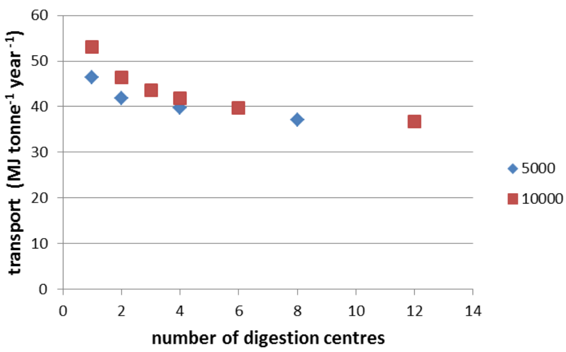
Figure 4. Increasing the number of digestion centres

The resultant energy balances for an area of 400 km^2 and two population densities are shown in Figure 5. It has been assumed that there are an equal number of digesters at each centre thus values are represented at all values. A population density of 10,000 persons km^{-2} in 400 km^2 would require 13 digesters below 3500 m^3 working volume which can be located in 1, 2, 3, 4, 6 or 12 centres.

A larger number of local centres, rather than a few large-scale ones, provides a better energy balance. This is mainly a result of reduction in the transport energy requirements, as shown in Figure 5b.



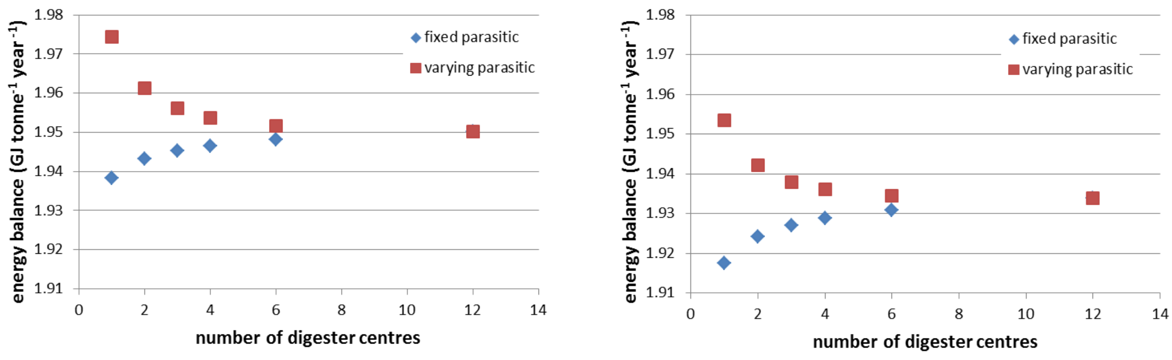
a) Total net energy



b) Transport component (note y-axis units)

Figure 5. Energy balance versus number of digestion centres for population densities of 5000 and 10000 persons km^{-2} (Farm-based, without digestate spreading)

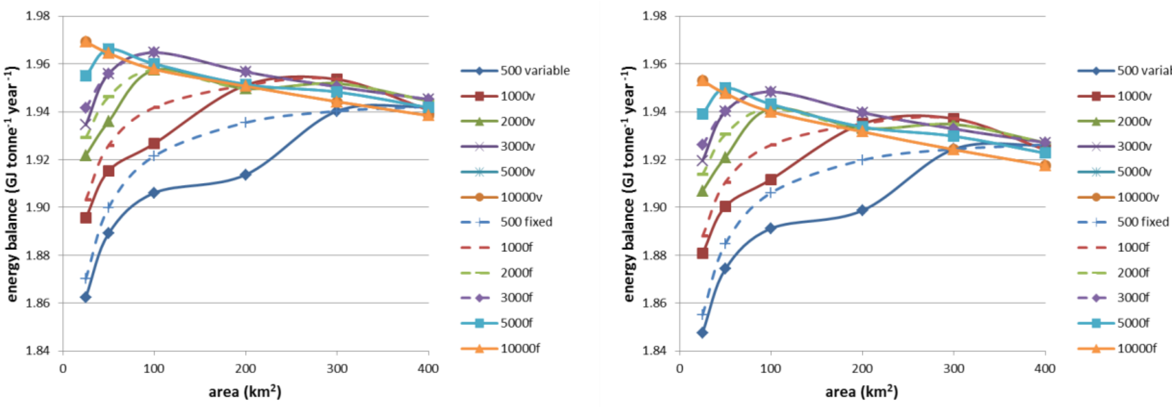
Variations in parasitic energy. A further consideration is the parasitic electrical energy requirement. In the previous examples this was taken as a constant value per tonne of feedstock at all scales. It is usually the case, however, that at larger scales the specific energy requirement reduces as larger capacity machinery becomes more efficient. Figure 6 shows the result of changing the parasitic energy requirement per tonne of waste processed at each digestion centre to a linear range from 40 kWh tonne^{-1} if the supply is less than 20,000 tonnes to 30 kWh tonne^{-1} above 180,000 tonnes year^{-1}. The latter case represents an area of 400 km^2 with a population density of 10,000 persons km^{-2}, corresponding to a city of 4 million inhabitants. The large volumes of waste processed at a single plant mean that changes to the parasitic requirement make a relatively large difference to the balance.



a) without spreading b) with spreading

Figure 6. Energy balance for fixed and variable parasitic energy demands versus number of digestion centres, at a population density of 10000 persons km^{-2} (Farm-based)

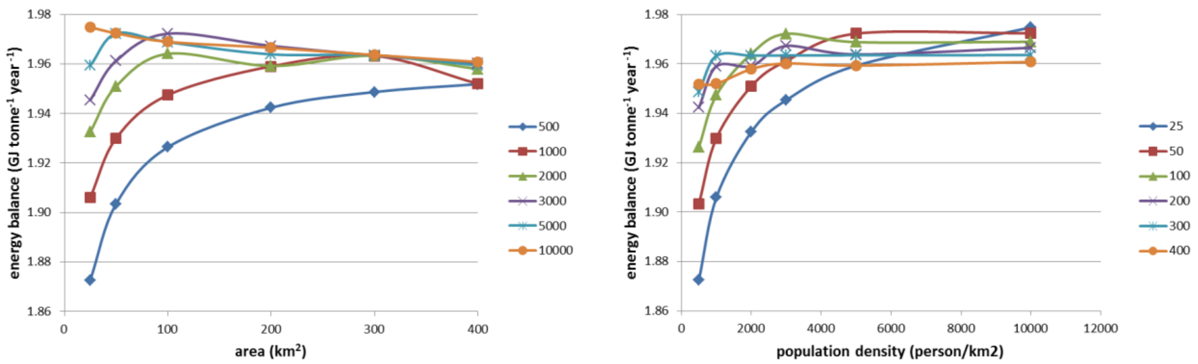
Waste transport. The energy requirement for transport of the waste per unit weight is also unlikely to be a fixed value irrespective of the total quantity. Where small quantities are moved on a daily basis a smaller vehicle would be used. In this scenario it is assumed that if the quantity of waste is less than 15 tonnes day^{-1} it will transported in a lorry with gross weight between 7.5 and 17 tonnes and a fuel requirement of 0.156 l tonne^{-1} km^{-1}. Otherwise the waste is transported on a rigid lorry greater than 17 tonnes gross at 0.076 l tonne^{-1} km^{-1}. Figure 7 shows the effect of varying the energy requirement for transport on the overall net energy balance.



a) without spreading b) with spreading

Figure 7. Energy balance for fixed and variable fuel consumption per tonne of food waste transported versus collection area for different population densities (persons km^{-2}) (Farm-based)

Location of digester. The previous scenarios have all assumed that the digesters are on farms, located at the centre of the digestate spreading area. An alternative scenario is that the digester is placed at the collection point in the centre of the population area and the digestate is then transported to one or more farms for spreading. This scenario therefore assumes there is no requirement for transportation of the food waste after collection, and the digestate is transported to the relevant farm in a rigid lorry of gross weight greater than 17 tonnes. The fuel requirement is therefore 0.076 litres tonne^{-1} km^{-1}. The energy balance under this scenario (assuming all of the digestate goes to a single site) is shown in Figure 8.

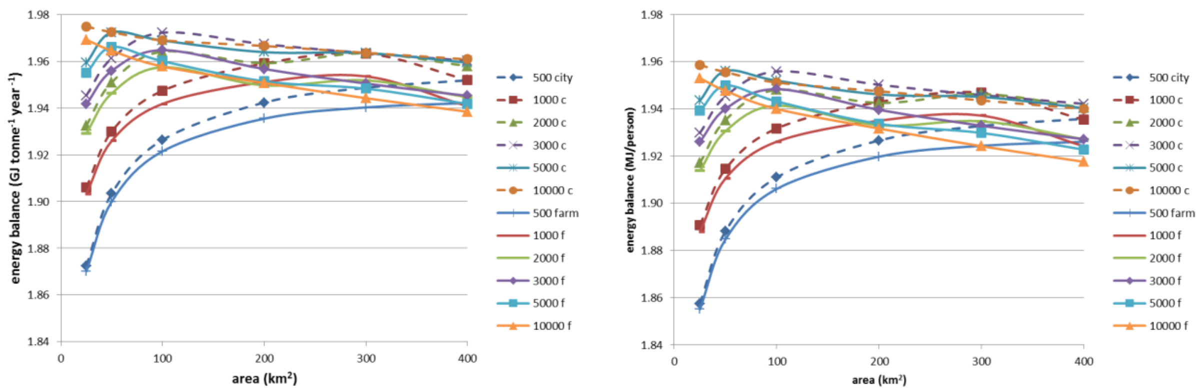


a) Versus collection area for different population densities (persons km^{-2})

b) Versus population densities for different collection areas (km^{2})

Figure 8. Energy balance for fixed fuel consumption per tonne of digestate transported (City-based, without digestate spreading)

A comparison of the results of the farm-based and city-based digestion energy balances is shown in Figure 9. The higher values for the city-based digesters are due to the reduction in material to be transported: as some of the food waste is converted into biogas the mass of digestate to be transported from a city-based digester is lower than the original amount of food waste which must be transported to a farm-based plant. This assumes that the digester is run on a pure food waste feedstock, without addition of water for dilution, and that digestate separation is not practiced.



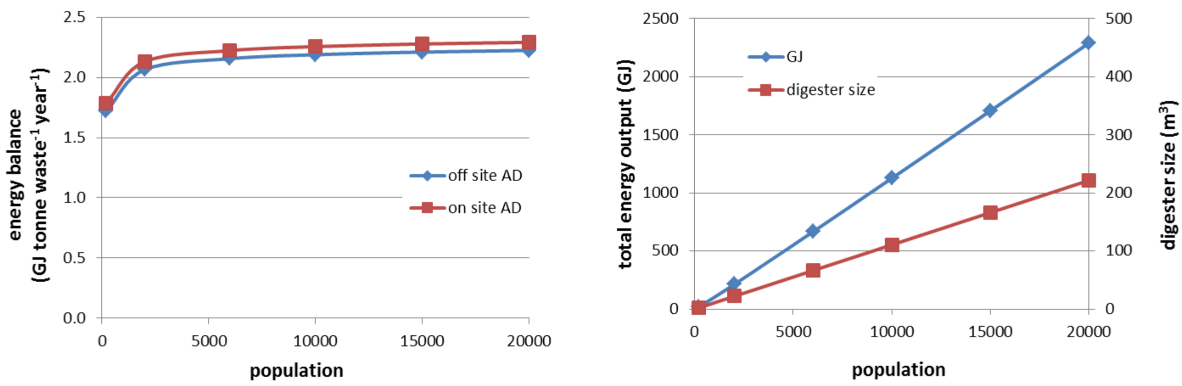
a) without spreading

b) with spreading

Figure 9. Energy balances for farm and city-based digestion versus collection area for different population densities (persons km^{-2}) (assuming fixed parasitic load (40 kWh tonne^{-1}) with transport in > 17 tonnes rigid vehicles, as in initial reference scenarios)

3.3.2 Point sources - individual organisations

Figure 10 shows the results of modelling with populations from 200 to 25000 people whose waste is generated in a small area (e.g. from a restaurant or canteen) so that the fuel requirement for collection is effectively zero; and with a digester located either on site or a specified distance away. The smallest population used is slightly less than that in the case studies in the following sections (~350 people at Welbeck College), while the largest corresponds to the British Army's base at Camp Bastion in Afghanistan, at the upper end of the range for institutional catering on a single site. The net energy production per tonne is lower for small populations, mainly reflecting the small size of digester required and the greater heat losses. This effect is only significant at population sizes below ~5000, equivalent to a single institution (hospital or prison) up to a sizeable village. Digester size is a linear function of population, while the total net energy production is close to linear. Details of the energy balance calculations are given in Table 1. Transport of food waste or digestate is assumed to be in a 7.5 to 17 tonne rigid lorry as the quantities of material are relatively small.



a) Energy balance per tonne b) total energy output and digester size

Figure 10. Energy balance, energy output and digester size versus population for point sources of food waste (without spreading).

Table 3.1. Results for point source modelling with different populations (no spreading)

Parameters	On-site digester, fixed rates for parasitic energy, and digestate and waste transport						
Population	200	2000	6000	10000	15000	20000	no.
Digester input	10	100	300	500	750	1000	tonnes
Digester capacity required	2.2	22.2	66.5	110.9	166.4	221.8	m3
Digestate transport	0.03	0.09	0.16	0.20	0.25	0.28	km
Waste transport	0.00	0.00	0.00	0.00	0.00	0.00	km
Energy inputs required (/year)							
Waste collection	0	0	0	0	0	0	GJ
Waste transport	0.00	0.00	0.00	0.00	0.00	0.00	GJ
Digestate transport	0.67	6.72	20.19	33.69	50.58	67.50	GJ
CHP supplied electricity	1.44	14.4	43.2	72	108	144	GJ
Imported electricity	0	0	0	0	0	0	GJ
Boiler/CHP supplied heat	8.92	54.78	136.88	211.94	301.37	387.89	GJ
Imported gas for heat	0	0	0	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	pre	pre	pre	digester
Pasteuriser heat	2.57	25.28	75.52	125.69	188.35	250.98	GJ
Total energy inputs	12.05	80.90	211.74	334.76	483.66	629.35	GJ
Energy balance							
Energy in methane produced	33.2	332.2	996.5	1660.9	2491.4	3321.8	GJ
Exported electricity	10.2	101.9	305.6	509.3	764.0	1018.6	GJ
	2.8	28.3	84.9	141.5	212.2	283.0	MWh
Exported heat	7.7	111.3	361.4	618.5	944.3	1273.0	GJ
	2.1	30.9	100.4	171.8	262.3	353.6	MWh
Energy in upgraded CH4	0	0	0	0	0	0	GJ
Total exported energy	18	213	667	1128	1708	2292	GJ
Balance (total)	17	206	647	1094	1658	2224	GJ
(per person)	86.0	103.2	107.8	109.4	110.5	111.2	MJ/person
(per tonne)	1.72	2.06	2.16	2.19	2.21	2.22	GJ/tonne

3.4 Conclusions

The modelling is based on a number of simplifying assumptions. Some of these were examined in the scenarios tested, and the output clearly indicates where the overall results are sensitive to these. The parameter values used will also have a significant effect: for example the fuel consumption for collection of food waste from distributed household sources is an average based on calculations, while real values may vary considerably between schemes (see VALORGAS deliverable D2.7). The approach adopted does however provide a rational basis for the comparison of options. It is possible to identify the optimum collection area for a digestion plant receiving material from distributed sources: too small, and the effects of greater heat loss from a small digester are noticeable, whereas when the area becomes too large the additional energy expended to transport waste and digestate outweighs any benefits from increased scale. This optimum area varies with population but in dense urban areas smaller collection areas are clearly favoured in terms of net energy yield. In the examples above only one scenario for energy conversion was considered, based on the use of an on-site CHP plant. In practice very small units such as the smaller point sources may use the biogas directly as a fuel in boilers or on-site vehicles; while larger plants may adopt gas upgrading to a quality suitable for vehicle use or grid injection.

The energy balances calculated above do not include embodied energy for the digestion plant or ancillaries, but presentation of the output in this way provides an energy 'budget' for the scheme which allows calculation of the energy 'pay-back' period when values for embodied energy are known, or assessment of what is affordable in energy terms to achieve a reasonable period for recovery of the energy invested. The theoretical study thus provides a framework for comparison with the following case studies, and a useful guide to areas where more reliable information is needed on actual values of fuel consumption and energy conversion efficiency.

3.5 References

AEA (2010) *2010 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting* Available from: http://archive.defra.gov.uk/environment/business/reporting/conversion-factors.htm

4 Case Study of Harrogate District Hospital: Investigating the potential for small-scale anaerobic digestion onsite

In this case study the potential for onsite anaerobic digestion at a hospital was assessed. Hospitals generally provide meal service three times a day for patients, and canteens where staff and visitors can buy meals while onsite. There is significant potential for food wastage, arising from factors such as the requirement to provide adequate meals to infirm patients who may be unable to eat all of the food provided, or the provision of excess food to ensure patient choice (Precey, 2008). Food wastage in hospitals is of particular concern in terms of cost and patient health impacts. Uneaten food has implications for patient health, if patients are not consuming the recommended intake of 1800-2200 kcal/day. This also can result in delayed recovery due to undernutrition and prolonged hospital stays, with their associated cost implications (Barton et al., 2000). This is in addition to the direct cost of food that is paid for, prepared and then wasted; one major UK study found the costs of food wastage in hospitals across the country to be up to £26 million per year (Ssentif, 2011).

A number of studies have noted significant food wastage from patient plates, kitchen overproduction and unsold food in canteens (Pocock et al., 2009; Laurent, 2011), and a few studies have attempted to quantify food wastage for diverse purposes including patient nutritional intake (Barton et al., 2000) or determination of suitability for incineration (Li and Jenq, 1993). A survey of 32 hospital plate waste studies found a median plate waste (food that is served but not eaten) rate of 30%, with a range between 6-65% (Williams and Walton, 2011) while a Welsh study found rates of post-production food wastage from 6% up to 60% within a group of three hospitals (Sonnino and McWilliam, 2011). They calculated potential savings of up to £758,000 across the three hospitals if waste were reduced to the level of the best-performing quartile of their sample.

The factors contributing to food wastage in hospitals are many and varied; a few of these are summarised below (NHS Estates, 2005):

- Organisational factors
  - Bulk food supply in which bulk trays have a set number of meals, which may exceed number of patients
  - Inappropriate length and timing of meals
  - Disturbances during mealtimes
- Patient health-related factors
  - Prescribed drugs or treatments resulting in poor appetite
  - Stress, pain and discomfort from medical treatment
  - Poor motivation to eat
  - Bereavement, loneliness and depression
  - Inability to swallow or consume food with dignity
- Assistance-related factors
  - Insufficient assistance to patients in eating
  - Food placed out of patients’ reach
  - Insufficient assistance in opening packets or removing lids
- Environmental factors
  - Uncomfortable eating position, cramped or cluttered conditions
  - Cutlery, crockery or environment is not suitable to meeting needs
  - Lack of privacy or lack of social interaction
- Meal service-related factors
  - Lack of patient choice

  - Inability to select food as close as possible to mealtimes
  - Unfamiliar and unclear routines and systems
  - Menu fatigue
- Food-related factors
  - Absence or presence of condiments or seasonings
  - Unfamiliar dishes or cooking methods
  - Unappetising appearance, smell or texture
  - Food not prepared in accordance with religious beliefs or dietary requirements

The delivery of food to patients in hospitals involves a complex chain of steps and staff, and inadequate delivery of any of the steps may lead to wastage. Figure 4.1 summarises the steps involved in food delivery in hospitals.

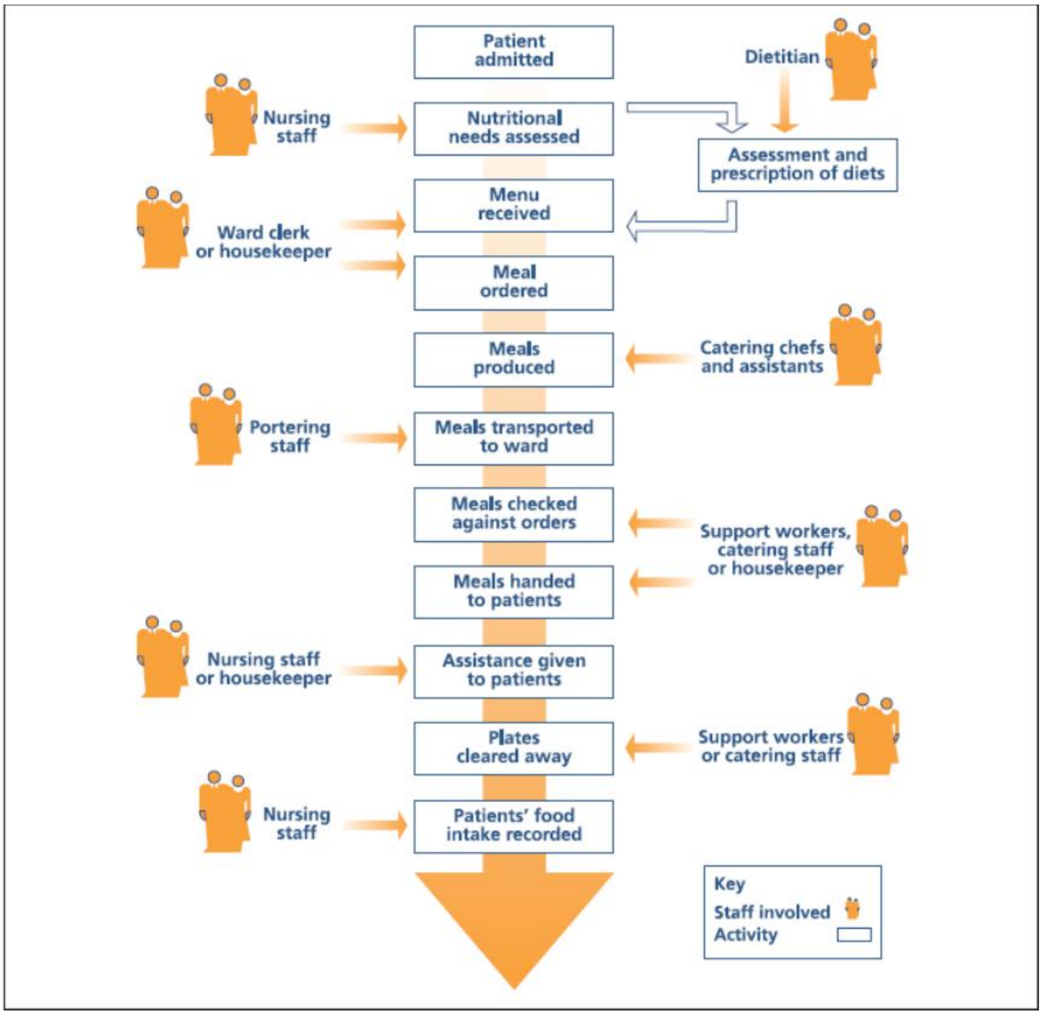


Figure 4.1 Steps involved in hospital food service delivery (NHS Estates, 2005)

Hospitals also have significant requirements for both electrical power and heating due to the activities occurring within them and the need to provide sufficient heat for patients who are spending the majority of time confined to a bed with little movement. These factors make hospitals potential candidates for onsite anaerobic digestion (AD), using food and other organic wastes generated onsite to produce electricity and heat that can be used to meet some of the hospital's own energy requirements.

The need for onsite heat and hot water is also substantial in hospitals; the high turnover and continual need for changing and cleaning of linens leads to high hot water usage for laundry and heat for drying. Autoclaving of equipment and other sterilisation requirements unique to hospitals also result in a high heat and hot water demand. These factors make hospitals good potential candidates for AD with biogas utilisation in a boiler, which is cheaper to install and operate than electrical generation equipment.

Harrogate District Hospital was chosen for this study as an example of a typical UK hospital that currently disposes of its food waste by maceration and discharge to sewer. Food waste quantities and management methods at HDH are examined with a view to its potential suitability for onsite AD, including a consideration of opportunities to supplement its energy requirements.

4.1 Harrogate District Hospital

4.1.1 Area and Population Served

Harrogate District Hospital (HDH) is located in Harrogate, North Yorkshire and serves a population of approximately 200,000 in Harrogate and the rural districts of North Yorkshire and North East Leeds (Harrogate and District NHS Foundation Trust, 2012). The HDH NHS Foundation Trust employs 2,500 staff based at the hospital and other locations.

Figure 4.2 Harrogate District Hospital (courtesy Harrogate and District NHS Foundation Trust)

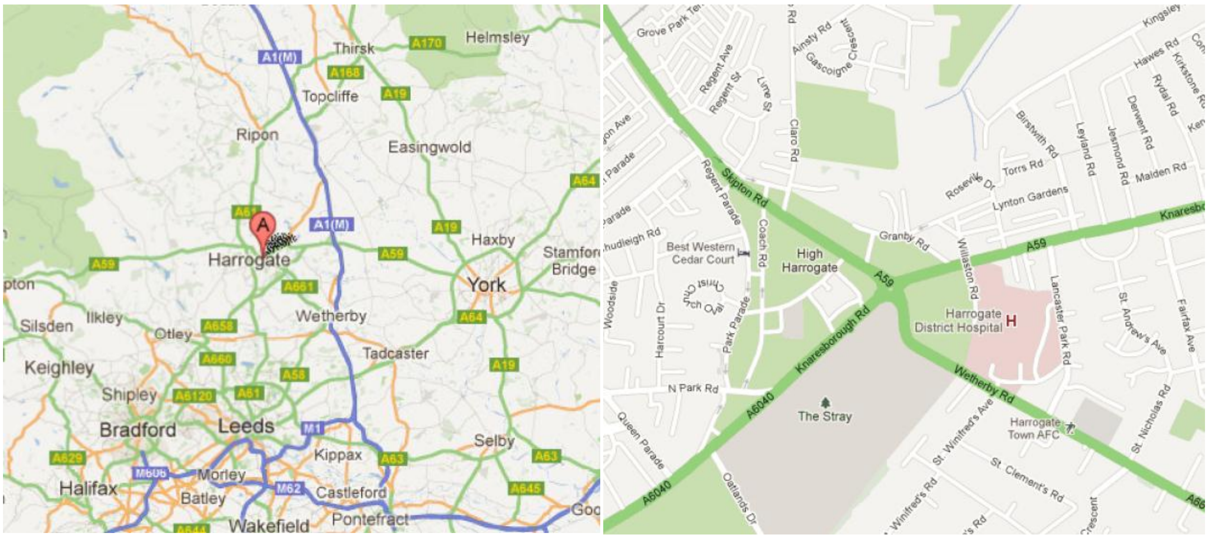


Figure 4.3 Location of the hospital (Google maps © 2012)

4.1.2 Site Characteristics and Waste Quantity Estimates

HDH has 533 patient beds, with an average occupancy of 84% (Department of Health, 2002). The hospital serves three meals a day to the majority of these patients, although not all are present for a full three meals (e.g. maternity, neonatal and short stay patients).

There are also some rooms onsite for doctors in training and other staff requiring overnight accommodation. The onsite canteen serves an average of 412 meals per day for staff and visitors. There are landscaped grounds set among the hospital buildings.

Food Waste

There has been no on-site measurement of food waste quantities at the hospital. A number of methods were used to estimate the quantities of waste that could be expected based on the number of beds, meals served and estimated wastage rates, coupled with data collected at other sites.

For clarity on terminology used in the report, the following definitions are provided:

Plate waste: refers to any food which was plated and then not eaten, either as a full meal or leftovers.
Production waste: is any food which is never served, this comes from peelings and preparation and also any over-production.
Total waste: is the sum of plate waste and production waste.

a) Data provided by the hospital

On average 1,058 patient meals are served at HDH per day. The meal consists of 113g protein, 57g potato and 57g vegetable, giving a total meal mass of 227g. This is somewhat low in comparison to meals served in Welsh hospitals ranging from 241-318 g (meals at the lowest end were in the medial rehabilitation ward, which is mostly elderly patients, while the high end was the spinal rehabilitation ward, with mostly young patients) (Sonnino and McWilliam, 2011). The average total amount of food served to patients daily is 1058 x 0.227 = 240.17 kg. The average plate wastage recorded is 3.7%; this is within the NHS's recommended maximum benchmark of 10% (NHS Estates, 2005), but it is an order of magnitude lower than the plate waste actually observed by Sonnino and McWilliam (2011) of 24-39%, leading to the question of whether 3.7% may be an overly low estimation of the actual wastage. Precey (2008), however, did find a range varying from 3.5-14.7% plate wastage in a survey of NHS hospitals.

Using the hospital's estimates, the average weekly waste is:
240.17 kg x 7 days x 0.037 wastage = 62.2 kg plate waste from patient meals

This does not include wastage from other areas. These are estimated as below.
The canteen serves 412 meals daily; a larger meal size in the canteen of 300 g rather than 227 g is assumed (this is based on healthier paying patrons receiving larger meals, and higher up in the range from Sonnino and McWilliam (2011)). Assuming a slightly lower wastage rate of 3.5% gives:

412 meals/d x 0.300 kg/meal x 7 days x 0.035 wastage = 30.3 kg plate waste from the canteen

This gives a total of 62.2 + 30.3 = 92.5 kg/week average plate waste.

This does not include production waste; as no estimates were provided for this, an estimate for production waste was developed using a care institution for which data could be obtained, and added to the plate waste.

b) UK Residential home study

A study carried out at a UK residential home looked at production waste from the kitchen only. The residential home serves an average of 36 meals/day and measurement of their kitchen production waste gave a result of 8.9 kg. This is an average of 0.25 kg per meal total food waste (Jemison, 2012).

Estimated HDH Food Waste Quantities
0.25 kg/meal x (412 + 1058) meals/day x 7 days/week = 367.5 kg/week production waste
367.5 kg/week production waste + 92.5 kg/week plate waste = 2,572 kg/week total waste
2,572 kg/week x 52 weeks/yr = 134 tonnes per annum

c) Values from a similar hospital

A food waste audit was previously carried out for Stockport NHS Trust (SNT), a hospital in Stockport, near Manchester UK (Moss, 2011). It has a similar management system to that at HDH and also provides three meals per day to patients and has an onsite canteen. It is larger in size, with 800 beds as compared to HDH’s 533. The figures from SNT were therefore scaled down by a factor of (800/533) = 0.67 to estimate food waste quantities at HDH.

Data were collected at SNT over the course of a week by physical collection of food waste in buckets in the main areas of catering including the production service and return from the wards. A bucket weight of 7 kg was used as an average by which the number of buckets collected was multiplied, at an average of 53 buckets per day from the canteen and all bedside meal services. Multiplication by this factor gives:

SNT Food Waste Quantities
53 buckets x 7 kg/bucket x 7 days/week = 2,597 kg food waste/week
2,597 kg/week x 52 weeks/yr = 135 tonnes per annum

Extrapolated HDH Food Waste Quantities
2,597 kg/week x 0.67 = 1,730 kg per week
1,730 kg/week x 52 weeks/yr = 90 tonnes per annum

d) Literature search

A number of studies have been performed to quantify food wastage in hospitals; however, most of these consider plate and serving waste only and not production waste, as their primary concern is the impacts on patient health resulting from the difference between recommended nutritional intake amounts and actual food intake. Also, these papers were concerned with wastage rates as a percentage of food served, but may not quantify the actual amount of waste.

Williams et al. (2003) found average plate waste rates of 30-40% in Australian hospitals, and a later, more extensive study by the same authors (Williams and Walton 2011) gave a range of 6-65% plate waste, still with a median of 30%. Barton et al. (2000) found plate wastage from 32-42% with tray waste (meals prepared but not served) at 11%, and estimated that this was costing a total of £139,655 per year for the hospital studied. Since these studies, however, did not give quantities for the amount of food produced and served, no conclusions can be drawn on the actual waste quantities.

Edwards and Nash (1999) found plate wastage of 40% from meals of an average weight of 138 g – this equates to approximately 55 g/meal. These meals were generally lunch and dinner services; while the investigators quantified breakfast wastage at 23%, they did not measure the size of the breakfast meal. Sonnino and McWilliam (2011) found plate wastage of 24-31% on meal sizes of 241-318 g, equating to 58-99 g/meal waste. These were again based on lunch and dinner; they did not quantify the breakfast meal service or its wastage rate. In the absence of information on food waste from breakfast services, it could be assumed that the breakfast meal might yield about half of the amount of waste from the two other services, based on the fact that it is a smaller meal and had a lower wastage rate in one study. Therefore, multiplying the amount of per-meal food waste by 2.5 per day gives food waste arisings of 138, 145 and 246 g/patient/day, respectively.

WSP (2010) put together an estimate for food waste from hospitals based on combining data from two studies, firstly Tudor et al. (2008) who determined a total waste production of 5.5 kg per patient per day, but without determining composition of the waste and therefore proportion of food waste. A compositional fraction of 17% food waste was then taken from Altin et al. (2002) from their study of hospital waste composition, to give an overall food waste arising of 0.95 kg/patient/day; this is substantially higher than the estimates above and differs by an order of magnitude from the 0.095 kg/patient/day of Pocock et al. (2009).

An estimate of 0.1-0.2 kg/patient/day multiplied by the 533 beds at HDH equates to 53-106 kg/day or 373-746 kg/week; however this is just plate and serving waste, and does not include production waste. Using a factor of 0.95 kg/patient/day gives 3.5 tonnes/week.

Shiv (2009) measured food wastage from kitchens serving 278 beds at Norfolk Norwich University Hospital (NNUH) over a two-week period and found an average total wastage rate of 0.31 kg/patient/day with a standard deviation of 0.06 kg/patient/day. For 533 beds at HDH, this equates to 1.2 tonnes/week or 60 tonnes/year.

A regression was done using results from four studies from which actual waste quantities and number of beds were available. The first study was of a small care home, where the 36-bed facility was found to produce 76.18 kg/week waste (Jemison, 2012); because the home served only one meal per day, the number of beds was divided by three to give a point on the graph comparative to the hospitals which provide three meals per day. The second study surveyed four hospitals in Turkey (Altin et al., 2002); the other two were described above for SNT and NNUH (Moss, 2011; Shiv, 2009).

While it is methodologically poor practice to compare estimates obtained for such varying conditions and by different methodologies, it can be seen from Figure 4.4 that a reasonable relationship appears to exist between number of beds and waste quantities for those studies.

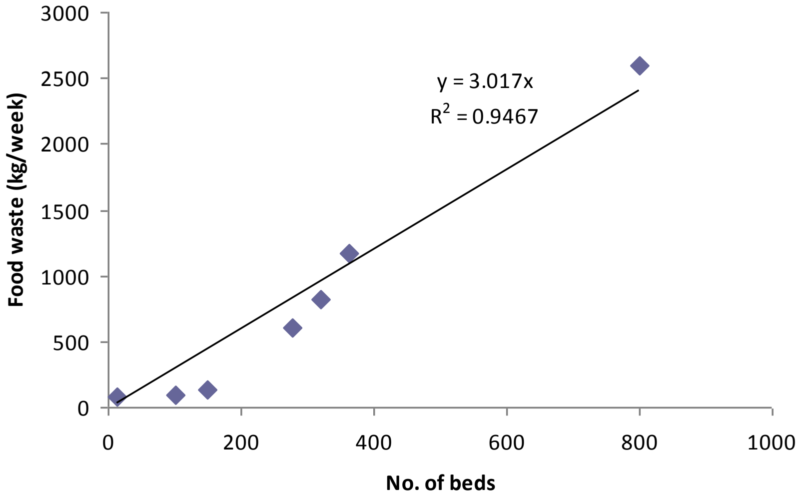


Figure 4.4 Linear regression of weekly waste vs. number of beds (Jemison, 2012).

The regression indicates a weekly waste quantity, in kg, of approximately 3 times the number of beds; in the case of HDH this equates to (3 x 533) = 1599 tonnes per week.

After consideration of the range of values arrived at by the methods above, a low, medium and high estimate for food waste production at HDH was settled on:
Low estimate: 1.3 tonnes per week (68 tonnes $year^{-1}$)
Mid estimate: 1.6 tonnes per week (83 tonnes $year^{-1}$)
High estimate: 2.2 tonnes per week (114 tonnes $year^{-1}$)

Green Waste
The hospital's landscaped grounds were measured using Google Earth aerial photos and found to cover approximately 749 m^2.

Figure 4.5 Aerial View of HDH with Grass Areas Highlighted (Google maps © 2012)

Based on Defra's (2009) grass yield figure of 8 tonnes dry matter per hectare for under non-optimal conditions, with a dry matter (DM) content estimated at 20%, this was calculated to yield approximately 3 tonnes per year of grass cuttings. These could theoretically be processed in an onsite anaerobic digester; however, since grass cuttings can be recycled by leaving where they are cut at no cost, there is no economic advantage to collecting and diverting grass to anaerobic digestion

4.1.3 Current Waste Processing Infrastructure

The main method of disposal for food waste at HDH, rather than collection and transport to offsite processing or disposal facilities, is onsite disposal via the wastewater system. HDH, like many other hospitals in the UK, has a macerator – a unit that mechanically grinds up food waste with water, allowing the effluent to pass into the wastewater system. The advantages of a macerator include the reduction in waste for collection and disposal to landfill, and in attraction of vermin to refuse areas. The disadvantages include the high water demand and the impact on the sewer network of high-strength wastewater resulting from the addition of food waste. This can lead to blockages, and in certain conditions to pipe corrosion due to sulphides produced by microbial breakdown of organics under anaerobic conditions. The following is a quote from the Water UK:

"Sewerage Undertakers have experienced increasing numbers of sewer blockages and pollution incidents relating to fat, oil, grease and general food debris. There are approximately 200,000 blockages throughout the UK every year of which 75% are caused by fat, oil and grease. Clearing these blockages costs millions of pounds a year."
Water UK *'National Guidance for Healthcare Waste Water Discharges'* (2011)

Water UK opposes the use of macerators and has asked that the government "consider imposing a ban on installations where discharges arrive in public sewers". They point to research carried out for the Department for Environment, Food and Rural Affairs (Defra) which found that the kerbside collection of food waste produced lower greenhouse gas emissions and lower overall financial costs when compared with the use of macerators (Water UK, 2009).

At the level of the individual site, however, the use of a macerator at HDH is cheaper than paying a waste collection contractor to collect food wastes. If the government were to proceed with a ban on macerators, this would require that the hospital find another disposal outlet for its food waste.

A macerator requires power to operate: the macerator in use at HDH (Dawson MMP Model DR300) has a 0.4 kW motor which is operated for 15 minutes per hour between the hours of 8 am and 4 pm, with additional units running for 45 minutes after each meal service – a total of 4.25 hours per day of operation. This is a power draw of 1.4 kWh per day, or 511 kWh per year. The power cost of running the macerator, at an estimated cost of electricity of 4.3 p kWh^{-1} (HDH, 2012), would therefore be about £22 per year. The hospital could also be subject to a surcharge for the discharge of wastewater with a higher biochemical oxygen demand (BOD) as a result of the addition food waste, as is the case for some facilities. The hospital has confirmed, however, that it is not currently subject to a surcharge (HDH, 2012).

4.2 AD Modelling

An anaerobic digestion model developed at the University of Southampton (Salter, 2010) was used to calculate outputs for digestion scenarios using the different estimates of waste quantities available from the hospital.

4.2.1 Modelling Runs

The model was run three times, using the different estimates of food waste available:
Run 1: Low Estimate: 68 tonnes $year^{-1}$ food waste
Run 2: Mid Estimate: 83 tonnes $year^{-1}$ food waste
Run 3: High Estimate: 114 tonnes $year^{-1}$ food waste
HDH is approximately 30 km from York, so average air and ground temperatures for York were used in heat loss calculations.

Savings and Offsets in Energy, Waste Disposal and Greenhouse Gas Emissions
After calculating the outputs of the digester, a second set of calculations were carried out to quantify potential savings in energy, waste disposal and greenhouse gas emissions. These are described below.

Energy
Figure 4.5 shows the energy consumed during fiscal year 2010-2011 at HDH.

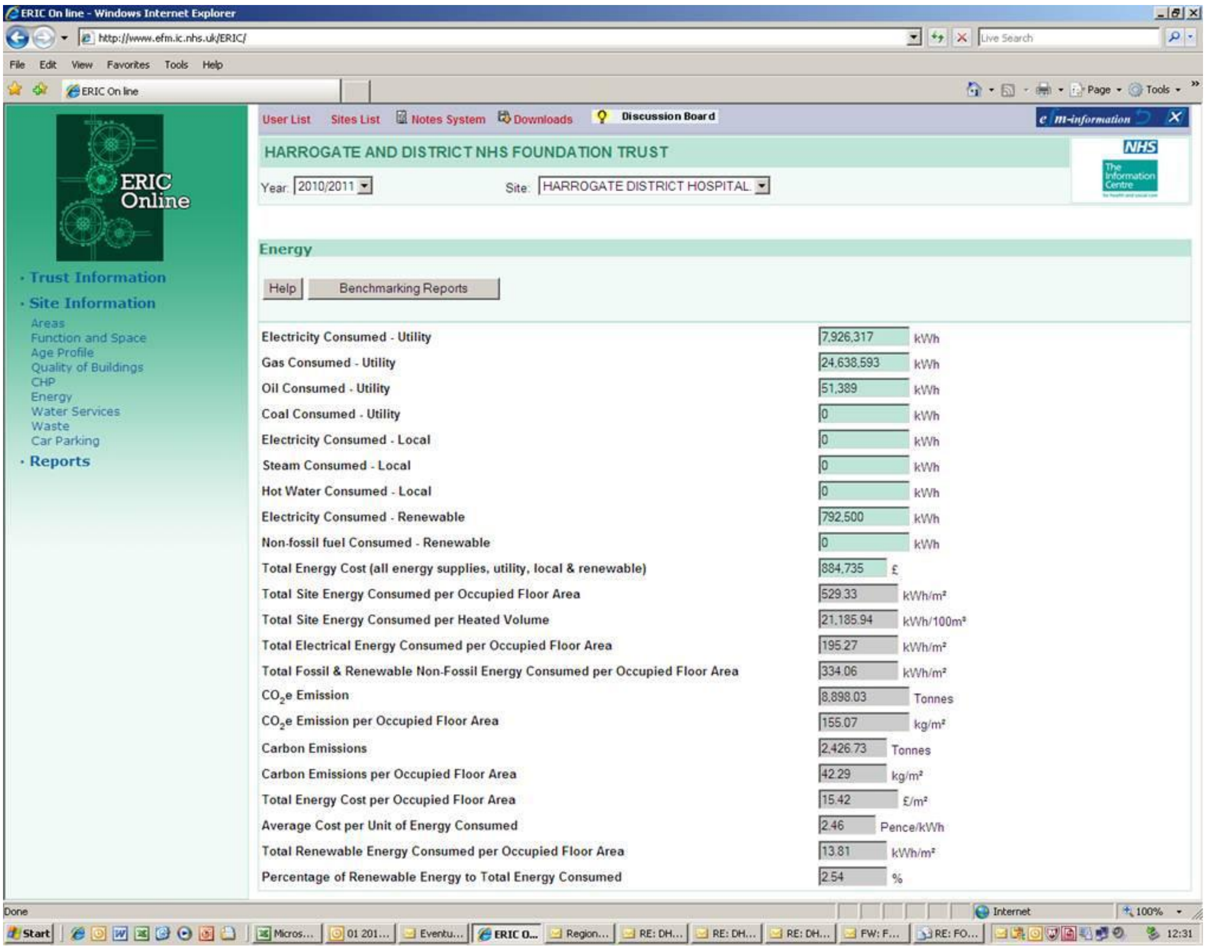


Figure 4.5 Screenshot of energy usage at HDH, 2010-2011(ERIC online, 2012)

The total utility electricity consumed was 7.9 MWh, while gas and oil for heating totalled 24.7 MWh. The average cost of energy was 4.3 p/kWh for electricity (HDH, 2012) and 2.2 p/kWh for heat. Total CO_2e emissions for the year were 8,898 tonnes.

Waste

Figure 4.6 shows the waste disposal amounts for high temperature and landfill disposal of clinical and general waste from the hospital.

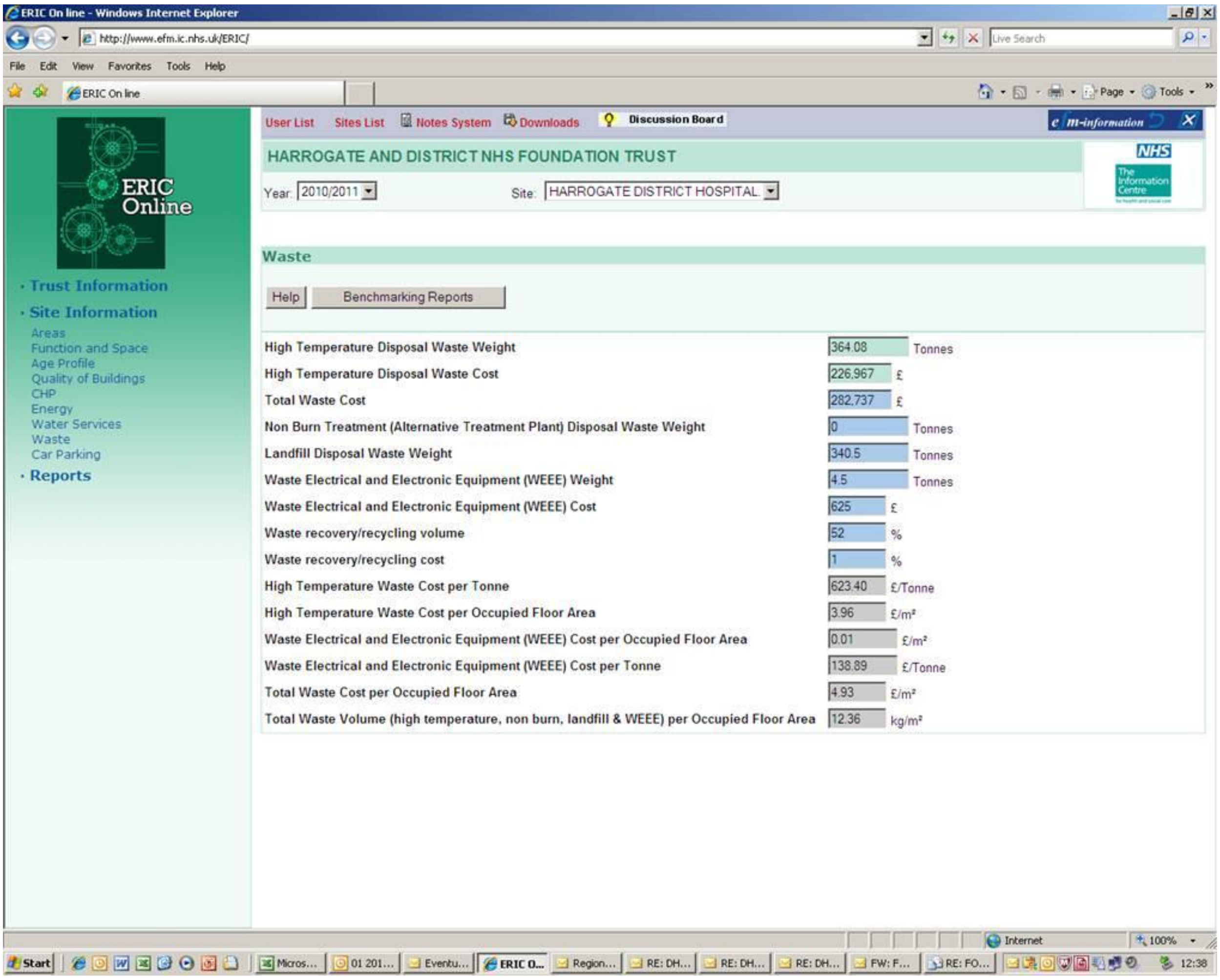


Figure 4.6 Screenshot of waste statistics at HDH, 2010-2011(ERIC online, 2012)

The total waste cost was £282,737 for the year, which after subtraction of the costs for high-temperature disposal (£226,967) and WEEE recycling (£625) equates to £55,145 for the landfill disposal of 340 tonnes of waste, indicating a disposal cost of £162 per tonne for general waste.

As stated previously, the primary method of food waste disposal at HDH is disposal to the sewer system via a macerator.

If a ban on macerators were to be implemented, requiring the hospital to send all of its food waste for landfilling, the hospital would need to pay to dispose of additional tonnes of food waste at its current disposal cost of £162/tonne.

4.3 Results and Discussion

Tables 4.1 and 4.2 below show the parameters and outputs that could potentially be associated with an onsite AD plant, for the estimated waste quantities. Table 4.1 shows the outputs for a CHP, while Table 4.2 shows the outputs for a boiler.

Table 4.1 AD Modelling Outputs for Harrogate District Hospital – CHP

Energy and material outputs (/year)	Run 1 - Low Estimate	Run 2- Mid Estimate	Run 3 - High Estimate	
Digester input	68	83	114	tonnes
Digester capacity required	15	18	25	m^3
Digester retention time	74	74	74	days
Methane produced	6306	7697	10572	m^3
Methane available	6243	7620	10466	m^3
Biogas (volume)	10872	13271	18227	m^3
Biogas (mass)	13	16	23	tonnes
Digestate	55	67	91	tonnes
Electricity produced	78	96	131	GJ
	21743	26539	36451	kWh
	3	3	4	kW generator
Heat produced	112	136	187	GJ
Upgraded biogas	0	0	0	m^3
Waste transport diesel	0	0	0	litres
Total energy output	190	232	319	GJ
Energy inputs required (/year)				
Waste transport	0	0	0	GJ
Digestate transport	6	8	10	GJ
CHP supplied electricity	10	12	16	GJ
Imported electricity	0	0	0	GJ
Boiler/CHP supplied heat	43	51	65	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	18	22	30	GJ
Total energy input	62	73	96	GJ
Energy exports				
Energy in methane produced	226	276	379	GJ
Exported electricity	68	84	115	GJ
	19	23	32	MWh
Exported heat	69	86	122	GJ
	19	24	34	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	137	170	237	GJ
Energy Balance	128	159	223	GJ
	1.9	1.9	2.0	GJ/tonne

Table 4.2 AD Modelling Outputs for Harrogate District Hospital – Boiler

Energy and material outputs (/year)	Run 1 - Low Estimate	Run 2- Mid Estimate	Run 3 - High Estimate	
Digester input	68	83	114	tonnes
Digester capacity required	15	18	25	m^3
Digester retention time	74	74	74	days
Methane produced	6306	7697	10572	m^3
Methane available	6243	7620	10466	m^3
Biogas (volume)	10872	13271	18227	m^3
Biogas (mass)	13	16	23	tonnes
Digestate	55	67	91	tonnes
Electricity produced	0	0	0	GJ
	0	0	0	kWh
	0	0	0	kW generator
Heat produced	190	232	319	GJ
Upgraded biogas	0	0	0	m^3
Waste transport diesel	0	0	0	litres
Total energy output	190	232	319	GJ
Energy inputs required (/year)				
Waste transport	0	0	0	GJ
Digestate transport	6	8	10	GJ
CHP supplied electricity	0	0	0	GJ
Imported electricity	10	12	16	GJ
Boiler/CHP supplied heat	43	51	65	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	18	22	30	GJ
Total energy input	62	73	96	GJ
Energy exports				
Energy in methane produced	226	276	379	GJ
Exported electricity	0	0	0	GJ
	0	0	0	MWh
Exported heat	147	181	253	GJ
	41	50	70	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	147	181	253	GJ
Energy Balance	128	159	223	GJ
	1.9	1.9	2.0	GJ/tonne

The amount of energy supplied by a digester could be 19-32 MWh of electricity and 19-34 MWh of heat with a CHP, or 41-70 MWh of heat alone with a boiler; this is less than 1% of the hospital's current utility-supplied electrical or heating demand. Annual cost savings for reduced electricity and heat at the hospital's current cost would be between £1,000-£2,000 (€1,250-€2,500). There would be no benefit in avoided waste disposal cost, as currently food wastes are disposed of, without charge, to the sewer system via a macerator. If macerators were to be banned or phased out in the future, however, there could be a case for considering onsite AD at HDH.

As noted previously, some grass IS produced onsite that could potentially be included in the digester feedstock. The quantity of 3 tonnes per year, however, is small relative to the 68-114 tonnes per year of food waste (4% or less of the total) so as to have little impact on digestion. Also, as grass has a lower biochemical methane potential than food waste (Salter, 2010) sizing a digester for only the food waste would be more economical. In addition, the inclusion of grass would generate more digestate, the land application of which could be an issue on the hospital's limited grounds.

A boiler for biogas utilisation would have lower capital and operating costs than a CHP, and the availability of onsite heat may be useful for laundry facilities. The hospital currently sends its laundry out for cleaning by an offsite contractor; a case could perhaps be made for cleaning of sheets onsite using the hot water resulting from the AD system, which could also have local employment benefits and save on transport cost.

There is currently no kerbside food waste collection from households in the Harrogate area. The introduction of a food waste collection scheme in the future, however, would open up the possibility of food waste from HDH being included in the household food waste collection scheme. This would provide an alternative outlet for HDH's food waste and allow digestion of the food waste without the complexities of building an AD plant onsite at the hospital.

4.4 Conclusions

The construction of an anaerobic digester onsite at HDH could enable the generation of approximately 19-32 MWh per year of renewable electricity and 19-34 MWh per year of heat using a CHP, or 41-70 MWh of heat with a boiler, for use onsite. This is not likely to be sufficient to justify the building of a digester when the hospital has the macerator and sewer disposal option available to it. If this condition were to change or energy costs to rise, onsite AD may become a more viable option. Based on its location in a residential community that is well-serviced by waste collection infrastructure, however, the best option would be to have food waste from the hospital collected along with food and organic wastes from the surrounding area for processing in a larger, centralised AD plant.

4.5 Acknowledgements

Thanks are due to: Pamela Coatham and David Moss at Stockport NHS Trust, and also the staff at the offices handling Freedom of Information requests particularly at Harrogate District Hospital, but also at Stockport and Southampton NHS Trusts.

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5 Case Study of HMP Hewell: Investigating the potential for small-scale onsite anaerobic digestion

5.1 Introduction

A recent study suggested that the UK prison sector is unlikely to be a major contributor of food waste (Pocock et al., 2009). The case of prisons is nevertheless interesting due to their highly specific circumstances: a prison is a closed environment, with tightly controlled access and limitations on movements of personnel and vehicles into and out of the site. An anaerobic digester providing the means to process waste onsite allows a corresponding reduction of waste vehicle movements on and off the site, and a greater degree of self-sufficiency in energy and waste disposal for the institution. Additionally, the implementation of an anaerobic digester within the prison environment could potentially be beneficial for the inmates and for society. Firstly, through source segregating waste inmates develop better recycling practices which may continue after their release. Additionally there may be scope for inmates to benefit from involvement with an onsite AD plant. It could provide an opportunity for training and employment in operation of the plant and food waste collection system, and related areas such as sustainable waste management, energy generation and digestate utilisation.

Prisons provide job training and life skills courses for inmates with the goal of better preparing them for integration into society after release (PET, 2007; Cheshire Life, 2011). Behaviour within prisons and reoffending rates have both been shown to be improved by work, which also teaches valuable transferable skills (Scott and Derrick, 2006). At HMP Hewell, the subject for this case study, workshops are available to inmates in areas including Construction Industry Training, double glazing manufacture, industrial cleaning, waste management, laundry and contract services. The open section of the prison additionally offers external college courses, Open University distant learning and a range of ICT, Literacy and Numeracy courses. The prison also offers employment throughout the estate in Farms and Gardens, Kitchen and full time employment via its Resettlement to Work Scheme (Ministry of Justice, 2012).

Prisons in the UK are high recyclers; over 90 of the 134 prisons in England and Wales have waste management units, in which offenders sort materials for recycling, including plastics, paper, card, metals and textiles. In the financial year 2007-08 the average diversion rate for prisons with waste management units was 41.4%, as compared to 34% achieved by local authorities in England and Wales (Edwards, 2009). Some prisons are achieving rates beyond 60% (Custodial Review, 2011; Edwards, 2009), by including food waste recycling.

A number of UK prisons have dewatering and/or composting systems for their food waste.
HMP Prescoed, Wales achieves a 70% diversion rate (Edwards, 2009) with a waste management system that includes an IMC dewaterer and Big Hanna composter processing 60 kg of food waste per day, produced by 180 prisoners being served meals twice a day. HMP Styal women's prison also has an IMC/Big Hanna system, which produces 9 tonnes per year of compost for the ornamental gardens on the prison grounds. The large vegetable garden provides employment for prisoners and supplies vegetables that are used by prisoners in self-catering units to prepare their own meals. The garden has lifted the morale throughout the prison (Cheshire Life, 2011) and has allowed prisoners to train for National Open College Network (NOCN) qualifications in horticulture, to be succeeded by National Proficiency Tests Council (NPTC) /City & Guilds qualifications in the future (Custodial Review, 2011).

HMP Kirkham, HMP Lewes and HMYOI (young offenders' institution) Swinfen Hall all adopted in-vessel composting technology in 2005/06 (NOMS, 2006), followed by HMP Morton Hall, Lincolnshire (Green Today, 2009). HMP Channing Wood has a Ridan composting system that was installed in 2011 (Ridan, 2011) processing 2 tonnes of food waste per month.

At least two institutions have introduced vermicomposting as a beneficial way to manage food waste. HMP Leyhill started with a wormery and expanded this to a social enterprise encompassing a farm producing organic apples, soft fruits, potatotes and salad vegetables, for sale to prison staff, along with rearing pigs and chickens. The development of the project facilitated inmates' gaining 42 City and Guilds qualifications in tractor and forklift driving and plant machinery between them as they worked to level the land and build the farm (A4E, 2012).

Similarly, the Erlestoke Entreprise project at HMP Erlestoke has developed the first Community Interest Company (CIC) within a prison, which includes vermicomposting among activities including recycling of metals, plastics and wood; building garden furniture; creating hanging baskets and vegetable baskets; and polytunnel horticulture growing vegetables, herbs and flowers. The project is an enterprise employing 100 inmates, getting training in horticulture, waste recycling and management, woodcraft, beekeeping, business studies, shopkeeping, conservation, bookkeeping and accounting, sales and purchasing, customer care, management, manufacturing and life-skills (Prisoners' Education Trust, 2007).

A number of prisons in the US also separate food waste for composting offsite or onsite. Avenal State Prison, California has been separating food waste and grass clippings for composting offsite at San Joaquin Composting since 2001, diverting 5 tonnes per month of food waste (CalRecycle, 2002a). Brown Creek Correctional Institute, North Carolina installed a 'Greendrum' in-vessel composting system in 1999, processing an average of 733 kg/day food waste with 6 kg/day paper towels (RKB, 1999). Folsom State Prison, California diverted organic materials to a composting facility owned and operated by the Prison Industry Authority (PIA) which operated from 1994 to 2001 (CalRecycle, 2002b).

To date, however, only one prison is known to use anaerobic digestion for processing its food waste. HMP Guys Marsh near Shaftesbury in Dorset, UK has adopted a Bioplex digester to process 10 tonnes of food waste per month resulting from its 1,700 meals per day served to 570 prisoners, saving £18,000 per year on landfill fees (PCS, 2010). Heat and electricity from the biogas will be used for onsite energy demand, including heat for a new greenhouse that has been installed in the garden associated with the digester. The garden will allow inmates to develop skills in the horticultural and environmental fields through a variety of allotments and a small tools maintenance workshop (FOGM, 2011). There are 8 prisoners employed in the waste collection system and plant operation, with a planned increase to 12 in the near future (Trades Union Congress, 2011).

The only other known example of an AD plant located on prison premises is for treatment of sewage rather than food waste. The Cyangugu prison in Rwanda has an onsite AD system in place to produce biogas from the connected latrine system. The gas is piped directly to the onsite kitchens and the digestate is used as a fertiliser in the prison grounds. This system produces 78000 litres of biogas per day which offsets the kitchen energy use by 80% (Kigali Institute of Science, Technology and Management, 2002).

The aim of this study is to consider the feasibility of source separation and AD of food waste in the prison environment, based on a case study of HMP Hewell.

5.2 HMP Hewell

Her Majesty's Prison (HMP) Hewell is a correctional facility located in Redditch, Worcestershire. It was created by an amalgamation of three former prisons on the site in 2008 - HMP Hewell Grange, HMP Blakenhurst and HMP Brockhill. These units house three different categories of prisoner. Blakenhurst is Category B (Closed prison – adult male prisoners who are a risk to the public but do not need the highest level of security and the aim is to make escape very difficult); Brockhill is Category C (Closed prison - Adult male prisoners who cannot be trusted in an open prison but are unlikely to try to escape) and Hewell is Category D (Open prison - Adult male prisoners who are a low risk and are unlikely to escape) (DirectGov, 2012; BBC, 2008).

The Category D unit, Hewell Grange, is an old country estate previously owned by the Earl of Plymouth, and sold to the government in the early 20th Century. It is a Grade II listed building (English Heritage, 1986a) and its parkland is on the National Register of Historic Parks and Gardens (English Heritage, 1986b). The site encompasses a significant parcel of land in addition to the prison buildings, including ornamental gardens, a dairy farm and farm shop.

Figure 5.1 Hewell Grange unit of HMP Hewell. Source: **http://en.wikipedia.org/wiki/File:Hewell.jpg**

5.2.1 Population and area served

HMP Hewell has an operational capacity of 1263 prisoners. This population is split between open and closed communities, with 187 prisoners in the open community and the remainder in the closed community. Prisoners are housed in single- or double-occupancy cells in most of the site (Blocks 1 through 6), except for one dormitory-style accommodation in Block 8, the former Hewell Grange (Ministry of Justice, 2012).

There are different procedures for eating meals and therefore food waste collection methods for the two types of prison groups. The 187 inmates in the open community eat meals in a central dining room. The remainder of the inmates eat meals within the confines of their cells. (Personal communication, Meeting with HMP Hewell staff 6/01/12).

Figure 5.2 English Heritage map for HMP Hewell showing Listed areas in green. Farm is non-protected area northwest of the listed area. (English Heritage, 1986)


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Figure 5.3 Aerial view of HMP Hewell; Hewell Grange at bottom left. (Bing maps © 2012)

There are two other prisons within a 30 km radius of HMP Hewell. These are HMP Birmingham, with an operational capacity of 1450 prisoners, and HMP Long Lartin, with an operational capacity of 622 prisoners. The locations of the prisons are shown in Figure 5.4.

Figure 5.4. Locations of HMP Hewell and neighbouring prisons

5.2.2 Food Waste Quantity Estimates

HMP Hewell currently has no system in place for source segregation of food waste, and therefore no measured values are available for the quantities produced. A literature search on food waste arisings in prisons produced some data for estimation of quantities.

There are 134 prisons in England and Wales (Ministry of Justice, 2011) but relatively little data is currently available on the amounts of biodegradable waste that they produce (Pocock et al., 2009; O'Brien, 2012). Two surveys were carried out by HM Prison Service (Hansard, 2008), between May 2006 - February 2007 and December 2007 - January 2008 respectively. The results indicated an average value of around 1.40 kg/person-week, and are summarised in Table 1. The report noted however that there were data collection problems in the first survey; while the second survey was apparently carried out during the Christmas-New Year period and while waste generation rates may vary less in prisons than in the outside world this is not necessarily the most representative period. A value of 1.42 kg/inmate-week is quoted in a report by WSP (2010), but this appears to refer to the same survey.

Table 5.1. Summary of HM Prison Service food waste survey (based on Hansard, 2008)

	May 2006 - Feb 2007	Dec 2007 - Jan 2008
No. of prisons responding	32	51
Operation capacity (prisoners)	17416	30121
Average food waste (kg/person-week)	1.45	1.34
Average prison population for the year	79000	80000
Food waste across prison service (extrapolated) kg/week	115	107
Food waste across prison service (extrapolated) tonne/year	5957	5574

HMP Channing Wood, Newton Abbot has implemented a Ridan composting system to process the food waste that is produced on site (Ridan, 2011). All of the waste that arises from food preparation is composted, in addition to plate scrapings. The total comprises approximately 2 tonnes of food waste per month produced by 1100 individuals present for three meals every day (Pocock et al., 2009). This equates to 0.42 kg/person-week, which is considerably lower than the average quoted in the HM Prison Service survey. An article on HMP Prescoed in Wales, which has adopted an IMC dewatering system followed by a Big Hanna composter, reported around 60 kg of food waste a day from 180 inmates equating to approximately 2.3 kg/person-week (Edwards, 2009); the number of individuals does not include staff, however, who may also use the site catering services.

Published records of the quantities of food waste resulting from correctional institutions in the United States were used for comparison. Broad River Correctional Institution in South Carolina began composting food waste arising from meal preparation in 1990. It houses 1000 inmates and produces 453 - 1360 kg (1000-3000 lbs) of organic waste per week (Sherman-Huntoon, 2000). This is 0.45-1.36 kg/person-week, which is consistent with the figures for HM Prison Service above. A study on food waste produced by prisons in the New York area found that approximately 0.45 kg of waste was produced daily per prisoner (or 3.15 kg/person-week). This figure was based solely on waste produced during food preparation, without plate scrapings (Marion, 2000). This is considerably higher than the quantities produced both by Broad River Correctional Institution and in HM Prison Service. The report points out, however, that food wastage rates are high across public institutions in New York. The lower cost of food in the US as compared to the UK may also contribute to the higher rate of overproduction.

Management staff at HMP Hewell have estimated that approximately 1.5 tonnes of food waste are produced on a weekly basis (personal communication). Based on an occupational capacity of 1263 people this equates to 1.2 kg/person-week. This is only slightly lower than the average value quoted from the HM Prison Service study.

On the basis of the above it was decided to adopt for calculation purposes the estimated value of 1.5 tonnes per week, equating to 78 tonnes per year of food waste for HMP Hewell.

5.2.3 Agricultural Manures

HMP Hewell has an onsite dairy farm with 120 head of Jersey cattle. These are housed for five months over the winter and are milked twice a day throughout the year (Personal communication, Meeting with HMP Hewell staff 6/01/2012). This means that slurry and milking parlour washings are produced throughout the year, with higher rates in the winter when the animals are indoors, compared to the summer when they are in barns for milking but spend the rest of the time in the fields.

Co-digestion of food waste with agricultural waste such as cattle slurry has benefits in improved process stability and better biogas production than from either substrate alone (Zhang et al., 2012). A mature dairy cow produces an estimated 19.4 tonnes of excreta per year (Burton and Turner, 2003). There are also non-milking cattle associated with dairy cows (e.g. calves) which have a lower rate of manure production. 120 head and associated other cattle can potentially produce 3,566 tonnes per year of manure; if slurry is captured during milking times for 7 months of the year, and all of the time for the other 5 months of the year, around 50% of the total annual manure production could be conservatively estimated to be collectable and available for digestion.

Table 5.2. Estimated Manure Production from HMP Hewell onsite dairy farm

Dairy Cows	Other Cattle	Dairy Cow Manure Factor	Other Cattle Manure Factor	Annual Production	Collection Factor	Annual Collectable Production
head	head	tonnes/head	tonnes/head	tonnes/year	%	tonnes/year
120	107	19.4	11.6	3,566	50%	2,140

The annual cattle manure amount of 2,140 tonnes per year could be co-digested with the 78 tonnes per year of food waste produced by the prison. This would require a larger digester than utilisation of the food waste alone, but although on a per-tonne basis cattle manure has a much lower biochemical methane potential than food waste, the high quantities of cattle manure would yield a greater biogas production overall.

5.2.4 Green Waste

Additional sources of organic waste arising at HMP Hewell are grass cuttings from the ornamental gardens and vegetable waste from the onsite farm shop.

5.2.5 Glycerol

HMP Hewell has a processing plant to produce biodiesel from used cooking oil, which is then used to fuel vehicles for use on site (Personal communication, Meeting with HMP Hewell staff 6/01/2012). This process produces glycerol as a by-product. Small quantities of glycerol can be anaerobically digested in conjunction with other materials (Fountoulakis and Manios, 2009), so this material could potentially be used as an additional co-substrate if an anaerobic digester were to be implemented. The quantity of these wastes, however, is unknown and this option was therefore not included in the modelling.

5.2.6 Current Transport and Processing Infrastructure

Food waste. Food waste is currently included with the general refuse, which is compacted and sent to landfill at a cost of £100/tonne (Personal communication, meeting with HMP Hewell staff 6/01/12). At 1.5 tonnes/week this equates to £780/year spent on food waste removal from the institution. The nearest landfill is the Veolia Environmental Services Landfill in Bromsgrove, Worcestershire, 9.6 km to the northwest of HMP Hewell.

Green Waste and Manures. Grass and garden clippings from the ornamental garden onsite are composted, while manures are land applied on the dairy's pastureland. These options do not have major costs associated with them, particularly as biodiesel is produced onsite for site vehicles, avoiding the cost of diesel to operate manure spreading vehicles.

Current energy use on site

As noted earlier, the Hewell Grange unit of HMP Hewell is an old country house and due to the age of the property the rooms are large with high ceilings. In addition to this the windows are single glazed. The energy requirement to heat such a structure is very high, and as a result of the Grade two listed conservation status of the building alterations are difficult and expensive to make. The nature of the institution itself also results in high energy demand. In the closed sector of the prison the inmates are confined in cells for much of the day. This leads to high electricity consumption for lighting and entertainment purposes. It is also necessary to heat the building to higher temperatures than a domestic home, as the inmates are largely immobile for the majority of the time.

Data were provided by HMP Hewell on fuel and energy usage in the Hewell Grange core buildings and the industry and farm areas for the period between April 2006 and December 2011. Figure 2.3 presents the available data on consumption of gas, oil and electricity for the core site, and shows a strong seasonal variation in energy demand. Energy consumption by the prison farm and other industries is only 10% of that in the core site, but also shows a fall in summer which may reflect the fact that the dairy cattle are out to pasture at this time (Figure 2.4). The total and average monthly energy consumption for the financial year 2006-7 is shown in Table 2.3.

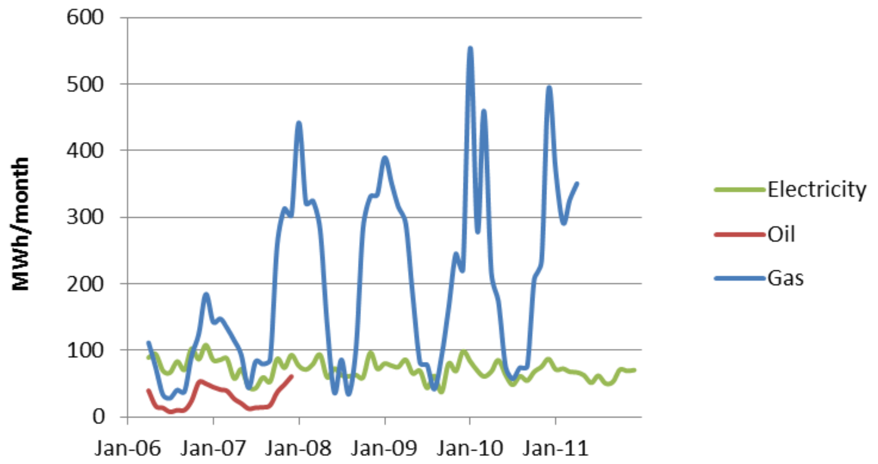

Figure 5.5 Electricity, oil and gas consumption data for Hewell Grange core, April 2006-December 2011

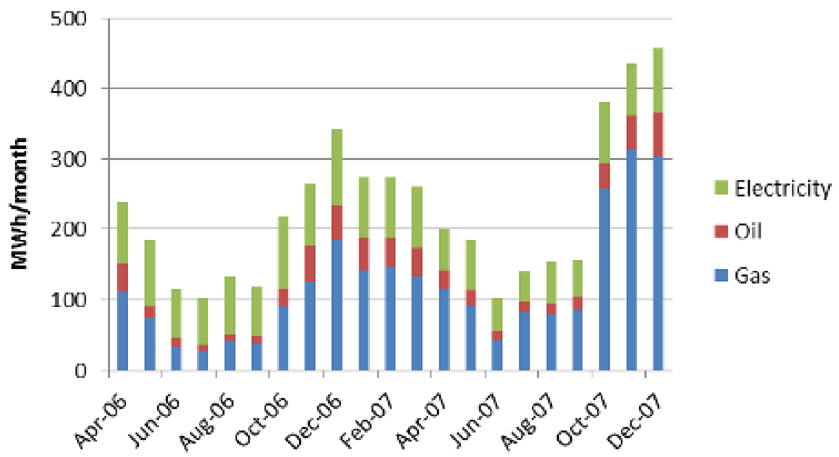

Figure 5.6 Total energy consumption of Hewell Grange core site April 2006 –December 2011

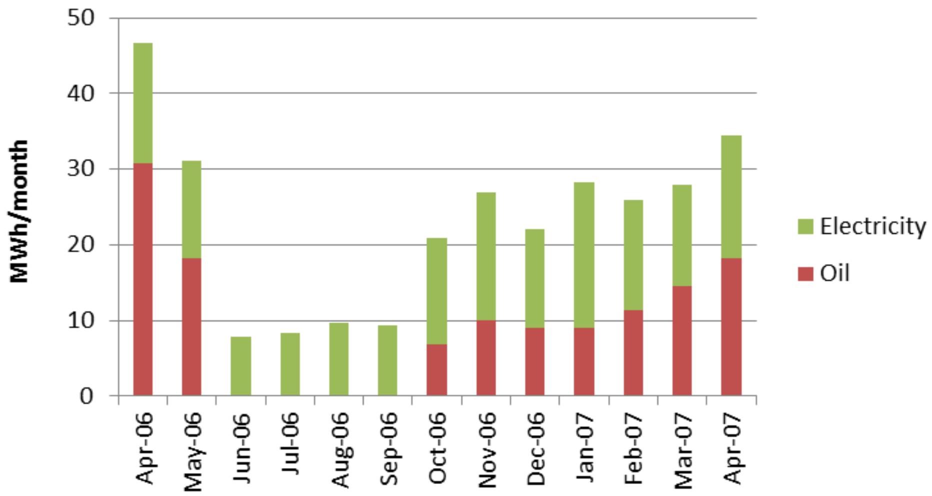

Figure 5.7 Energy consumption of Hewell Grange industries and farm 2006 - 2007

Table 5.3 Fuel and energy consumption of different areas of Hewell Grange April 2006-March 2007

	Core			Industries & Farms		Total
	Gas	Oil	Electricity	Oil	Electricity	
Monthly average	96	29	86	9	13	233
Monthly minimum	12	8	67	0	8	124
Monthly maximum	184	52	108	31	19	365
Annual total	1150	349	1030	110	155	2794

5.3 AD Modelling

The anaerobic digestion model developed at the University of Southampton (Salter, 2010) was used to determine potential outcomes for an anaerobic digester at HMP Hewell. The model was run three times, using varying inputs of the waste streams available.

5.3.1 Modelling Runs

Model Run 1 – Food Waste only
The model was run using the estimated quantities of food waste that could be collected from the catering facilities and returned trays from cells. This is a total of 78 tonnes per year of food waste.
Model Run 2 – Food Waste plus Cattle Slurry
The second model run was based on the estimated quantities of food waste (78 tonnes), plus cattle slurry from the agricultural operation onsite, estimated at 1,164 tonnes per year.
Model Run 3 – Other Prisons from area
There are two other prisons in the area, HMP Birmingham and HMP Long Lartin, with operational capacities of 1450 and 622 prisoners, respectively. A third model run was carried out for a digester processing food waste from all three prisons. The same per capita waste production rate of 1.2 kg/person-week was assumed for all three prisons, equating to 78 tonnes per year from Hewell, 90 tonnes per year from Birmingham and 39 tonnes per year from Long Lartin, for a total of 207 tonnes per year.

5.4 Results and Discussion

Tables 5.4 and 5.5 show the outputs and savings that could potentially be associated with an onsite AD plant, depending on the waste stream(s) processed. Table 5.4 shows the results of modelling using a CHP plant for biogas utilisation, while Table 5.5 gives results of modelling using a boiler for biogas utilisation.

Table 5.4 Modelling Outputs for Onsite Anaerobic Digestion at HMP Hewell – CHP

Energy and material outputs (/year)	Run 1 - Food Waste only	Run 2 - Food Waste + Cattle Slurry	Run 3 - Food Waste from 3 Prisons	
Digester input	78	1242	207	tonnes
Digester capacity required	17	105	46	m^3
Digester retention time	74	28	74	days
Methane produced	7233	23319	19196	m^3
Methane available	7161	23086	19004	m^3
Biogas (volume)	12471	39281	33097	m^3
Biogas (mass)	15	48	41	tonnes
Digestate	63	1194	166	tonnes
Electricity produced	90	289	238	GJ
	24940	80404	66188	kWh
	3	10	8	kW generator
Heat produced	128	413	340	GJ
Upgraded biogas	0	0	0	m^3
Waste transport diesel	0	0	927	litres
Total energy output	218	703	579	GJ
Energy inputs required (/year)				
Waste transport	0	0	33	GJ
Digestate transport	7	135	19	GJ
CHP supplied electricity	11	28	30	GJ
Imported electricity	0	0	0	GJ
Boiler/CHP supplied heat	47	405	104	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	20	318	53	GJ
Total energy input	68	577	192	GJ
Energy exports				
Energy in methane produced	259	835	688	GJ
Exported electricity	79	261	208	GJ
	22	73	58	MWh
Exported heat	82	8	236	GJ
	23	2	66	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	160	269	445	GJ
Energy Balance	150	126	387	GJ
	1.9	0.1	1.9	GJ/tonne

Table 5.5 Modelling Outputs for Onsite Anaerobic Digestion at HMP Hewell – Boiler

Energy and material outputs (/year)	Run 1 - Food Waste only	Run 2 - Food Waste + Cattle Slurry	Run 3 - Food Waste from 3 Prisons	
Digester input	78	1242	207	tonnes
Digester capacity required	17	105	46	m^3
Digester retention time	74	28	74	days
Methane produced	7233	23319	19196	m^3
Methane available	7161	23086	19004	m^3
Biogas (volume)	12471	39281	33097	m^3
Biogas (mass)	15	48	41	tonnes
Digestate	63	1194	166	tonnes
Electricity produced	0	0	0	GJ
	0	0	0	kWh
	0	0	0	kW generator
Heat produced	218	703	579	GJ
Upgraded biogas	0	0	0	m^3
Waste transport diesel	0	0	927	litres
Total energy output	218	703	579	GJ
Energy inputs required (/year)				
Waste transport	0	0	33	GJ
Digestate transport	7	135	19	GJ
CHP supplied electricity	0	0	0	GJ
Imported electricity	11	28	30	GJ
Boiler/CHP supplied heat	47	405	104	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	20	318	53	GJ
Total energy input	68	577	192	GJ
Energy exports				
Energy in methane produced	259	835	688	GJ
Exported electricity	0	0	0	GJ
	0	0	0	MWh
Exported heat	171	297	475	GJ
	48	83	132	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	171	297	475	GJ
Energy Balance	150	126	387	GJ
	1.9	0.1	1.9	GJ/tonne

The amounts of electrical power and heat produced are quite small in relation to the institution's energy requirements, being capable of meeting 3-9% of electrical demand, and/or 1-7% of heat demand of the Hewell Grange building.

Potentially of interest would be a digester that processed manure from the dairy along with food waste arising from the prison. Co-digestion of manure with food waste would require a digester six times larger than that required for food waste alone, with a resulting energy output about three and a half times higher than that for food waste alone. Carbon savings, in tonnes CO_2 equivalent, would also be about three and a half times higher for the scenario co-digesting manure than for food waste alone.

Additional benefits of slurry digestion include a biologically stabilized and more beneficial soil amendment than spreading of raw manure on land and reduction in CO_2 emissions (Amon et al., 2006), as well as generating additional power that could be used onsite.

The third scenario considered would be to combine food waste from two neighbouring prisons, Birmingham and Long Lartin. From this food waste, approximately 58 MWh of electricity and 66 MWh of heat could be produced with a CHP, or 132 MWh of heat with a boiler. However, the transport distances of 30 km from Birmingham to Hewell and 26 km from Long Lartin to Hewell were taken into account to calculate the diesel energy requirement. Based on a fuel consumption rate of 9.01 MJ $t^{-1}km^{-1}$ for a rigid 7.5-tonne refuse lorry (AEA, 2010), it was found that the energy required to transport the waste would be approximately 33 GJ, equal to 7.5% of the energy that could be produced by the digester.

At present there is no food waste collection scheme implemented in the area surrounding HMP Hewell (Redditch Borough Council, 2012). The institution is located between the towns of Bromsgrove (6 km) and Redditch (7 km), with populations of 93 400 and 78 700 respectively (Worcestershire County Council, 2012). At an average food waste generation rate of 50 kg per person per year (Banks, 2011), if the local council were to implement a food waste collection system in these two towns then the waste arising could be approximately 8600 tonnes per year. This could be added to the waste arising at the prison and digested. This would allow the council to increase its diversion rates, while providing gate fee revenue to the prison and allowing it to meet its energy requirements from biogas. The transport implications of such a scenario, however, could negate its utility, as it would require the movement of waste vehicles on and offsite, which as previously noted, is undesirable in a secure facility.

Alternatively, the institution could utilise an existing AD plant operating in its vicinity to process its waste. Currently the nearest operating AD plant processing food waste is at Cannock Chase (AD Portal, 2011), approximately 50 km from the prison. HMP Hewell could transport its food waste to the off-site plant where it could be digested. The transport requirements of hauling 78 tonnes per year 50 km would be equivalent to 35 GJ per year, based on a fuel consumption for a rigid 7.5 tonne refuse lorry of 9.01 MJ/t-km (AEA, 2010). This is equivalent to approximately 22% of the 160 GJ that could be produced from this amount of food waste, as calculated by the model.

5.5 Conclusions

An onsite AD plant operating on food waste from HMP Hewell could potentially produce, depending whether this is co-digested with cattle slurry, 22-73 MWh of electricity annually and 2-66 MWh of heat with a CHP, or 48-132 MWh with a boiler. This is quite a small amount relative to the site's energy requirements, meeting 3-9% of electrical demand and 1-3% of heat demand of the Hewell Grange building using a CHP, or 2-7% using a boiler.

From an energy perspective, therefore, an onsite AD plant for wastes produced at HMP Hewell would not have sufficient energy benefit to justify the costs of a plant. The potential inmate training and work benefits of having a working plant onsite may be worth consideration, however, especially from the view of integrating it into the current working farm. This could potentially make AD a possibility worth pursuing, beyond the energy balance alone.

5.6 Acknowledgements

Thanks to Darryl Jones and the other members of staff at HMP Hewell who provided information about the site and other institutions within the West Midlands Consortium.

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6 Case Study: Investigating the potential for small-scale anaerobic digestion at British Army installations

6.1 Introduction

Achieving greater sustainability in its operations is one of the goals of the UK's Ministry of Defence (MoD), not only to comply with UK government policies but also because of the many advantages to the military. Becoming more sustainable will use fewer natural resources, energy, fuel and water, and produce less waste which will save money across the Ministry.

The military has recognised that in addition to rising fuel costs, supply uncertainties, and stricter environmental regulations, the use of fossil fuels also has major operational constraints and risks (Dixon, 2011). In military operations in conflict areas, the cost of transporting fuel can be between two and ten times the ‘pump price’ (Ministry of Defence, 2011); moreover, since fuel must be imported and transported over long distances, usually in armoured convoys, the British army has calculated that it takes seven gallons of fuel to deliver one gallon to Afghanistan (Economist, 2009). Reducing fuel transport is a key strategic and safety consideration. In 2010 alone, 300 contractors were killed delivering fuel to Camp Bastion in Afghanistan. Similarly, from 2003-2007 one in eight US casualties in Iraq was a result of protecting fuel convoys, and this is one of the key motivations for the US military’s drive to invest in renewable energy technologies (Hargreaves, 2011). Finding ways to generate energy in camp would thus not only save money and logistics effort, but more importantly, lives. The MoD is currently consuming over 1.2 billion litres of fuel per year on transport alone (Dixon, 2011) and finding ways to reduce this fuel consumption is a priority for the military.

The MoD already has a number of projects focusing on green energy technologies. Key among these is the PowerFOB project, currently being tested at full scale at the MoD’s Episkopi training area in Cyprus. FOB is an acronym for Forward Operating Base, the term for bases in operational areas, closer to the front line than the main base. The project is a cooperative effort between the MoD, the Canadian Department of National Defence, U.S. Marine Corps and the British Antarctic Survey with suppliers of power management and renewable energy technologies, to meet energy demand and reduce demand for oil in the field (Dixon, 2011). PowerFOB uses renewable energies such as solar panels and wind turbines in combination with ‘smart grid’ energy and load management systems to support or replace diesel generators in providing power to bases, including communication kit, fridges, kitchen equipment and air conditioning in tents, thus reducing the demand for diesel fuel to be brought in to bases. The Cyprus base was chosen for testing as its climate is most suitable for emulating the hot and dusty conditions in Afghanistan. PowerFOB was trialled in July 2011 and initial deployment of some of the technologies has commenced in Afghanistan this year (Dixon, 2011), with further rollout planned after evaluation of the initial results.

The MoD has also developed a Waste Management Strategy with a number of ambitious objectives (MoD, 2010). The overarching one is for the MoD to become a zero-waste-to-landfill organisation. Immediate targets include reducing the total amount of waste generation by 20% by 2016/17, and increasing waste recovery by recycling, re-use, composting and energy from waste to 80% by 2016/17, of which 60% would need to be achieved by recycling and composting (MoD, 2010).

It is also hoped that sustainable development projects overseas may increase public support for the British Forces, especially in operational areas (MoD, 2010).

The purpose of this case study is to consider in this context whether anaerobic digestion has a role to play in the British Army, in the UK or overseas.

6.2 Food waste in the Army

In the Army, as in any large-scale catering establishment, the rate of food wastage can be expected to be higher than in family homes due to the necessity for serving larger numbers, providing choice, and with potentially less-predictable consumption patterns.

A considerable number of studies on food waste have been conducted for the US military. These date from the late 1940s when a study by Schor and Swain (1949) found average food waste rates in army messes of around 0.1 kg/person-day or approximately 5% of the edible food issued. King (1983) carried out extensive characterisation of the food waste from an in-house and a commercially-run army facility, and also looked at the influence on waste composition of factors such as the distance from pay day. She found an average of 0.7 lb (0.3 kg) food waste per meal, which over three meals per day would equate to a per capita rate of 0.9 kg/day. Brandhorst et al. (1995) evaluated food waste as part of the solid waste stream across a range of US Army installations, while Cox et al. (1991) and Rock et al. (2000) looked specifically at waste produced in field operations; the Cox study measured T Ration waste by volume and found 0.23 ft^3 per person per meal, which at an assumed specific gravity of 0.5 would equate to 3.2 kg per person per meal, or 7.6 kg/person-day. The other two did not quantify food wastage on a per capita basis. A recent study of two army base camps in the Balkans analysed changes in waste production and management during the transition from combat to long-term operations, and identified an increase in food waste generation rates from 190 kg to 275 kg per person per year (0.52 to 0.76 kg/person-day) associated with a change to A Rations (USACE, 2008). The potential for reduction of food waste in military operations has also been considered (Mann et al. 1994; Lenahan and Karwan, 2001).

In contrast, relatively few studies have focused specifically on food waste types and quantities in the British Army. Arneil and Badham (1949) reported average plate waste of 6.27% by weight in different units, similar to the values reported by Schor and Swain (1949). These studies are now dated, however, and many military bases have adopted the ‘Pay as you Dine’ approach where individuals select what to eat from a range of options (Sharpe, 2006). This can potentially reduce the amount of food waste produced, although its introduction has been contentious for other reasons (Tipping, 2008; Hill et al., 2011). Recent responses to parliamentary questions and requests made under the Freedom of Information Act 2000 and the Environmental Information regulations 2004 indicate, however, that the MOD does not hold data on the amount of food waste generated or the proportion of this which is segregated (Hansard, 2010; MoD, 2011). In addition to day-to-day waste production in catering facilities, however, other sources of food waste also represent a disposal cost and a loss of resources. The UK's Defence Storage and distribution agency disposed of 122,085 operation ration packs over a 5-year period to 2008, mainly due to expiry of shelf-life (Defence Management, 2008).

A number of studies on the potential for treatment of food waste have been carried out by the United States Military, as the US Department of Defence (DoD) is also being directed towards a more environmentally-friendly and sustainable-state of energy consumption. The chief driver for this is Executive Order 13423, a federal government initiative requiring federal agencies "to lead by example in advancing the nation's energy security and environmental performance" by meeting targets in areas such as energy efficiency, greenhouse gas emissions, renewable power, water and fuel conservation and pollution prevention (USEPA, 2009). Examples of these include participation in the PowerFOB initiative previously described; evaluation of waste-to-energy and composting technologies for food waste (Bost and Lee, 2004; Knowlton and Pickard, 2008) and initiation of composting at several U.S. army bases including Fort Hood, one of the U.S.' largest military installations (Waste management world, 2011).

MOD initiatives to improve handling of food waste have mainly focused on the introduction of waste collection, dewatering and aerobic composting systems at British Army bases in the UK. Examples include the IMC dewatering and composting systems in use at several UK bases (IMC, 2009) and a wormery for food waste at the UK's Permanent Joint Headquarters in Northwood opened in April 2008 (Defence Estates, 2009).

Solid waste on overseas military bases can be an environmental, health and even a political liability. When combat zone camps are established, however, solid waste management is often a low priority as the length of time that a certain base will be occupied is unknown (USACE, 2008).

6.3 Case studies for the British Army

Within the British Army, a number of different types of residential and operational units exist of varying sizes, both in the UK and overseas. For this study, three operational units of the British Army were chosen for analysis: two education and training bases in the UK, and one large operational base overseas.

6.3.1 Welbeck DSFC

Welbeck Defence Sixth Form College (DSFC) is a military college that provides secondary education to candidates for the British Armed Forces. Situated in Woodhouse near Loughborough, Leicestershire, it is a purpose-built learning institute for future Technical Officers. Students stay at the DSFC for two years, during which they complete AS-Levels and A-Levels (qualification courses for entry to British universities), as well as sport and military training. Each year 175 students are enrolled, with a total of 350 students boarding at the college at one time (Welbeck DSFC, 2009).

The College has an in-house catering service and catering staff prepare three meals a week for students and staff, on average making 6,700 fresh meals per week during the 40-week school year. (Welbeck DSFC, 2009). Food and drinks can also be purchased on site in the bar, and vending machines for hot and cold drinks and confectionery are located around the building. The catering service also provides support for external functions, ranging from small seminars to large-scale sporting events.

The College is located in 14.5 hectares of land including a range of grass and artificial surface sports pitches, and military training facilities such as a rifle range and obstacle course.

Food Waste Quantities. Food waste is not currently separated at the College, but is disposed of as part of the general refuse stream. As part of the current case study, a trial was carried out in which catering staff separated the food waste for a one-week period, and weighed it each day. Approximately 110 kg of food waste was generated during this week, corresponding to a wastage rate of 0.045 kg/person-day based on student numbers only. The school is in session for 40 weeks per year, which equates to 4.4 tonnes of food waste produced each year.

6.3.2 Worthy Down Defence Food Services School

The Defence Food Services School (DFSS) provides chef and steward training for the armed forces, and is located on two sites. The RAF Halton site near Aylesbury in Buckinghamshire provides training primarily for the Air Force, while Alexis Soyer House at Worthy Down in Hampshire provides training for Army personnel. The current case study focuses on the Worthy Down site which takes up to 915 trainees each year including Food Service Officers, Food Service Warrant Officers, Unit Catering Managers, Kitchen Managers, Class 1 Chefs, Class 3 Chefs, Gurkha/Royal Gibraltar Regiment Chefs, Unit Ration Personnel, Royal Logistical Corps Marine Personnel and those on a basic course for the Army / Combined Cadet Force. Facilities at the Worthy Down site include 14 kitchen classrooms, a Realistic Work Environment (RWE) dining area and a field training area, as well as instructional classrooms and a learning resource centre (MoD, N.D.).

Food Waste – Current Management and Quantities. As part of the training course, students at the Worthy Down site typically prepare three 3-course meals a day. The food is not served for human consumption, and therefore a large amount of waste is generated (IMC, 2009). The amount of food waste processed by the system is approximately 1.5 tonnes per day, which over the 40-week school term equates to 300 tonnes per year.

The food waste is currently treated by a form of in-vessel composting system which involves macerating and dewatering followed by addition of sawdust pellets to allow aerobic composting (Figures 6.1 and 6.2). Dewatering reduces the volume of food waste by 80%, leaving a much smaller quantity for composting (IMC, 2010). The school calculates that use of the dewatering systems has saved £50,000/year (€62,000/year at 30/06/2012) on food waste disposal costs. This food waste could, however, be digested rather than composted, which would give the same savings in disposal costs with the added benefits of electricity and heat as well as compost.

Figure 6.1 IMC Food waste processor at the Worthy Down Defence Food Services School (MoD, 2009).

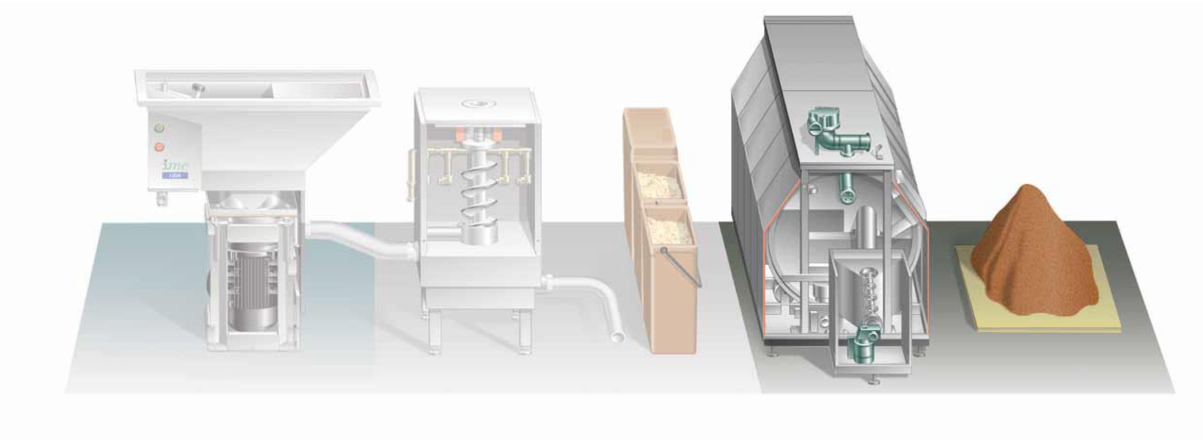

Figure 6.2. Food waste recycling diagram from Food Waste Recycling Brochure (Imperial Machine Company, 2010).

6.3.3 Camp Bastion, Afghanistan

Military bases overseas comprise a large part of the British Army's activities, with approximately 41,000 troops stationed in countries around the world, with the highest deployment in Afghanistan (BBC, 2008).

In Afghanistan, as in other overseas operations, troops live and work from bases, which can differ depending upon the mission type, duration, size, role, area of operation, host nation infrastructure, and the units that they support. The main base in Afghanistan is Camp Bastion, which is 40 km long and includes an airport that is busier than the majority of airports in the UK. Troops and supplies coming into Afghanistan first arrive at Camp Bastion before being deployed to Forward Operating Bases (FOBs) in operational areas. In addition to the airport, the base has its own police force, fire station, and water bottling plant. Typically there are 20,000-30,000 people at Camp Bastion at any one time (Hopkins, 2011).

Food Waste Quantities
Quantities of food needed to feed the large numbers of troops and local civilians working at the base are substantial – 27 tonnes per week of fresh fruit and vegetables alone are brought in to the base (Hopkins, 2011).

A US study of waste on two military bases in the Balkans found that food and vegetation waste made up 7-9% of the waste stream, with an estimated quantity of 188 kg/person-year or 3.6 kg/person-week (USACE, 2008). This amount of food waste is twice that of the typical UK household rate of 1.5-2 kg/household/week (WRAP 2009; Banks et al. 2011) which equates to 0.6-0.8 kg/person/week. The US Army figure is very high in comparison, but is consistent with the findings of King (1983) of 0.9 kg/person/day or 6.3 kg/person/week.

Extrapolating the figure of 188 kg/person-year gives an annual estimate of 3,762 tonnes of food waste per year for a camp serving 20,000 people.

Current processing and transport infrastructure
Currently the standard practices for waste management in Afghanistan include burying in offsite landfills, which in Afghanistan can be situated from 100 to 200 km away from camp. Transporting waste can be very expensive. Therefore waste is usually burnt in incinerators or open-air Burn Pits to reduce its volume before taking to landfill. Burn Pits use a significant amount of fuel and emit toxic gases and smoke which has led to some concerns of possible effects on soldiers' health (US DVA, 2012; Drummond, 2012; Ackerman, 2012). Camp Bastion has eight incinerators and one burn pit onsite (Hopkins, 2011) but food waste is a poor candidate for incineration or uncontrolled combustion, as its high water content means that a significant amount of energy must be used to dry it before it will combust.

Also of importance is the fact that any requirement for transport, including waste vehicles away from the camp, has major security implications associated with it, as there is the risk of attack during any transport.

Current energy use onsite
There are 250 onsite generators at Camp Bastion, which use a total of 18.2 million litres of diesel fuel per year. All of this diesel must be brought in to the site by overland transport in dangerous fuel convoys. Therefore any decrease in diesel demand would have a positive effect for the British Army.

6.4 AD Modelling

Modelling was carried out using the anaerobic digestion model developed at the University of Southampton (Salter, 2010), for the following 3 scenarios. Average air and ground temperatures from the nearest cities were used in heat loss calculations: Loughborough, Southampton and Kabul.

Model Run 1 – Welbeck DSFC, UK
The model was run using the estimated quantities of food waste that could be collected from Welbeck DSFC, a total of 4.4 tonnes per year of food waste.

Model Run 2 –Defence Food Services School, Worthy Down, UK
The second model run was based on the estimated quantities of food waste from the Defence Food Services School, a total of 300 tonnes per year.

Model Run 3 – Camp Bastion, Afghanistan
The third model run was based on the estimated quantities of food waste from Camp Bastion in Afghanistan, a total quantity of 3,762 tonnes per year.

6.5 Results and Discussion

Tables 6.1 and 6.2 show the outputs and savings potentially associated with an onsite AD plant for each of the three locations trialled, using either a CHP plant (Table 6.1) or boiler (Table 6.2) for biogas utilisation.

Table 6.1 Modelling outputs for onsite AD at British Army Installations - CHP

Energy and material outputs (/year)	Run 1 - Welbeck DSFC, UK	Run 2 - Worthy Down DFSS, UK	Run 3 - Camp Bastion, Afghanistan	
Digester input	4.4	300	3762	tonnes
Digester capacity required	1.0	67	834	m^3
Digester retention time	74	74	74	days
Methane produced	408	27821	348873	m^3
Methane available	404	27543	345384	m^3
Biogas (volume)	704	47967	601505	m^3
Biogas (mass)	0.9	60	747	tonnes
Digestate	3.5	240	3015	tonnes
Electricity produced	5	345	4330	GJ
	1407	95925	1202896	kWh
	0.2	12	145	kW generator
Heat produced	7.2	493	6186	GJ
Upgraded biogas	0	0	0	m^3
Waste transport diesel	0	0	0	litres
Total energy output	12	839	10516	GJ
Energy inputs required (/year)				
Waste transport	0	0	0	GJ
Digestate transport	0.4	27	340	GJ
CHP supplied electricity	0.6	43	542	GJ
Imported electricity	0	0	0	GJ
Boiler/CHP supplied heat	5.1	137	1242	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	1	76	925	GJ
Total energy input	7	214	2160	GJ
Energy exports				
Energy in methane produced	15	997	12497	GJ
Exported electricity	4.4	302	3788	GJ
	1.2	84	1052	MWh
Exported heat	2.1	356	4943	GJ
	0.6	99	1373	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	6.5	659	8732	GJ
Energy Balance	5.6	624	8356	GJ
	1.3	2	2	GJ/tonne

Table 6.2 Modelling outputs for onsite AD at British Army Installations – Boiler

Energy and material outputs (/year)	Run 1 - Welbeck DSFC, UK	Run 2 - Worthy Down DFSS, UK	Run 3 - Camp Bastion, Afghanistan	
Digester input	4.4	300	3762	tonnes
Digester capacity required	1.0	67	834	m^3
Digester retention time	74	74	74	days
Methane produced	408	27821	348873	m^3
Methane available	404	27543	345384	m^3
Biogas (volume)	704	47967	601505	m^3
Biogas (mass)	0.9	60	747	tonnes
Digestate	3.5	240	3015	tonnes
Electricity produced	0	0	0	GJ
	0	0	0	kWh
	0.0	0	0	kW generator
Heat produced	12.3	839	10516	GJ
Upgraded biogas	0	0	0	m^3
Waste transport diesel	0	0	0	litres
Total energy output	12	839	10516	GJ
Energy inputs required (/year)				
Waste transport	0	0	0	GJ
Digestate transport	0.4	27	340	GJ
CHP supplied electricity	0.0	0	0	GJ
Imported electricity	1	43	542	GJ
Boiler/CHP supplied heat	5.1	137	1242	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	1	76	925	GJ
Total energy input	7	214	2160	GJ
Energy exports				
Energy in methane produced	15	997	12497	GJ
Exported electricity	0.0	0	0	GJ
	0.0	0	0	MWh
Exported heat	7.2	702	9273	GJ
	2.0	195	2576	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	7.2	702	9273	GJ
Energy Balance	5.6	624	8356	GJ
	1.3	2.1	2.2	GJ/tonne

Welbeck DSFC. An onsite AD plant at Welbeck College could produce 1.2 MWh of electricity and 0.6 MWh of heat per year with a CHP, or 2 MWh of heat using a boiler. This would likely be too small to feasibly build and operate an onsite AD plant; likely a better solution would be for the college to team up with a local municipal or commercial food waste collection scheme, if any exist in the area. The main argument in favour of an onsite AD would be if it were useful for training purposes for students of the college, who would have the opportunity to gain skills in sustainable waste management and anaerobic digestion technology. This is likely to be true for military colleges of this size throughout the UK.

Worthy Down DFSS. An onsite AD plant at the Defence Food Services School at Worthy Down could generate 84 MWh/year of electricity and 99 MWh/year of heat with a CHP, or 195 MWh/year with a boiler. This represents a useful amount of power and would probably cover a significant proportion of the needs of the Worthy Down site. Beneficial use of digestate may also be relatively straightforward, as the site is in an agricultural area, while the MoD is itself a major landholder. The main objection to this plan is that it represents a waste of resources in a more fundamental sense: the prepared food could more profitably be donated to charities in the area or directly provided to individuals in need through the development of some kind of onsite charitable programme. Examples of some successful schemes and strategies can be found in the US EPA 'Waste not, Want not' guide (US EPA, 1999); the issue has recently come into prominence again in the UK with the proposal of a Food Waste Bill that would require large food retailers and manufacturers to donate surplus food to charities for redistribution or make it available for livestock feed (Hansard, 2012; CSC, 2012).

Camp Bastion. At Camp Bastion in Afghanistan, an onsite AD plant could generate 1,052 MWh/year of electricity and 1,373 MWh/year of heat with a CHP or 2,576 MWh/year with a boiler only. These amounts are relatively small in comparison to overall energy requirements; however the replacement of even one of the 250 diesel generators at Camp Bastion, for instance, would save lives by reducing the amount of diesel that needed to be brought into the site by overland convoy.

The UK has committed to leave Afghanistan by 2015 (Kirkup, 2011). Therefore a 20-year digester lifetime would not be of relevance to the Army. It could be possible, however, to leave the plant in place as a legacy for use by the local population. If the area is not repopulated to similar numbers as the current site, there would be little use for a digester of this size solely for food waste. If a centre of population or other activity such as a market or farm arises at this location, however, it may be possible to take advantage of the physical infrastructure left behind by the military.

The idea of using AD as part of a legacy to support the local population is already in practice by the US Army, which has produced a manual for installing very small-scale AD plants that can produce sufficient biogas to meet cooking and lighting requirements at the scale of a single household or more, from animal dung. Construction of a pilot installation in Kabul has been funded, and the US military has produced a manual for installation of small, low-tech plants in Afghanistan (US Forces Afghanistan, Joint Engineer Directorate, 2011). This is intended to be part of the legacy left by coalition forces. Indeed, the US Army Corps of Engineers has carried out a feasibility study as part of a selection process for potential renewable energy technologies to be included at the Afghanistan National Security University, the military training institute being developed by US and coalition forces as part of the legacy (USACE, 2011). It should be noted, however, that the report considers and rejects anaerobic digestion as unfeasible for the institute, due to its long payback time exceeding twenty years. Small-scale, low-tech biogas plants, however, are seen as a way forward for Afghan families in areas without access to electricity, and are being developed and promoted by the new Afghan Renewable Energy Department (ARED) as reported by the Afghanistan International Security Assistance Force (ISAF, 2011).

6.6 Conclusions

Although onsite anaerobic digestion would be possible at each of the studied sites, it is unlikely that digesters will be built at any of these three sites. For Camp Bastion, the planned shutdown of the site within three years makes the construction of a permanent digester impractical, unless the digester could be used by the local population after the exit of British forces. In the case of the Defence Food Services School, investment has already been made in a waste dewatering and composting system and the institution will likely wish to make full use of it during its lifetime.

6.7 Acknowledgements

Thanks to Captain Mick Peters, Defence Food Services School, and Mr Alan Hayes, Welbeck DSFC who provided information about their respective sites and other aspects of British Army operations.

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7 Case Study of Barrett's Mill Anaerobic Digester (BMAD): Small-scale community AD plant in South Shropshire

7.1 Introduction

This study concerns a demonstration plant being developed to meet the needs of small-scale community AD projects. The scale of an AD plant is often measured either by the feedstock throughput or by the continuous electrical output from an associated CHP unit. Typical sizes of projects currently being developed in the UK are in excess of 10,000 tonnes year^{-1} and in excess of 250 kW$_e$. Evergreen Gas Ltd (http://evergreengas.co.uk/) is a relatively new business whose aim is to develop much smaller AD plants in response to market demand and in response to UK government policy, which seeks to increase the number of rural and community AD plants. The scale of AD plants being developed by Evergreen Gas is in the range 250 to 5000 tonnes year^{-1} (10 to 250 kW$_e$).

The first step in the planned development of small-scale community AD is to build a pilot project. This will be sited at Barrett's Mill near Ludlow in South Shropshire, which is also the location of the Evergreen Gas office and is the home of Michael Chesshire, one of the founders of the company. The project has been given the title Barrett's Mill Anaerobic Digester (BMAD).

7.2 Feedstock

Feedstock for BMAD will be from flexible and multiple sources. The total quantity is designed to be approximately 300 tonnes year^{-1} (6 tonnes week^{-1}), equivalent to an output of 7.5 kW$_e$. Typical sources will be household and restaurant food waste from the local community, and commercial food waste from local businesses, supplemented by manure, grass silage and fodder beet from a neighbouring farm.

The design throughput of 300 tonnes year^{-1} makes this a smaller scale plant than most digesters currently operating. This scale was specifically chosen for a number of reasons:

i) It meets the requirements of the Environment Agency's T25 exemption, concerning small anaerobic digestion plants built and operated at non-agricultural premises(EA, 2010). The exemption allows a maximum of 50 m^3 of waste to be stored and treated onsite, at a minimum retention time of 28 days. The digester's capacity of 38 m^3 gives a retention time of 54 days at the design loading rate of 5.9 kg VS m^{-3} day^{-1}

ii) It will be used for research purposes and will therefore often be loaded to the limit, which has the potential for process upset; while this may be unacceptable for a large project, a smaller plant can be recovered and re-started with fewer logistical and other issues than a larger plant.

iii) It is at located at the residence of the owner, and it was therefore desired to limit the amount of feedstock that needed to be imported.

iv) The location itself is at the end of a farm track which is not amenable to a large number of deliveries.

v) Although over the medium term the current economic situation leans in favour of larger plants, being able to demonstrate the technology at a smaller scale opens up opportunities for the longer term.

Feedstock either will be collected by Evergreen Gas in a vehicle with a payload of one tonne, or will be delivered by the neighbouring farmer from adjacent fields, or by a contractor in a vehicle with a payload of no more than 3 tonnes. It is anticipated that the maximum transport distance for feedstock to BMAD will be 10 km, but part of the ethos of the project is to keep this to a minimum; an output from the monitoring of the project will be the total feedstock miles in a given year. Figure 7.1 shows the location of the plant and of nearby towns and villages which could act as potential feedstock sources.

Figure 7.1 Location of plant and population centres within a radius of 2.5, 5, 7.5 and 10 km. (Google Maps © 2012).

There is an anaerobic digestion plant in the area, in the town of Ludlow; this plant was also developed by Michael Chesshire before being sold to BiogenGreenfinch. It processes 5,000 tonnes per year of food waste from municipal and commercial sources in Shropshire and Wales.

7.3 Process Description

Feedstock Reception. Feedstock will be delivered into a sealed reception building and will be stored on the floor. The maximum amount to be stored within the building at any one time will be 4 days of digester feedstock, i.e. a maximum of 3.5 tonnes.

The concrete floor of the reception building includes a drainage system which leads to a sump from where liquids leaching from the feedstock and washwater are pumped into the digester.

7.3.1 Anaerobic Digester

The design of the digester represents a departure from conventional tank design, aimed at reducing capital and operating costs by incorporating standard components selected for durability and ease of maintenance.The anaerobic digester is a concrete tank which is 1.5 metres below ground and 1.0 metre above ground. In plan view it is rectangular, 2.4 m wide by 7.2 m long, making it a plug-flow by design; with a freeboard allowance of 300 mm the effective digester volume is 38 m^3. The digester roof comprises a set of covers fabricated in glass-reinforced polyester (GRP). The digester walls and floor are insulated to minimise heat loss by sections of pre-formed polyurethane foam.

The digester is mixed by the traditional method of gas recirculation whereby a small gas compressor recirculates biogas through a set of nozzles cast into the concrete base of the digester.

The digester is maintained at its design temperature (in the range 30 to 55 ^{o}C) by circulating hot water through a series of heat exchanger pipes fixed to the internal wall of the digester.

Digester Feed System. A feed hopper with a working volume of 1.2 m^3 (1 tonne) is installed within the reception building; this volume represents one day's feed for the digester. The hopper is filled once per day using a bucket loader. An auger feeds the material directly into the digester below the gas seal. This auger is operated automatically every 4 hours.

Digester Discharge System. An outlet connection is fitted to the digester tank at the opposite end to the feed. A macerator to reduce particle size to <12mm and a discharge pump are installed on the outlet.

Pasteurisation. Because the digester is designed to process food waste and because it is intended that the digestate is to be PAS110 compliant, a pasteurisation stage is included to pasteurise all the digestate. The system comprises an insulated covered tank with a capacity of 2.5 m^3, which represent half a week's production of digestate. The pasteurisation tank is mixed by a digestate recirculation pump and is heated by an internal heat exchanger through which hot water is circulated.

The pasteurisation cycle starts when the pasteurisation tank is empty. The tank is filled by the manual operation of the digester discharge pump; the heating is switched on and remains on until the pasteurisation tank has maintained a temperature of >70^{o}C for a period of > 1 hour; the pasteurisation tank is then emptied.

Digestate Press. A screw press, which is located on a raised platform, separates the pasteurised digestate into a liquid fraction and a solid fraction. The press is fed by a pump which acts as the pasteurisation discharge pump. The solid fraction falls into a small heap, capacity 0.6 m^3 (0.5 tonnes), below the screw press; the liquid fraction flows by gravity into a liquor transfer tank, capacity 2.4 m^3 from where it is pumped to a remote storage tank.

7.3.2 Digestate storage and utilisation

Until the AD plant achieves PAS110 accreditation there will be no storage of solid and liquid digestate on the site. When it is produced the digestate will be removed to a site where there is remote storage of both solid and liquid digestate, which will be used beneficially on farmland. This procedure will enable the plant to qualify for an Environment Agency T25 exemption since the maximum amount of material defined as waste which will be on site at any one time will be no more than 50 tonnes.

When PAS110 accreditation is achieved the digestate will no longer be classified as a waste. Solid digestate will then be stored in a clamp, capacity 30 tonnes, equivalent to 6 months of production. Liquid digestate will be stored in an above-ground cylindrical tank, capacity 90 m^3, equivalent to 6 months production.

With PAS110 accreditation, markets for the solid and liquid digestate will be developed; for example the solid digestate may be sold to local horticulture and the liquid digestate to the neighbouring farm. The Teme valley around Tenbury, for instance, is well-known locally for market gardening, and could be a good potential market for digestate.

7.3.3 Biogas storage and utilisation

Biogas is collected from the digester and piped to a separate double-membrane gas holder, capacity 100 m^3. From the gas holder gas is piped to a CHP unit and to a gas boiler.

The CHP unit comprises a gas engine driving a single-phase alternator, with full heat recovery from the engine jacket water, oil cooler and exhaust. At full load the fuel rating of the biogas input to the engine is 28 kW_{th}, the electricity output 7.5 kW_e and the heat recovered 17 kW_h. The electricity output will be synchronised with the grid; the CHP will meet the needs of the onsite electricity with the surplus being exported. The heat output will be utilised for digester heating, for pasteurisation and for domestic on-site heat demand.

Secondary uses of biogas are: first, to pipe a small amount (7 m^3 day^{-1}) to the domestic property on the site where an Aga cooker is installed in the kitchen; second, for a demonstration biogas-to-vehicle-fuel upgrade plant. If 25% of the biogas were used for vehicle fuel, this would be about 4500 kg $year^{-1}$ of methane, which, at 16 km kg^{-1}, would enable a car or van to drive about 72,000 km $year^{-1}$.

Figure 7.2 Aga cooker running on biogas at Barrett's Mill site. Photo: Evergreen Gas Ltd.

7.3.4 Process control and monitoring

The AD plant will be automatically controlled from a central panel which will include a data logger which will collate data from field-mounted instruments. This will enable plant performance to be evaluated and a mass & energy balance to be produced.

7.4 Process calculations

The projected performance of the plant based on one third manure, one third crops and one third domestic kitchen waste is shown in Tables 7.1, 7.2 and 7.3. The ratios are on the basis of equal yields of methane rather than on equal mass.

The total feedstock throughput in this case study is less than the nominal design of 300 tonnes year^{-1} because of the high dry matter of the poultry manure.

7.4.1 AD Modelling

In addition to the developer's process calculations given below, modelling was carried out using the anaerobic digestion model developed at the University of Southampton (Salter, 2010).

The model was run for a plant at Barrett's Mill using the given quantities of 75 tonnes per year of chicken manure, 115 tonnes per year of grass silage and 85 tonnes per year of kitchen waste, with the waste characteristics as shown in Table 7.1. The potential outputs were determined for biogas utilization in a CHP or boiler, or upgrading of the gas with and without compression. The average monthly temperatures in the town of Ludlow were used for heat loss calculations. An average transport distance of 5 km was used for kitchen waste, while agricultural wastes from the neighbouring farm were assigned a transport distance of zero.

Table 7.1. Feedstock properties and calculations

Feedstock	Units	Value
Poultry Manure		
- Number of Broiler Chickens	no.	4,000
- Mass of Manure	tonnes $year^{-1}$	75
- Dry Matter	%TS	50
- Organic Dry Matter	%VS	90
- Biological Methane Production (BMP)	m^3 CH_4 $tonne^{-1}{}_{VS}$	260
- Methane Percentage of Biogas	%	60
- Dry Matter	tonnes $year^{-1}$	38
- Organic Dry Matter	tonnes $year^{-1}$	34
- Methane Production	m^3 $year^{-1}$	8,800
- Biogas Production	m^3 $year^{-1}$	14,600
Grass Silage		
- Crop Area	ha	2.2
- Crop Yield (Fresh Material)	$tonne.ha^{-1}$ $year^{-1}$	52
- Crop Mass (Fresh Material)	tonnes $year^{-1}$	115
- Dry Matter	%TS	25
- Organic Dry Matter	%VS	95
- Biological Methane Production (BMP)	m^3 CH_4 $tonne^{-1}$ VS	320
- Methane Percentage of Biogas	%	55
- Dry Matter	tonnes $year^{-1}$	29
- Organic Dry Matter	tonnes $year^{-1}$	27
- Methane Production	m^3 $year^{-1}$	8,700
- Biogas Production	m^3 $year^{-1}$	15,900
Kitchen Waste		
- Number of Households	no.	770
- Mass of Kitchen Waste per Household	kg hh^{-1} $year^{-1}$	110
- Mass of Kitchen Waste	tonnes $year^{-1}$	85
- Dry Matter	%TS	28
- Organic Dry Matter	%VS	89
- Biological Methane Production (BMP)	m^3 CH_4 $tonne^{-1}{}_{VS}$	420
- Methane Percentage of Biogas	%	62
- Dry Matter	tonnes $year^{-1}$	24
- Organic Dry Matter	tonnes $year^{-1}$	21
- Methane Production	m^3 $year^{-1}$	8,900
- Biogas Production	m^3 $year^{-1}$	14,300
Total Feedstock		
- Mass of Feedstock	tonnes $year^{-1}$	275
- Dry Matter	%TS	33
- Organic Dry Matter	%VS	91
- Biological Methane Production (BMP)	m^3 CH_4 $tonne^{-1}{}_{VS}$	321
- Methane Percentage of Biogas	%	59
- Dry Matter	tonnes $year^{-1}$	90
- Organic Dry Matter	tonnes $year^{-1}$	82
- Methane Production	m^3 $year^{-1}$	26,400
- Biogas Production	m^3 $year^{-1}$	44,800

Table 7.2. Anaerobic digestion parameters

Anaerobic Digestion	Units	Value
Feedstock		
- Mass	kg day^{-1}	753
- Specific Gravity	tonne m^{-3}	1.06
- Volume	m^3 day^{-1}	0.71
- Dry Matter	kg day^{-1}	247
- Organic Dry Matter	kg day^{-1}	225
Digester		
- Digester Capacity	m^3	38
- Organic Loading Rate	kg VS m^{-3}_R day^{-1}	5.9
- Hydraulic Retention Time	d	54
Biogas		
- Methane Production	m^3 day^{-1}	72
- Biogas Production	m^3 day^{-1}	123
- Biogas Production	kg day^{-1}	150
- Specific Biogas Yield	m^3 day^{-1} m^{-3}_R	3.2
Digestate		
- Mass of Digester Feedstock	kg day^{-1}	753
- Mass of Biogas	kg day^{-1}	150
- Mass of Digestate	kg day^{-1}	603
- Dry Matter	%TS	16
- Organic Dry Matter	%VS	78
- Dry Matter	kg day^{-1}	94
- Organic Dry Matter	kg day^{-1}	73

Table 7.3. Energy outputs

Energy	Units	Value
Biogas		
- Methane Production	m^3 day^{-1}	72
- Biogas Production	m^3 day^{-1}	123
- Fuel Value of Biogas	kW_{th}	30
CHP		
- Fuel Input	kW_{th}	28
- Electricity Output	kW_e	7.5
- Heat Output	kW_{th}	17.3
Aga Cooker		
- Fuel Input	kW_{th}	2

During the BMAD trials, which will take place over several years, different combinations of feedstock will be evaluated in order to assess different combinations in the context of community anaerobic digestion.

The project is also planning to use biogas as a vehicle fuel. Using approximately 25% of the biogas for that purpose would equate to approximately 4500 kg $year^{-1}$ of methane, which based on 16 km kg^{-1} would enable a car or van to cover about 72,000 km per year.

7.5 Results and Discussion

Table 7.4 shows the outputs and savings that could potentially be associated with an onsite AD plant, depending on the mode of biogas utilisation, based on the AD modelling.

Table 7.4 Modelling Outputs for Onsite Anaerobic Digestion at Barrett's Mill AD

Energy and material outputs (/year)	CHP	Boiler	Biogas Upgrade	Biogas Upgrade & Compression	
Digester input	275	275	275	275	tonnes
Digester capacity required	83	83	83	83	m^3
Digester retention time	100	100	100	100	days
Methane produced	26411	26411	26411	26411	m^3
Methane available	26147	26147	26147	26147	m^3
Biogas (volume)	44876	44876	44876	44876	m^3
Biogas (mass)	55	55	55	55	tonnes
Digestate	220	220	220	220	tonnes
Electricity produced	328	0	0	0	GJ
	91065	0	0	0	kWh
	11	0	0	0	kW generator
Heat produced	468	796	0	0	GJ
Upgraded biogas	0	0	26147	26147	m^3
Waste transport diesel	66	66	66	66	litres
Total energy output	796	796	0	0	GJ
Energy inputs required (/year)					
Waste transport	2	2	2	2	GJ
Digestate transport	25	25	25	25	GJ
CHP supplied electricity	40	0	0	0	GJ
Imported electricity	0	40	88	116	GJ
Boiler/CHP supplied heat	131	131	0	0	GJ
Imported gas for heat	0	0	154	154	GJ
Pasteuriser inclusion	pre	pre	pre	pre	digester
Pasteuriser heat	67	67	67	67	GJ
Total energy input	206	206	277	305	GJ
Energy exports					
Energy in methane produced	946	946	946	946	GJ
Exported electricity	288	0	0	0	GJ
	80	0	0	0	MWh
Exported heat	337	665	0	0	GJ
	94	185	0	0	MWh
Energy in upgraded CH4	0	0	937	937	GJ
Exported energy	625	665	937	937	GJ
Energy Balance	590	590	660	631	GJ
	2.1	2.1	2.4	2.3	GJ/tonne

7.6 Conclusions

The future of small-scale community AD plants will depend on successful demonstrator projects of which BMAD is planned to be one. This project will show how mixed feedstocks from different parts of a community, in particular farms and households, can be co-digested to good effect. BMAD itself is probably too small to be a commercial pre-cursor and a typical commercial project on a community level might be one where 2,500 households, local commercial kitchens and a medium sized farm work together on a project with an electricity output of 100 kW.

7.7 Acknowledgement

Thanks to Michael Chesshire as the main author of this study, and provider of the data used in the Southampton model.

7.8 References

Environment Agency. 2010. *T25 – Anaerobic digestion at premises not used for agriculture and burning of resultant biogas.*16 February 2010. http://www.environment-agency.gov.uk/static/documents/Business/T25_exemption.pdf Accessed 9 July 2012.

8 Case Study of the Port of Dover: Investigating the potential for onsite AD

8.1 Introduction

There are over 950 ports, harbours, piers and jetties around the UK coastline (Ports UK, 2012). Ports are centres for the transfer of goods and people into and out of the country, and thus are of economic and political importance; 90% of all European Union external trade passes through sea ports (European Commission, 2007). The passage of goods and people through ports also leads to waste arisings, both from land-based operations within the port itself and from the wastes generated on ships carrying passengers, crew and freight for extended periods, which as a consequence have been producing waste requiring disposal.

In previous centuries, waste from ships was simply dumped overboard. In the second half of the 20th century, however, increasing awareness of the environmental consequences of indiscriminate sea dumping led to calls for regulation to control pollution, beginning with the International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL) in 1954, aimed primarily at oil pollution from tankers and large vessels (Butt, 2007).

Sea dumping of solid wastes from ships was first restricted in 1973, when the International Convention for the Prevention of Pollution from Ships was signed; this was modified by the Protocol of 1978 and is known as MARPOL 73/78; Annex V is specific to solid waste. This regulation and the International Safety Management (ISM) code are both under the auspices of the International Maritime Organisation (IMO). EU Directive 2000/59 (port reception facilities for ship-generated waste and cargo residues) requires ports to provide reception facilities for ship-generated waste that cannot be disposed of at sea, in accordance with the MARPOL 73/78 regulations (Butt, 2007).

With a view to meeting the fundamental requirements of MARPOL, the International Maritime Organization (IMO) produced its Comprehensive Manual on Port Reception Facilities (1999) and the Guidelines for Ensuring the Adequacy of Port Waste Reception Facilities (Resolution MEPC.83(44)). Building on these guidelines, they have then established a Guide to Good Practice for Port Reception Facility Providers and Users in 2009 (IMO, 2009).

There have been calls for ports to 'undertake a sustainable approach to disposal of ship generated waste, particularly with respect to recovery and recycling'(Butt, 2007). A major challenge for ports is to provide adequate facilities for waste from cruise ships. Although ships can incinerate some of their waste and dispose of bottom ash overboard in accordance with MARPOL 73/78, these can be used only when the ship is a minimum of 12 miles from land, or further in some sensitive areas such as parts of the Caribbean (Butt, 2007). Additionally, no plastic can be disposed of by incineration.

Despite the acknowledged demand for waste reception facilities, some ships are prevented from maximally recycling by lack of port storage or treatment facilities – Butt (2007) gives the example of one P & O cruise ship, which is incinerating paper waste rather than recycling it, due chiefly to a lack of onshore recycling facilities, in addition to a lack of available storage space on board.

It is due in part to examples like this that the IMO refers to 'the need to tackle the long-standing problem of the inadequacy of port reception facilities' as one of the main drivers to developing the previously-mentioned Guide to Good Practice (IMO, 2009).

This need to provide adequate facilities for responsible management of wastes also represents an opportunity. Sustainable management of organic wastes through anaerobic digestion has the potential not only to meet waste handling needs, but to introduce additional revenue streams for the port through the generation of electricity and/or heat. The aim of this study is to examine the possibility of introducing AD of food waste at the Port of Dover.

8.2 Port of Dover

The Port of Dover is Europe's largest international passenger ferry port and one of the world's busiest roll-on roll-off (ro-ro) ferry ports (Dover Harbour Board, 2012). It is also the UK's second busiest cruise ship port, with 17% of the cruise market, exceeded only by Southampton at 50% (Butt, 2007). As a major arrival port for ferries and cruise ships, the Port of Dover receives substantial amounts of waste and has the potential to make this into an opportunity for managing the waste in a sustainable and economically beneficial manner.

The Port is a trust port and statutory corporation established by Royal Charter in 1606. It is owned and administered by the Dover Harbour Board and covers a land area of 947 km^2, including the Port Zone and its terminals. The port facilities are divided into 2 main areas, the Eastern Docks and the Western Docks. The Eastern Docks are located to the east of the town centre, while the Western Docks lie to the south of the town centre. Traffic through the port includes ro-ro ferries and cargo ships, which primarily operate from the Eastern Docks, while the Western Docks contain two terminals for cruise liners, which are also used for grain exports out of season, in addition to an aggregates berth and a marina. Two bunker barges also operate at the port to provide low sulphur fuel to the ferries (Dover Harbour Board, 2010).

Figure 8.1 shows the location of main operational units of the port facilities.

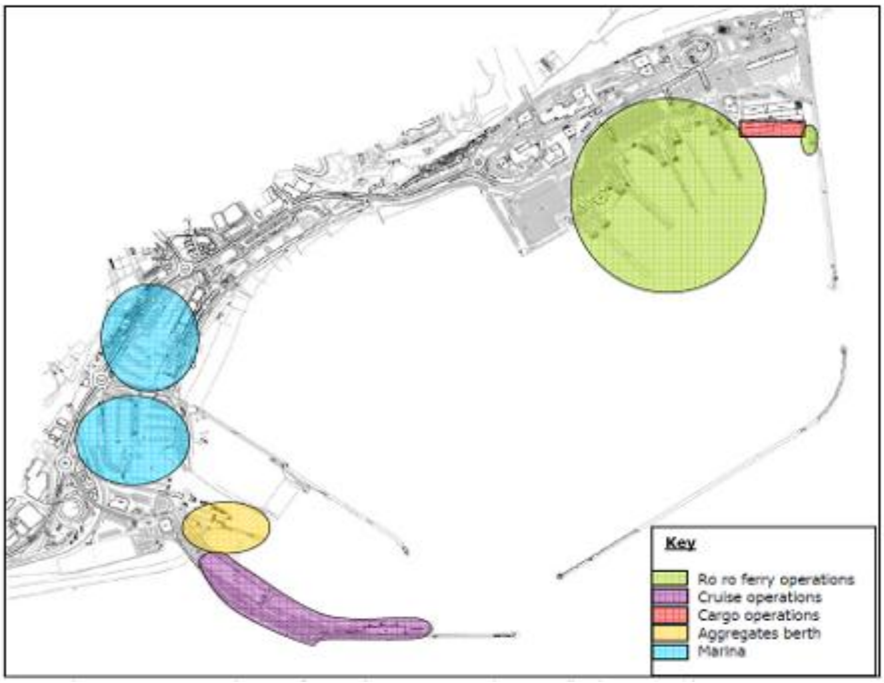

Figure 8.1 Shipping operations at the Port of Dover (Dover Harbour Board, Crown Copyright 2006)

The Dover Harbour Board (DHB), which manages the Port, has already made significant inroads toward new waste management solutions for the numerous waste streams handled at the Port. DHB recognises the importance of better waste management solutions for reducing costs and meeting environmental objectives set out in its Environmental Policy (Dover Harbour Board, 2011).

8.2.1 Area and Population Served

The Port hosts significant yearly passenger and freight traffic. Table 8.1 shows the numbers of vessels, passengers and freight tonnages passing through the Port from 2004-2011. Note that the term 'Vessels' denotes the number of vessel visits rather than separate vessels (e.g. a ferry that goes back & forth five times in a day is counted as five vessel visits).

Table 8.1 Port of Dover Cargo, Passenger and Vessel Traffic, 2004-2011 (Dover Harbour Board, 2012)

	2004	2005	2006	2007	2008	2009	2010	2011
Cargo-DCT								
Tonnes	263,885	165,176	201,390	259,557	209,399	230,000	272,336	291,110
Vessels	117	106	158	165	146	160	155	152
Pallets	183,646	121,144	150,782	208,936	165,471	167,358	802,578	883,075
Cargo-ED1-Livestock								
Tonnes	0	0	n/a	4,078	11,831	0	261	759
Vessels	0	0	106	92	69	0	2	8
Cargo-Grain								
Tonnes	47,574	79,340	58,443	47,710	29,464	19,679	35,668	31,201
Vessels	14	23	19	20	10	6	10	10
Aggregate								
Tonnes	247,033	224,344	187,009	235,000	181,473	151,529	132,247	102,541
Vessels	46	48	38	48	37	32	27	23
Marina								
Visiting Yacht Days	9,543	8,946	8,832	8,900	8,227	9,160	9,212	7,608
Cruise								
Passengers	178,847	159,226	215,624	212,496	273,817	286,034	307,223	223,825
Vessels	126	111	136	132	144	143	167	136
Ferries								
Vessels	22,402	20,432	21,413	21,440	20,617	20,742	19,837	17,443
Catamaran	2,964	3,054	1,337	1,251	1,095	581	0	0

The Port of Dover is interested in developing onsite waste management solutions, with a view to further increasing the sustainability of its operations and realizing commercial benefit from providing a waste management service. Being located next to the busiest shipping lane in the world, they see a potential market opportunity through assisting vessels in responsibly offloading their waste (Dover Harbour Board, 2012). They have already engaged in discussions with numerous suppliers of energy-from-waste technologies, to discuss the potential for energy from waste from the Port's MSW and/or International Catering Waste (ICW) streams.

DHB spent significant amounts on waste disposal, electricity consumption and carbon tax in 2011 (Dover Harbour Board, 2012), and expects these costs to increase significantly in the future. These costs are among the drivers for new waste management solutions. Through new waste management technologies, DHB hopes to:

- Minimise waste disposal and energy costs
- Maximise revenue from waste within the Port
- Improve the sustainability of port operations (Dover Harbour Board, 2012)

8.2.2 Site Characteristics and Waste Quantities

The port handles over 20 waste streams each year, of which the largest are MSW (approximately 750 tonnes per year) and ICW (approximately 330 tonnes per year). The cost of managing these two waste streams comprises 90% of the port's waste disposal budget (Dover Harbour Board, 2012).

Food Waste Quantity Estimates

The major food waste stream coming into the port is International Catering Waste (ICW), which are referred to as Category 1 ICW and defined in the Port of Dover Ships' Waste Management Plan (Dover Harbour Board, 2010) as "Any food waste and its packaging, such as tins, cardboard, glass jars, egg and milk cartons, from a means of transport operating outside the EU." Specific procedures are required, however, for ICW, as they are considered Category 1 Wastes and controlled under the Animal By-products (ABP) regulation.

The Port's monthly waste records from 2010 and 2011 give total waste amounts for Category 1 waste. However since this total includes both food waste and packaging, the amount of digestible material – food waste and some paper/card packaging – would need to be estimated. No composition audits of the waste have been carried out at the Port, and therefore the non-digestible fraction of the waste is unknown. For the purposes of this study, it will be assumed to be digestible.

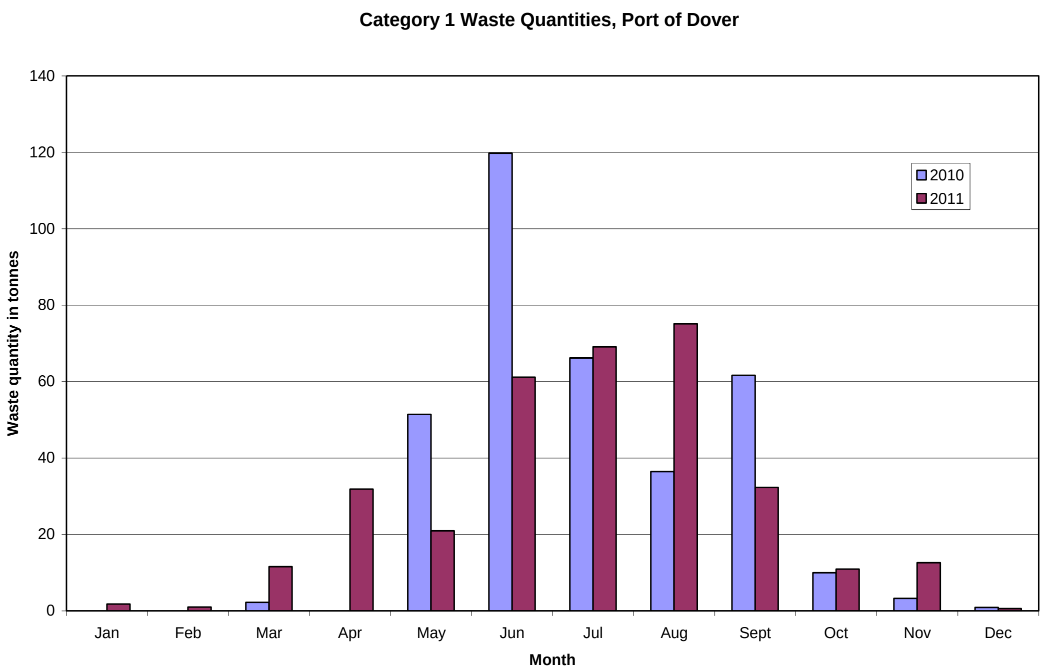

Figure 8.2 Port of Dover ICW waste quantities, 2010 and 2011 (Dover Harbour Board, 2012)

Onsite Land Availability

An anaerobic digester could potentially be located onsite if sufficient land area is available. The port is also preparing for a redevelopment of its Wellington Dock area, which could potentially be a good opportunity for infrastructure development for a district heating system (Dover Harbour Board, 2012). This could provide the necessary infrastructure for utilisation of heat from an onsite CHP or boiler associated with an AD plant.

Figure 8.3 Western Docks, Port of Dover

Figure 8.5 Eastern Docks, Port of Dover

Figure 8.6 Port of Dover marina, with cliffs in background

8.2.3 Current Transport and Processing Infrastructure

International Catering Waste

The numerous cruise ships, ferries and cargo ships that bring people and goods across the ocean from international destinations also bring with them significant amounts of waste from their onboard foodservice operations, which are then collected at the Port of Dover for disposal as international catering waste (ICW).

International catering waste is defined as catering waste that originates from means of transport operating internationally (i.e. outside of the EU), and is considered to be high risk category 1 animal by-product (ABP). This is based on the risk of the introduction of diseases to the UK from international transport (Defra, 2009). Therefore the control measures for ICW are very strict.

ICW from the Port of Dover is currently disposed by deep landfill.
The disposal site is Viridor's landfill site at Canterbury, a distance of 17 miles (27 km). The current cost for managing the ICW, including on-site management, transport and disposal, is approximately £94,500 per year, equating to about £286/tonne. The bulk of this cost is passed through to the carriers from which the waste originates as a disposal charge (Dover Harbour Board, 2012)

The port has considered the transport and traffic impacts of collecting waste; it is not likely to be a significant additional impact within the context of the high traffic levels currently seen by the Port (Dover Harbour Board, 2012).

Current Energy Use Onsite

The overall electrical energy demand is approximately 2 MW for the Eastern Docks and 1 MW for the Western Docks, totalling 3 MW for the port overall. The port has a small onsite CHP plant processing waste oil from offsite and providing electricity and heat at a reduced price. The CHP provides 150 kW of power and operates for 12 hours per day (Dover Harbour Board, 2012).

8.3 AD Modeling

Modelling was carried out using the anaerobic digestion model developed at the University of Southampton (Salter, 2010), to determine potential outcomes for an anaerobic digester at the Port of Dover.

The model was run using the average quantity of Category 1 ICW received by the Port of Dover of 350 tonnes per year (Dover Harbour Board, 2012).

8.4 Results and Discussion

Table 8.2 shows the outputs and savings that could potentially be associated with an onsite AD plant, depending on whether a boiler or CHP plant is used for biogas utilisation.

Table 8.2 Modeling Outputs for Onsite Anaerobic Digestion at the Port of Dover

Energy and material outputs (/year)	CHP	Boiler	
Digester input	350	350	tonnes
Digester capacity required	78	78	m^3
Digester retention time	74	74	days
Methane produced	32458	32458	m^3
Methane available	32133	32133	m^3
Biogas (volume)	55961	55961	m^3
Biogas (mass)	69	69	tonnes
Digestate	281	281	tonnes
Electricity produced	403	0	GJ
	111912	0	kWh
	13	0	kW generator
Heat produced	576	978	GJ
Upgraded biogas	0	0	m^3
Waste transport diesel	0	0	litres
Total energy output	978	978	GJ
Energy inputs required (/year)			
Waste transport	0	0	GJ
Digestate transport	32	32	GJ
CHP supplied electricity	50	0	GJ
Imported electricity	0	50	GJ
Boiler/CHP supplied heat	164	164	GJ
Imported gas for heat	0	0	GJ
Pasteuriser inclusion	pre	pre	digester
Pasteuriser heat	91	91	GJ
Total energy input	253	253	GJ
Energy exports			
Energy in methane produced	1163	1163	GJ
Exported electricity	352	0	GJ
	98	0	MWh
Exported heat	412	815	GJ
	114	226	MWh
Energy in upgraded CH4	0	0	GJ
Exported energy	764	815	GJ
Energy Balance	725	725	GJ
	2.1	2.1	GJ/tonne

An anaerobic digester at the Port of Dover could potentially produce 98 MWh of electricity and 114 MWh of heat using a CHP, or 226 MWh of heat alone with a boiler. A 13 kW generator is minimal in relation to the Port's overall 3 MW electrical demand, however the Port does have another example of a 150 kW CHP that meets some of the power requirements, and therefore another plant could also produce a small amount of supplementary power. An energy gain of 2.1 GJ/tonne of waste has a higher benefit than the current costly practice of deep landfill burial.

8.5 Conclusions

An onsite AD plant operating on international catering waste from the Port of Dover could potentially have a net energy yield of 725 GJ, or 2.1 GJ/tonne. This would meet only a very small fraction of the port's energy demand. Current regulatory requirements for international catering waste, however, would preclude the development of a digester for this waste.

8.6 Acknowledgements

Thanks to Keith Riley of Veolia and Bob Goldfield, Vicki Case, Jack Goodhew, David Parkes and Barbara Buczek of the Port of Dover who have provided information about the Port.

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9 Case Study of University of Southampton: Investigating the potential for onsite anaerobic digestion

9.1 Introduction

The University of Southampton is an example of a medium-sized University campus, with a number of characteristics that make it a distinct community, in some respects similar to a small town – its land area, population and the breadth of activities taking place within it require appropriate physical infrastructure and a range of services including accommodation, transport, retail, leisure, and food services (Zhang et al. 2011). It has significant requirements for energy and waste disposal, has its own landscaped grounds (and therefore demand for soil amendment), and has substantial volumes of food waste, paper and card waste, and green waste.

9.2 University of Southampton

9.2.1 Area and Population Served

The University of Southampton has just over 5,000 staff and a student community of approximately 23,000. It has a total of five campuses, four of which are located in the city of Southampton, and the fifth in Winchester; a future sixth campus is being developed in Iskandar, Malaysia. The campuses within Southampton are the Highfield Campus, Avenue Campus, Southampton General Hospital and National Oceanography Centre Southampton (NOCS). The main campus is the Highfield campus, and the closest to this is the Avenue campus, which lies within 2 km of the main campus. There are also a number of halls of residence within a 5 km radius of the Highfield campus. This case study will focus primarily on the Highfield and Avenue campuses, and the halls of residence. The Hospital, NOCS and Winchester campuses are left outside of the scope of this study due to their geographical distance. According to data provided by the Student & Academic Administration Department, Management Information Team (miteam@soton.ac.uk) the student population served by the Highfield and Avenue campuses was approximately 19,200 students as of December 2012, and from this 4,200 of the staff were estimated to be based at the two campuses. The overall numbers also include part-time students and staff, and therefore do not fully reflect the number of people using the two campuses each day, but provide an estimate.

Figure 9.2 Highfield campus map

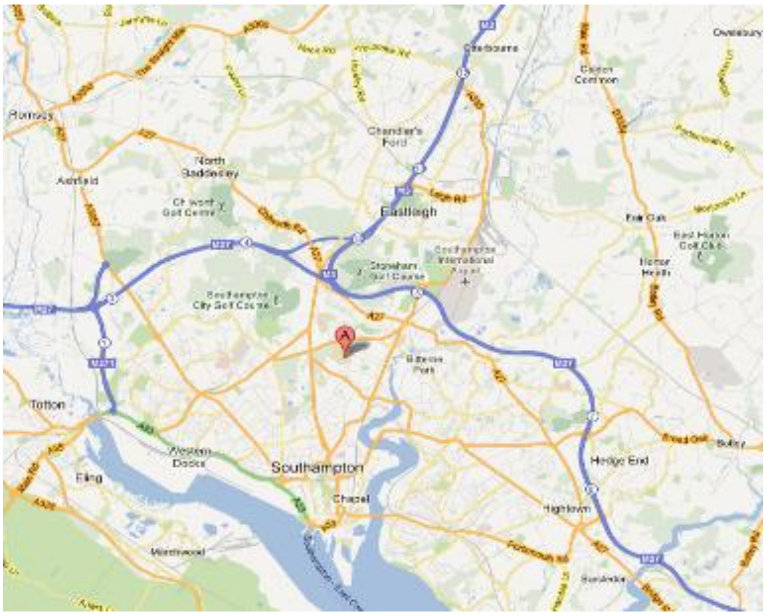

Figure 9.1 Location of University of Southampton, Highfield campus

There are a number of halls of residence in close proximity to the Highfield campus. Each provides accommodation for the 30 weeks of the school year for undergraduate and postgraduate students. Their names and sizes are shown in Table 9.1. The halls of residence provide housing for a total of 4,634 students during the academic year.

Table 9.1 Halls of Residence serving Highfield and Avenue Campuses

Hall of Residence	Number of Students
Bencraft Court	228
Gateley Hall	160
Highfield Hall	180
Romero Hall	254
Shaftesbury Flats	10
St. Margaret's House	96
Montefiore Cluster	1472
Glen Eyre Cluster	1919
Total	4634

9.2.2 Site Characteristics and Waste Quantities

The campus buildings comprise lecture and study halls, libraries, office space, catering facilities and sports and entertainment facilities. There are also landscaped grounds with extensive grass coverage, as well as shrubs and trees. The various activities on the campus give rise to discarded paper and cardboard, food waste, and green waste, three potential substrates for anaerobic digestion (AD) in addition to other waste streams such as dry recyclables and general refuse.

Waste Collection and Measurement

The Estates and Facilities department at the Highfield Campus is responsible for the contracting of waste collection and management services at the Highfield and Avenue campuses, and halls of residences in Southampton, as well as the Winchester campus. The other campuses are responsible for their own wastes.

General waste is collected across campus in lined bins. The liners are then collected by facilities staff and placed into 1100 litre bins which are weighed and collected by the waste contractor.
According to the University's webpages (University of Southampton, 2012), the University produced a total of 2000 tonnes of waste in 2008/2009, approximately 45% of which was recycled. Waste audit results indicated that up to 67% of the waste is potentially recyclable.

Food Waste Quantity Estimates
Food waste comprises approximately one quarter of the University's general waste (Fidoe 2010). There are a number of catering outlets on campus as well as student halls of residence with foodservice and self-catered kitchen facilities. The largest catering outlet is the Staff Club, on the Highfield campus, providing food service for faculty and post-graduate researchers. It includes cafes, sandwich bars and hot food counters, with accompanying kitchens and prep areas. The Piazza in the students' union building, also on the Highfield campus, has a number of hot food counters and cafes, providing food primarily for students. In addition to these two main catering units, there are a number of smaller lunch counters and cafés in various buildings on the two campuses (the Life Sciences building, Avenue Humanities building, Hartley Library and Nuffield Theatre).

A food waste study was carried out in the academic year 2009-2010 (Fidoe, 2010) determining the quantities of food waste being produced at the time, by tallying bin weights for the general waste bins outside of the main catering facilities and multiplying this by a factor of 55%, the percentage of the waste estimated to be food waste, according to earlier composition studies of waste from those areas of the campus (Shi 2006).

At the time of the study, data from 2009 onward was not yet available and therefore bin weights from the years 2006-2008 were compiled to give average monthly data over 3 years. The average food waste produced in each month was calculated by applying the food waste composition factor of 55%; this is shown in Table 9.2.

Table 9.2 Estimate of food waste available for digestion from major catering outlets on campus – before introduction of source separation program (2009)

	Total Waste collected (tonnes)				Food waste
Month	2006	2007	2008	Average	(tonnes)
Jan	-	14.9	7.5	11.2	6.2
Feb	-	-	17.3	17.3	9.5
Mar	-	13.7	7.9	10.8	6.0
Apr	-	13.8	-	13.8	7.6
May	-	16.6	-	16.6	9.2
Jun	12.3	6.9	5.6	8.3	4.6
Jul	14.2	-	3.8	9.0	5.0
Aug	8.0	9.8	6.1	8.0	4.4
Sep	10.6	8.2	1.5	6.7	3.7
Oct	21.6	-	10.9	16.2	9.0
Nov	24.2	19.3	13.6	19.0	10.5
Dec	8.9	10.2	5.9	8.3	4.6
Total annual quantity					**80.1**
Average monthly quantity					**6.7**

By these calculations, there is an estimated annual quantity of 80.1 tonnes of food waste from the major catering outlets, producing an average of 6.7 tonnes of food waste each month.

Separate Food Waste Collection

A separate food waste collection program is now being rolled out at the Highfield and Avenue campuses. Beginning in the autumn of 2010, separate food waste bins have been provided at the main catering outlets, in the kitchens and customer areas. Small kitchen caddies have also been provided to kitchenettes and staff tea break areas in the academic buildings, plus a small pilot in self-catered kitchens of student halls of residence. The kitchen caddies and canteen bins are regularly emptied into separate food waste wheelie bins by cleaning staff. There are currently 24 wheelie bins of 240-L capacity provided on the University sites, and 190 kitchen caddies. Figure 9.3 shows the bins provided in kitchenettes and canteens.

Figure 9.3 Food waste receptacles at the University. Left: Kitchen caddy. Right: Canteen bins.

At the time of this study, data on waste quantities collected was available from the start of the program in October 2010 up to April 2012.

Table 9.3 Quantities of food waste collected in early stages of source separation program (2012)

	Food Waste collected (tonnes)		
	2010	2011	2012
Jan		1.4	6.3
Feb		1.7	8.9
Mar		2.2	5.8
Apr		2.5	3.8
May		4.7	
Jun		3.5	
Jul		3.3	
Aug		3.5	
Sep		3.5	
Oct	0.4	6.5	
Nov	1.5	9.4	
Dec	0.6	5.2	
Total	**2.5**	**47.3**	**24.7**
Monthly Average	**0.8**	**3.9**	**6.2**

In the 19 months since the commencement of the program, a total of 74.6 tonnes of food waste have been collected from the University's sites within the city of Southampton (two campuses and three halls of residence: Highfield campus, Avenue campus, Connaught Hall, Glen Eyre Hall, Highfield Hall). In the most recent year of the program, the monthly average food waste collected was 6.2 tonnes, similar to the figure estimated earlier.

Commencing in the summer of 2012, separate food waste collection will be provided to the self-catered kitchens in all halls of residence, for a total of 655 kitchen caddies once the program has been fully rolled out.

The quantity of food waste that could be generated from the halls of residence can be estimated by extrapolation of household food waste quantity data. At an average waste generation rate of 50 kg $person^{-1}year^{-1}$, over the course of the 30-week academic year this would be equal to 28 kg per student. Some of this quantity is already being collected, however, as the first phase of the program has included the catering facilities provided in Connaught Hall, Highfield Hall and part of the Montefiore cluster. These serve an estimated 700 students, which, subtracted from the total of 4,634 students in residence, leaves a total of 3,934 students to which the food waste collection system will be rolled out in the next year. At a food waste production rate of 28 kg per student, this could yield approximately 110 tonnes per year of additional food waste, or 9 tonnes per month.

The monthly tonnages will increase as the program is rolled out to further locations including all of the halls of residence. In addition, in two of the academic buildings the University is currently trialling a two-bin system in which one container is provided for food waste and a second for mixed recycling; no container is provided for general refuse. The University's contractor can process the majority of dry wastes at their Materials Recycling Facility, thus allowing the provision of general waste containers to be omitted. This is hoped to save money on refuse disposal and increase participation in recycling, with a resulting increase in diversion rates.

Another factor that should act to increase quantities of food waste collected is increasing participation rates as users become familiar with the food waste bins and kitchen caddies.

Green Waste

The landscaping activities of the University produce a significant amount of green waste from grass cutting, and clippings of trees and shrubbery. There is a small open windrow composting area on site for trimmings, as well as a wood chipper for woody wastes to be used as mulch on flowerbeds to discourage weed growth. Grass clippings may be composted or left where cut to decompose and return nutrients to the soil naturally. The University does not have data on the volumes of green waste produced, as these wastes are not tracked. It would, however, be possible to process some of these wastes in an anaerobic digester if this were found to be more beneficial for economic or environmental reasons.

For this reason, Mulley (2006) developed an estimate of the amount of grass cuttings produced annually on campus. This study used aerial photographs of the University to calculate the campus area covered by grass, then combined this with data provided by Estates and Facilities on the volume of grass collected from cutting a known area and the frequency of cutting over a year. After converting this volume to mass, it was estimated that 242 tonnes per year of grass cuttings are produced at the University, an average of 20 tonnes per month (Mulley 2006; Fidoe 2010).

Paper and Cardboard Waste
There is a mixed recycling program on campus for a range of dry recyclables including plastic, glass and metal containers, as well as paper and cardboard. The University's 1100 litre mixed recycling bins are weighed as they are emptied, giving the total weight of all the waste the University recycles. An estimate of the paper and card was made from summer 2009 figures. The estimated total weight of recyclable material was 156 tonnes for 3 months.

Out of this mixed recyclables stream, the proportion comprised by paper and cardboard was calculated by comparing the weights of smaller bins that were streamed by recyclable material. These smaller bins were also weighed before emptying into the larger bins. From this weight comparison it was determined that 94% of the recyclable stream was paper and cardboard. This gives a total of 49 tonnes of paper/card sent for recycling each month (Fidoe, 2010).

9.2.3 Current Transport and Processing Infrastructure

Food Waste
Food waste collected from the campus is picked up by the University's collection contractor, Eco Food Recycling Ltd, and taken for in-vessel composting at the company's site in Parley, Bournemouth, a distance of 50 km from the University.

Green Waste
As stated previously, the current management of green wastes is primarily through use as mulch, via chipping for woody wastes, and leaving grass clippings on the lawns where they are cut. Costs for managing this waste are therefore minimal, and alternative use of the green waste would not have avoided disposal costs. However the use of green waste could increase the amount of energy produced by an anaerobic digester and thus have a positive impact on the economics of the digester.

Paper/Card Waste and General Refuse
Recycling and general refuse are both collected by the University's general waste collection contractor (Greenstar, a subsidiary of Biffa). As part of the recycling stream, paper/card waste is taken to a Materials Recycling Facility (MRF) in North London, a distance of 209 km. General refuse is taken to a landfill in Squab Wood, Romsey, a distance of 16.6 km. Diverting food waste, and some paper and card to digestion would save on transport emissions and the energy associated with the sorting and reprocessing of the material.

9.2.4 Current Energy Production and Use On Campus

The University has two natural gas-fired CHP plants which operate with a 37.2% electrical efficiency (Fidoe, 2010). These provide approximately half of the total heat and electricity demand of the campus (M. Turner, 2012 *pers. comm.*) and are fired by natural gas, which could be partially replaced by biogas from an AD plant. The Highfield campus has an average energy demand of 3100-3500 MWh per month during the winter (ICT, 2012). There is also a six-lane 25 metre-length swimming pool on campus, which could be a suitable heat load for a CHP or boiler running on biogas from an anaerobic digester.

9.3 AD Modelling

Modelling was carried out using the anaerobic digestion model developed at the University of Southampton (Salter, 2010), for the following four scenarios.

Model Run 1 – Food Waste only
The model was run using the current quantities of food waste collected in the source separated collection system only, with no green waste or paper/card added. This is a total estimated quantity of 75 tonnes per year of food waste.

Model Run 2 – Full Food Waste Rollout
The second model run was based on the estimated quantities of food waste that could be collected once rollout to all halls of residence is complete, for a total estimated food waste quantity of 185 tonnes per year. Again no green waste or paper/card was included in this scenario.

Model Run 3 – Full Food Waste Rollout Plus Paper/Card
The third model run was based on the estimated full rollout food waste quantity of 185 tonnes per year, with an additional 75 tonnes per year of paper and card waste (to give a C:N ratio of 30).

Model Run 4 – Full Food Waste Rollout, Plus Paper/Card and Green Waste
The fourth model run was based on the estimated full rollout food waste quantity of 185 tonnes per year, plus all campus grass clippings estimated at 242 tonnes per year, plus all paper and card waste – an additional 585 tonnes per year (to give a C:N ratio of 30).

Savings and Offsets in Energy, Waste Disposal and Greenhouse Gas Emissions
After calculating the outputs of the digester, a second set of calculations were carried out to quantify savings in energy, waste disposal and greenhouse gas emissions. These are described below.

Energy
The Highfield campus has an average energy demand of 3100-3500 MWh per month during the winter (ICT, 2012) and energy produced from an on-campus anaerobic digester processing wastes from the University would only ever meet a small portion of that. A more representative example would be the energy load of a single building, such as Building 38, in which the Staff Club catering facilities are housed. This building had an average electrical consumption of 41 MWh per month from April 2011 – April 2012, and average heat consumption of 59 MWh per month over the same period.

The University's average cost for electricity is approximately 10.5 p/kWh, and for heat approximately 3.7 p/kWh (as calculated from ICT, 2012).

Waste
There is now separate food waste collection at the University with food waste taken to a site in Bournemouth for in-vessel composting. There is an AD plant under development in the same area, which will receive the University's food waste, once operational.

The University's current cost for the food waste collection service is approximately £9,000 per year. The cost of £9,000 divided by the current collected tonnage of 75 tonnes per year gives an overall cost of £120 per tonne. If the food waste collection system were not in place, food waste would remain a part of the general waste stream, and be sent to landfill. For general waste the University pays £3.99 per bin for transport, and disposal cost of £108/tonne which includes the Landfill Tax and gate fee for the landfill site. There is also a rental charge of £0.20 per day per bin.

Paper and cardboard are part of the recycling stream, for which the University pays a fee of £5.75 per bin plus £0.20 per day bin rental. Although collection bins would still be required, diverting food waste to an onsite AD plant would decrease the tonnages of food waste and recyclable paper being transported and processed offsite.

9.4 Results and Discussion

Tables 9.4 and 9.5 shows the outputs and savings that could potentially be associated with an onsite AD plant, depending on whether a CHP (Table 9.4) or boiler (Table 9.5) is used.

The tables above show that, depending on the waste streams processed, an onsite AD plant could provide sufficient electrical power and heat to meet a portion of the energy demand of the Staff Club catering facility’s building – this would range from the small fraction of 3% of its heating and electrical needs if only the current food waste quantities were processed, up to 79% of its electrical and 84% of its heat requirements if all food wastes, green wastes, and paper and card from the two campuses and all halls of residence were processed. If a boiler were used, the amount of heat that could be supplied ranges from 6% of the building’s heat requirements for the current food waste scenario, up to 156% of its heating requirements – ie., sufficient heat for this building plus surplus heat which could be used in other buildings.

In terms of the overall campus, the highest output would only ever meet a fraction of the overall energy demand, which exceeds 3100 MWh per month in the winter. The exported energy of 2-4 GJ/tonne, however, represents an energy benefit from the waste that is not currently being realised under the current offsite composting system.

Table 9.4 Modelling Outputs for Onsite Anaerobic Digestion at Southampton University – CHP

Energy and material outputs (/year)	Run 1 - Current Food Waste	Run 2 - Full Rollout Food Waste	Run 3: Full Rollout Food Waste plus some Paper/Card	Run 4: Full Rollout Food Waste, Green Waste, Paper/Card	
Digester input	75	185	260	1012	tonnes
Digester capacity required	17	41	100	546	m^3
Digester retention time	74	74	128	179	days
Methane produced	6955	17156	32817	153196	m^3
Methane available	6886	16985	32489	151664	m^3
Biogas (volume)	11992	29580	55452	257686	m^3
Biogas (mass)	15	37	68	315	tonnes
Digestate	60	148	192	697	tonnes
Electricity produced	86	213	407	1901	GJ
	23981	59154	113151	528211	kWh
	3	7	14	63	kW generator
Heat produced	123	304	582	2716	GJ
Upgraded biogas	0	0	0	0	m^3
Waste transport diesel	0	0	0	0	litres
Total energy output	210	517	989	4618	GJ
Energy inputs required (/year)					
Waste transport	0	0	0	0	GJ
Digestate transport	7	17	22	79	GJ
CHP supplied electricity	11	27	32	76	GJ
Imported electricity	0	0	0	0	GJ
Boiler/CHP supplied heat	43	91	146	504	GJ
Imported gas for heat	0	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	pre	digester
Pasteuriser heat	19	47	65	254	GJ
Total energy input	64	140	209	684	GJ
Energy exports					
Energy in methane produced	249	615	1176	5487	GJ
Exported electricity	76	186	375	1826	GJ
	21	52	104	507	MWh
Exported heat	80	213	436	2213	GJ
	22	59	121	615	MWh
Energy in upgraded CH4	0	0	0	0	GJ
Exported energy	156	399	811	4038	GJ
Energy Balance	146	378	781	3933	GJ
	2	2	3	4	GJ/tonne

Table 9.5 Modelling Outputs for Onsite Anaerobic Digestion at Southampton University – Boiler

Energy and material outputs (/year)	Run 1 - Current Food Waste	Run 2 - Full Rollout Food Waste	Run 3: Full Rollout Food Waste plus some Paper/Card	Run 4: Full Rollout Food Waste, Green Waste, Paper/Card	
Digester input	75	185	260	1012	tonnes
Digester capacity required	17	41	100	546	m^3
Digester retention time	74	74	128	179	days
Methane produced	6955	17156	32817	153196	m^3
Methane available	6886	16985	32489	151664	m^3
Biogas (volume)	11992	29580	55452	257686	m^3
Biogas (mass)	15	37	68	315	tonnes
Digestate	60	148	192	697	tonnes
Electricity produced	0	0	0	0	GJ
	0	0	0	0	kWh
	0	0	0	0	kW generator
Heat produced	210	517	989	4618	GJ
Upgraded biogas	0	0	0	0	m^3
Waste transport diesel	0	0	0	0	litres
Total energy output	210	517	989	4618	GJ
Energy inputs required (/year)					
Waste transport	0	0	0	0	GJ
Digestate transport	7	17	22	79	GJ
CHP supplied electricity	0	0	0	0	GJ
Imported electricity	11	27	32	76	GJ
Boiler/CHP supplied heat	43	91	146	504	GJ
Imported gas for heat	0	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	pre	digester
Pasteuriser heat	19	47	65	254	GJ
Total energy input	64	140	209	684	GJ
Energy exports					
Energy in methane produced	249	615	1176	5487	GJ
Exported electricity	0	0	0	0	GJ
	0	0	0	0	MWh
Exported heat	166	426	843	4114	GJ
	46	118	234	1143	MWh
Energy in upgraded CH4	0	0	0	0	GJ
Exported energy	166	426	843	4114	GJ
Energy Balance	146	378	781	3933	GJ
	2	2.0	3.0	3.9	GJ/tonne

9.5 Conclusions

An onsite anaerobic digester for the Highfield and Avenue campuses, processing food waste only or food waste with paper/card and green waste, could generate a net energy output of from 2-4 GJ/tonne, depending on the waste stream processed and the mode of biogas utilisation. This would provide sufficient energy to meet from 3%-80% of the staff canteen's electrical and heating needs.

9.6 Acknowledgements

The authors wish to thank Mike Travers and Mark Turner of the Estate and Facilities department at the University of Southampton for their help in supplying data on the University's waste and energy management.

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10 Case Study of Indian Institute of Technology (IIT) Delhi: Investigation of potential for onsite AD

10.1 Introduction

The present study conducted at IIT Delhi was undertaken to analyse the waste generation potential in the campus, its potential to generate biogas and the techno-economic feasibility of biogas as a replacement cooking fuel. It therefore had the following objectives:

1. To analyse the quantities of biodegradable waste generation rates in IIT campus.
2. To analyse biogas production potential from the available food wastes.
3. To make a techno-economic feasibility analysis for biogas production and its application.
4. To calculate the reduction in the GHG emissions by replacement of liquefied petroleum gas (LPG) as a cooking fuel.

10.2 IIT Delhi

IIT Delhi campus is situated at Hauz Khas in South Delhi and extends to an area of 1.3 km^2 (Figure 10.1). Bounded by the Sri Aurobindo Marg on the east, the Jawaharlal Nehru University Complex on the west, the National Council of Educational Research and Training on the south, and the New Ring Road on the north, the Institute campus is flanked by Qutub Minar and the Hauz Khas monuments. Well connected to the major city centres by road, the Institute campus is about 19 km from the Delhi Main Railway Station, 14 km from the New Delhi Railway Station, 21 km from the Inter-State Bus Terminal and 10 km from Delhi Airport. With topographical features imaginatively laid out in a picturesque landscape, numerous buildings of different types and wide roads, the campus presents a spectacle of harmony in architecture and natural beauty.

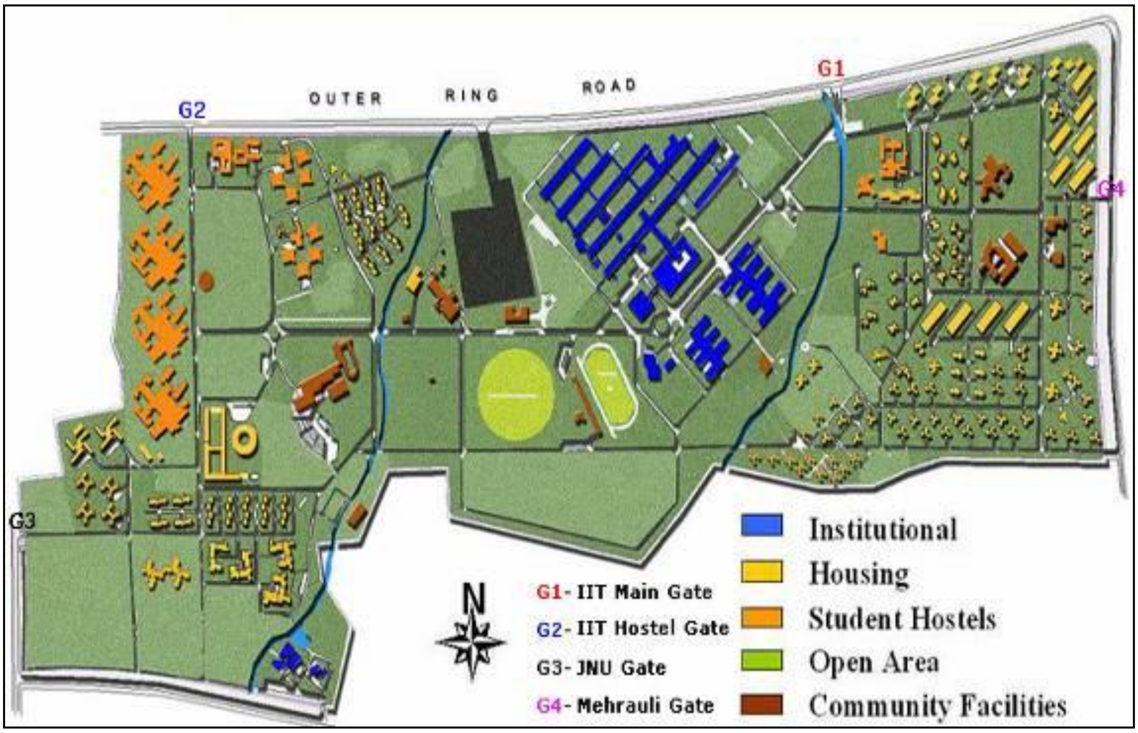


Figure 10.1 Geographical layout of IIT Delhi campus
(Source: http://www.iitd.ac.in/content/map-and-location)

The campus area is divided into four functional zones:
- Residential zone for students;
- Residential zone for the faculty and staff;
- Academic zone for academic buildings and workshops; and
- Cultural-social and recreational zone for students.

As the site is elongated in shape, the last two zones are located mid-way between the two residential zones in order to reduce walking distance. The main academic building accommodates various teaching and research activities. The campus also offers amenities such as a staff club, hospital, shopping centre, bank, post office, telecom centre, community centre, stadium, playing fields, etc.

IIT Delhi has 13 Departments, 11 Centres, 2 Schools, 450 Faculties, 1175 Staff members and about 5000 students. It has 12 hostels (10 boys and 2 girls) and approximately 1600 family residences that make it a fully residential campus for all faculty, staff members and students with a total population of about 15,000.

10.3 Food waste survey and collection

Previous work in the VALORGAS project has shown that food waste collected from different sites in Europe is similar in composition and characteristics (see deliverable D2.1), but no data were available on the quantities or characteristics of food waste from IIT Delhi. A survey was therefore conducted to determine the type and amount of waste generated on the IIT campus.

At the primary level, information about the wastes collection, frequency of collections and types of vehicles used was gathered by personal interaction with sanitary inspectors at IIT, the waste collection contractor, rag pickers and the workers who segregate the waste. Data was collected on the different types of waste-generating sites (domestic properties, restaurant and catering facilities, food markets and hostel messes and canteens), waste segregation methods, present use of waste and dumping sites for non-biodegradable wastes.

At the secondary level physical quantification and qualification of waste was done with 20 households (out of 1600), 12 hostel messes and 4 canteens in IIT. The survey was carried out in two seasons, one in summer and the other in winter, to check for seasonal variations in food waste generation. The residents, the person in charge of the hostel and the canteen owners were supplied with two bins and plastic bags free of charge. The supply of plastic bags and bins encouraged active participation of the people in IIT Delhi. Sets of two dustbins (1 green for biodegradable and 1 for non-biodegradable waste) were installed in the households, hostel messes and canteens for quantification and characterisation of the waste generated in the campus. The workers of the waste collection contractor daily collected the wastes from the bins kept in the households and canteens by means of a bicycle or tricycle. Regular daily feedback was compiled from the workers to evaluate the pattern of the waste generation and collection in the campus. The waste was collected in black plastic bags. The worker was given the responsibility to write the type of waste (biodegradable or non biodegradable) on the plastic bag using a sticker and a marker. The segregated waste was weighed on a balance at the dumping ground. Data was collected regularly for a month and the average of the weights was calculated. Figure 10.2 illustrates the methodology adopted for the waste collection in the campus.

a) and b) Colour-coded waste collection bins

c) Biodegradable waste collection trolley

d) People segregating the waste

e) Segregated biodegradable waste

f) Segregated polyethylene waste

g) Segregated rubber & biomedical waste

h) Segregated glass bottle waste

Figure 10.2 Waste collection trials at IIT Delhi

10.3.1 Characterisation of food waste and feedstock preparation

Food waste for biochemical evaluation was collected from the staff canteen of IIT after lunch at between 3:00 - 4:00 pm. The feedstock for the experiments consisted mostly of cooked food such as rice, pulses, cooked vegetables like potato, peas etc, pieces of Indian bread (chapattis) and leavened bread. The food waste was shredded in a grinder to reduce the particle size as well as for proper mixing of the waste material. The biochemical parameters are based on analyses of 6 samples (3 in summer and 3 in winter). The analytical methods used for the biochemical characterisation such as TS, VS, moisture, fat, sugars, proteins, hemicellulose, cellulose etc were according to Standard Methods (APHA, 2005). pH value was determined using a pH pen (Hanna instruments).

10.3.2 Semi - continuous digestion trial

To evaluate the biogas generation potential of the food waste a semi-continuous digestion trial was carried out. The food waste feedstock for the trials was taken from the staff canteen and prepared as described above. The trial was carried out in summer at ambient temperatures in the mesophilic range (around 32 °C) (Figure 10.3).

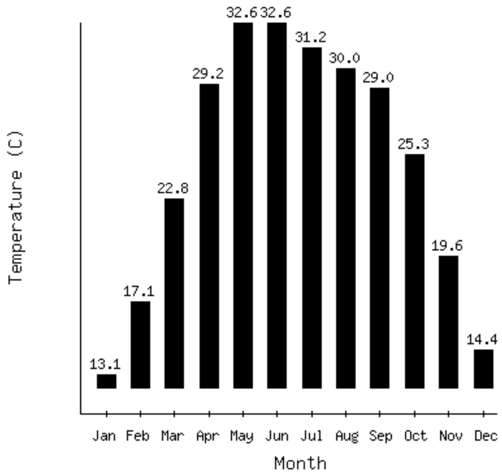


Figure 10.3. Monthly temperatures in Delhi, India (Observation period: 1995/1 - 2009/11) http://mohapl.dyndns.org/temptrendmon/INDELHI.html?city=Delhi&country=India&region =Asia&units=C

The digester used was cylindrical in shape, and of the floating dome type (Figure 10.4). . The digester had a total and working volume of 300 L and 280 L respectively and the dome had a volume of 150 L. It was equipped with gas and effluent outlets and a feeding inlet. A semi continuous mode of feeding was followed followed by withdrawing a known quantity of digestate every day.

To provide a source of microorganism-enriched inoculum digestate was taken from an existing biogas plant in the campus operating on cow dung. 280 L of cow dung digestate was prepared by diluting with water in the ratio of 1:1. For the first month, the digester was left undisturbed and without feeding. After this, it was fed with the homogeneous ground mixture of food waste from the staff canteen for five successive weeks, on a feed of 1.5 kg food waste

+ 5 kg water After stabilisation of the digester the solids content was increased from 5% TS to 10 % TS by reducing the quantity of water in the feedstock mix to 1.5 kg.

Gas Measurements: Daily biogas production was measured using the gauge on the dome (Figure 10.4), and the volume was then converted to and expressed as the volume under standard temperature and pressure (STP, 0 °C, 1 atm). Methane and carbon dioxide in the biogas were measured using a gas chromatograph (Agilent GC).

Figure 10.4 Experimental semi-continuous biogas plant installed in the campus

10.4 AD Modelling

The University of Southampton's AD model was run using the waste quantities estimated for the IIT Delhi campus. The potential outputs of a CHP and boiler were determined, but as the more likely use for biogas in this situation would be direct use of the gas as a replacement for LPG, the potential outputs for upgrading and compressing the gas. Instead of the model's default values for food waste parameters, these were substituted by the empirically-determined values found in the laboratory study, as follows: TS 24% ; VS 93% of TS ; methane yield 0.3 m^3 $kgVS^{-1}$; methane percentage 55%.

10.5 Results and discussion

10.5.1 Survey and collection of the food waste in IIT Delhi

Primary level. Data and information gathered by personal interaction with sanitary inspectors at IIT, waste collection contractor, rag pickers and the workers who segregate the waste are tabulated in Table 2.

Table 10.1 Collection parameters for food waste collection in the campus

No	Parameter	Result
1.	Type of vehicle used for collection	Tricycle-Rickshaw and bicycle
2.	Frequency of collection	Once daily –in the morning
3.	Population served	Residential Houses(1600),canteens and hostel messes
4.	Collection at hostel mess and canteens	By piggery waste collectors in the morning
5.	Total manpower involved in the collection of waste in the campus	50 workers

Data on the different types of waste-generating sites (Hostels, Residential areas and Academic areas), levels of awareness about biogas production from food waste, present use of waste and dumping sites for non-biodegradable wastes were also collected by interviewing the owner of the facility.

Secondary level - waste quantity and quality. The food waste generated in the campus is from three categories:

Residential households: Total waste – app **1000** kg day^{-1}
Canteens: 4 canteens – 20 kg food waste day^{-1} per canteen, Total waste – app **80** kg day^{-1}
Hostels: 10 boys hostels - average 43 kg day^{-1}, total **430** kg day^{-1}; 2 girls hostels - 45 kg day^{-1} per hostel, total **90** kg day^{-1}.

The total amount of food waste generated in the campus is approximately **1600** kg per day. The results are summarised in Table 10.2.

Table 10.2 Data on the different types of waste generating sites in the campus

No.	Waste generating site	Number	Population Served	Sampling	Quantity of wastes generated	Total
1.	Horticulture waste	Gardens and lawns	In spring and autumn	10 per season	1 tonne	1 tonne day^{-1}
2.	Residential households	1600 households	Average 4 per household = 6400 residents	20 households (out of 1600),average of 30 days collection data	600-700 g day^{-1} per household	1000 kg day^{-1}
3.	Canteens	4	200	Average of 5 days data per season(summer and winter)	20 kg day^{-1} per canteen	80 kg day^{-1}
4.	Hostel messes	10 boys hostels and 2 girls hostels	Average 400 students per hostel = 5400	Average of 5 days data per season(summer and winter)	Average 43 kg day^{-1} per hostel	520 kg day^{-1}

10.5.2 Characterisation of the food waste

The food waste composition expressed on a % dry weight basis is shown in Table 4. Mostly the waste is found in the acidic range. All the samples have high VS% content which indicated that the food waste is a rich nutritive resource. The characterisation also revealed variability in the TS content of the waste due to more watery food in summer, and variability between the other parameters due to the variation in the food cooked in the canteen per day. The characterisation of the food waste suggested that proper mixing of the food waste by using a grinder or a pulveriser is necessary in order to provide a balanced feedstock for AD.

Table 10.3 Average chemical composition of food waste

Parameter	**Summer** (Average of 3 samples)	**Winter** (Average of 3 samples)
Moisture	78.5%	73.5%
Total Solids (TS)	21.5%	26.5%
Volatile Solids (VS) (% of TS)	94%	93%
Ash	6%	7%
Carbon	65.7%	52.3%
Nitrogen	3.8%	2.90%
pH	4.9	5.2
COD gm/l	282.65	378.82
C/N ratio	17.3%	18.03%
Fat	4.5%	5.2%
Sugars (reducing)	7.2%	5%
Cellulose	9.2%	10.8%
Hemicellulose	3.3%	2.9%
Protein	23.5%	18.12%

The solids contents of the food waste as shown in Table 10.3 are similar to those of food waste generated in Europe (VALORGAS deliverable D2.1). The nitrogen contents on a wet weight basis (8.2 and 7.7 g kg^{-1} in summer and winter samples, respectively) are also comparable to European food waste. This indicates that digesters fed with IIT food waste may face the same challenges of high ammonia concentrations. The fat content, however, is much lower than in European food waste, which is typically ~15% of total solids. The relatively lower fat content in IIT food waste may alleviate some possible negative effects of fatty materials on digester operation, but this will also lower the specific methane potential.

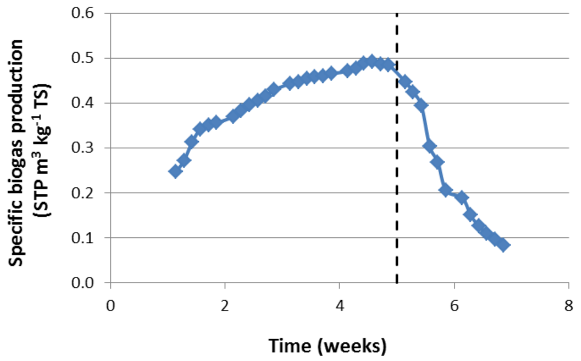
10.5.3 Semi-continuous digestion experiments

The feeding pattern during the experimental period is summarised below. Observations made on the biogas produced and on its composition are presented in Figures 10.10 and 10.11.

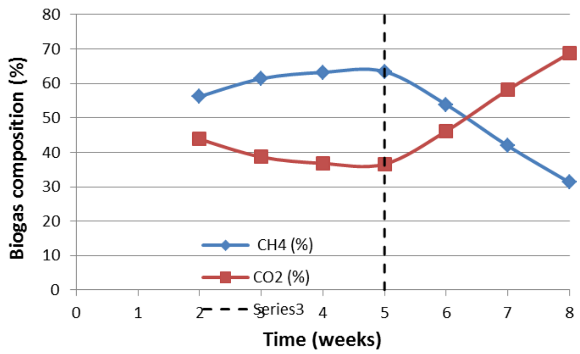
Table 10.4 Feeding pattern followed during the digestion period

Week	**Feed**	**Loading rate**	**Hydraulic retention time**
-4 to 0	Start-up initiated by charging the digester with appropriately diluted cow dung, then no feed for the first month	0	-
1 to 5	1.5 kg of food waste + 5 kg of water per day	1.2 kg TS m^{-3} day^{-1}	43 days
6 to 7	1.5 kg of food waste + 1.5 kg of water per day	1.2 kg TS m^{-3} day^{-1}	93 days

After feeding on food waste, there was a concomitant increase in the biogas yield in the first 3 weeks. The average biogas yield in week 4 and 5 reached around 0.48 STP m^3 kg^{-1} TS. The biogas methane content stabilised at around 60 %.The feeding strategy was then changed as shown in Table 10.4 with reduced water addition. This coincided with a rapid reduction in biogas production and a fall in biogas methane content. During the two weeks after the change in feeding the biogas yield decreased sharply, to 0.34 STP m^3 kg^{-1} TS in week 6 and 0.12 m^3 kg^{-1} TS in week 7 (Figure 10.5a). The biogas methane content was continuously monitored after digester feeding ceased at week 8, and it can be seen from Figure 10.5b that the methane percentage further dropped to 30% even one week after feeding ceased. The reasons for this failure were not clear but the work carried out indicated a potential biogas yield of ~0.5 m3 kg-1 TS from the campus food waste.



a) Specific biogas production



b) Biogas composition

Figure 10.5. Biogas production in semi-continuous digestion trial. (Vertical dotted line indicates change of feed TS)

10.5.4 Feasibility evaluation of cooking fuel replacement and GHG emissions reductions by biogas in IIT Delhi Campus

At present LPG is used as a cooking fuel in the campus. Hence, there is potential for production of biogas to replace LPG in hostels as well as reducing GHG emissions.

Table 10.5 Evaluation of biogas use as a cooking fuel and for GHG emissions reduction

Food waste	1.6 tonnes day^{-1}
Digester input of food waste	584 tonnes $year^{-1}$
Digester loading	2 kg VS m^3 day^{-1}
Digester capacity required	131 m^3
Biogas produced	58400 m^3 $year^{-1}$
Methane produced	32120 m^3 /$year^{-1}$ (55 % CH4)
Digestate	467 tonnes $year^{-1}$
Biogas as cooking fuel – LPG replacement	
CV of LPG	46.1 MJ kg^{-1}
CV of biogas	20 MJ kg^{-1}
1 kg LPG	≈ 2.5 m^3 biogas
58400 m3 biogas $year^{-1}$	23360 kg LPG
1 LPG Cylinder	14.2 kg of LPG gas
23360 kg of LPG	1645 cylinders
Average number of students in each hostel	400
LPG consumption in each hostel	25 cylinders $month^{-1}$ = 300 cylinders $year^{-1}$
For 12 hostels in IIT	3600 cylinders $year^{-1}$ are required
Biogas produced can fulfil the demand of	5.5 hostels with 1645 cylinders

Yearly savings in costs by replacement of LPG	
Cost of 1 LPG cylinder	Rs 400 = £ 4.5 = € 5.8
Replacement value of 1645 cylinders	Rs 6,58,000/yr = £ 7478/yr = € 9675
GHG emissions reductions by replacement of LPG with biogas in IIT	
1 kg LPG	30 % propane, 70 % butane
Carbon in 1 kg LPG	0.3* 36/44 = 0.25 kg = 0.83 kg 0.7* 48/58 = 0.58 kg
After combustion (i.e. oxidation) of 1 kg LPG with 0.995 oxidation factor	44/12 * 0.83 * 0.995 = **3.028 kg (CO_2)** carbon dioxide
Hence 23360 kg LPG will give	71 tonnes of CO_2 eq
584 tonnes year^{-1} of food waste will reduce	**71 tonnes year^{-1} of CO_2 eq** (GHGs)

The University of Southampton's AD model was also run with the same waste quantities and the empirically-determined parameters substituted for the default food waste values as previously noted. The results are shown in Table 10.6.

Table 10.6 AD Modelling outputs for IIT Delhi

Energy and material outputs (/year)	CHP	Boiler	Upgrade gas	Upgrade & compress gas	
Digester input	584	584	584	584	tonnes
Digester capacity required	131	131	131	131	m^3
Digester retention time	74	74	74	74	days
Methane produced	39105	39105	39105	39105	m^3
Methane available	38714	38714	38714	38714	m^3
Biogas (volume)	71099	71099	71099	71099	m^3
Biogas (mass)	91	91	91	91	tonnes
Digestate	493	493	493	493	tonnes
Electricity produced	485	0	0	0	GJ
	134831	0	0	0	kWh
	16	0	0	0	kW generator
Heat produced	693	1179	0	0	GJ
Upgraded biogas	0	0	38714	38714	m^3
Waste transport diesel	0	0	0	0	litres
Total energy output	1179	1179	0	0	GJ
Energy inputs required (/year)					
Waste transport	0	0	0	0	GJ
Digestate transport	56	56	56	56	GJ
CHP supplied electricity	21	0	0	0	GJ
Imported electricity	0	21	97	139	GJ
Boiler/CHP supplied heat	157	157	0	0	GJ
Imported gas for heat	0	0	185	185	GJ
Pasteuriser inclusion	pre	pre	pre	pre	digester
Pasteuriser heat	112	112	112	112	GJ
Total energy input	244	244	348	390	GJ
Energy exports					
Energy in methane produced	1401	1401	1401	1401	GJ
Exported electricity	464	0	0	0	GJ
	129	0	0	0	MWh
Exported heat	536	1022	0	0	GJ
	149	284	0	0	MWh
Energy in upgraded CH4	0	0	1387	1387	GJ
Exported energy	1001	1022	1387	1387	GJ
Energy Balance	935	935	1039	997	GJ
	1.6	1.6	1.8	1.7	GJ/tonne

The modelling results in Table 10.6 differ slightly from those in Table 10.5; this is due to the different modes of calculation, rounding, and use of rules-of-thumb vs. first principles. For example, the methane and biogas quantities in Table 10.6 were modelled based on the parameter of 0.3 m^3 CH_4 kg^{-1} VS and 55% methane, while the annual quantities Table 10.5 were based on daily averages scaled up to predicted annual quantities. The annual digestate tonnage expected was based on a rule-of-thumb estimate of 80% of input waste tonnage in Table 10.5, whereas in Table 10.6 it is calculated from the predicted quantity of mass converted to biogas, of which the composition and density was used to determine the mass converted, with the remainder becoming digestate. The digester capacities needed would also vary if different retention times were assumed. Based on the replaced LPG energy value of 46.1 MJ kg^{-1} assumed in Table 10.5, the overall energy yield from Table 10.5 is approximately 1078 GJ, which is roughly equivalent to the values found in Table 10.6.

10.6 Conclusions

Food waste is a promising substrate for biogas production in ambient mesophilic anaerobic conditions at IIT Delhi. The potential energy output from anaerobic digestion was compared to the cooking fuel demand to show how much of the current energy requirements could be met by cookstoves operated on biogas. This alternative route for food waste from the general waste stream of the campus to an onsite biogas plant would avoid the cost of transport to landfill. The generation of energy from raw biogas and its replacement of LPG as a cooking fuel also offsets greenhouse gas emissions, while there are additional benefits from the production of digestate for fertiliser.

10.7 Acknowledgements

Thanks to the maintenance department of IIT Delhi for the use of the help and providing manpower to do the collection and measurement work; and to Professor V.K Vijay for providing support and guidance wherever and whenever needed.

11 Case Study of Stratford-upon-Avon: Investigating the potential for town-scale anaerobic digestion

11.1 Introduction

A town is a unit that may be of sufficient size and produce sufficient waste to justify investment in an anaerobic digester. Small scale digestion - plants between 20kw and 200kw electrical output capacity (Woollacott et al., 2012) - does exist in the UK, although not to the extent targeted by the government. There are currently 214 AD plants in the UK, of which 146 are sewage sludge digesters. There are 68 commercial or farm-based AD systems in operation – a long way from the NFU / Defra 2009 targets as set out in the AD Shared Goals Report proposing 100 commercial systems and 1000 farm based systems by 2020 (Defra, 2009). It is, however, promising in light of the fact that in 2005 there were only two AD plants outside of the water industry (letsrecycle, 2012).

The aim of the current study of this study is to consider the feasibility of AD in the town of Stratford-upon-Avon, UK.

11.2 Stratford-upon-Avon

Stratford-upon-Avon is a market town in Warwickshire, in the West Midlands region of the UK. It is most well-known for its status as the birthplace and home of William Shakespeare, which has led to the growth of a large tourism industry around its historical significance and theatrical traditions; the town has a number of theatres and hosts an annual festival of works by Shakespeare and other playwrights, among numerous smaller arts and music festivals (Visit Stratford-upon-Avon, 2012).

Figure 1.1 Shakespeare's birthplace, one of Stratford's principal tourist attractions (source: www.visitstratforduponavon.co.uk)

11.2.1 Population and area served

Stratford-upon-Avon has a year-round population of approximately 25,000 inhabitants, although its numbers are swelled in the summer months by almost 4 million tourists per year (Woollacott et al., 2012). About 28% of these stay in the town for at least one night, with an average length of stay of 3.8 days (Stratford-on-Avon District Council, 2011). This has led to a large hospitality industry of hotels, guesthouses, bed & breakfasts, restaurants, cafes and other accommodation and food service establishments in the town. This in turn leads to substantial volumes of food waste being produced, which could potentially provide feedstock to an anaerobic digestion plant. The town is also quite compact, with the main commercial and residential area concentrated within a 5-km radius of the rail station (as measured on Google Earth; see map below for locations).

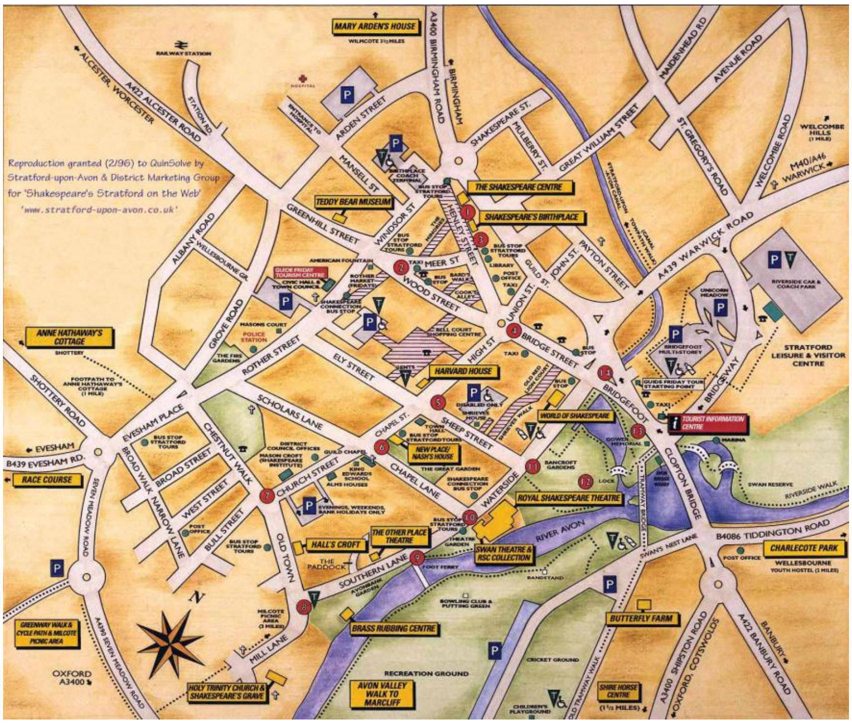


Figure 11.2 Tourism map of Stratford-upon-Avon (source: www.stratford-upon-avon.co.uk)

11.2.2 Waste Sources and Quantity Estimates

In the town of Stratford-upon-Avon and its environs, there are a number of different organic materials that could potentially provide feedstock for an anaerobic digestion (AD) plant. The following four streams were identified:

- Household food waste
- Food waste from the commercial hospitality sector (hotels, restaurants, etc.)
- Animal manures and slurries from the agricultural sector

Estimation of Current Quantities of Household Food Waste

The management of waste in Stratford-upon-Avon is the responsibility of the larger District of Stratford-on-Avon. Direct data on the amount of domestic food waste in the town is not available, as waste data is collected for the district, but not for individual units such as the town. To estimate the quantities of domestic organic food waste in the town of Stratford-upon-Avon, data on waste quantities in the District of Stratford-on-Avon was combined with population data for the district of Stratford-on-Avon and the town of Stratford-upon-Avon (Warwickshire Observatory, 2010).

A meeting with the District of Stratford-upon-Avon (Senior Waste Officer) confirmed that the total amount of food waste collected in the district in 2011 was 3,320 tonnes, as determined by waste composition studies and records of the total amount of waste at 51,454 tonnes. This figure corresponds to an average household waste production factor of 1.3 kg per household per week. Assuming the same per-household food waste production rate from the Town of Stratford-upon-Avon gives the results shown in Table 2.1 below.

Table 11.1 Estimated Household Food Waste Production

Local Authority	Population	People per household (estimated)	Number of households	Food Waste Production Factor kg/hh-week	Food Waste Produced tonnes/year
Stratford-on-Avon District	118,900	2.4	49,542	1.3 (calculated)	3,320 (actual)
Stratford-upon-Avon Town	25,000	2.4	10,417	1.3 (from above)	698 (calculated)

The table shows that approximately 700 tonnes of food waste per year is currently produced by households in the town of Stratford-upon-Avon.

Estimation of Current Quantities of Commercial Hospitality Food Waste

Estimation of quantities of food waste available from the commercial hospitality sector was carried out by adaptation of the methodology used by WRAP in its 2011 report, 'The Composition of Waste Disposed of by the UK Hospitality Industry' (WRAP, 2011) combined with data based upon the numbers of hospitality establishments - pubs, restaurants, hotels and quick service restaurants (QSRs) - in Stratford and environs.

To estimate the quantities of commercial waste potentially available, waste production factors were used for each type of establishment, multiplied by the number of establishments in each category. Expected waste production quantities would vary substantially depending on size of the establishment, number of meals served, logistical and supply chain arrangements (e.g. whether food is prepared fresh onsite or pre-processed in other facilities and delivered ready for final cooking), and seasonal variations. The range of potential waste production that can be expected from different types of facilities is shown in Table 11.2. This is shown for illustrative purposes only, to show the variation in waste production estimates that can arise. The average waste production factors used to estimate the quantity of hospitality waste in Stratford-upon-Avon are shown in Table 11.3 .

Table 11.2 Production Factors by Business Type for Waste

Business Type	Average Total Waste per Company, based on Business Size					
	1-9 employees (tonnes/yr)	10-19 employees (tonnes/yr)	20-49 employees (tonnes/yr)	50-99 employees (tonnes/yr)	100-149 employees (tonnes/yr)	250+ employees (tonnes/yr)
Hotel	11	32	40	129	152	339
Restaurant	9	38	97	18	69	251
Fast Food	6	18	54	112	262	375
Pub	24	61	53	108	262	375

Source: WRAP 2011: "The Composition of Waste Disposed of by the UK Hospitality Industry"; Table 18

Table 11.3 Median Production and Composition Factors by Business Type for Waste

Business Type	Total Waste per Company		Percentage of Food Waste in Total Waste
	Mean (tonnes/yr)	Median (tonnes/yr)	(%)
Hotel	149	66	37%
Restaurant	65	30	43%
Fast Food	23	12	48%
Pub	52	43	36%

Source: WRAP 2011: "The Composition of Waste Disposed of by the UK Hospitality Industry"; Tables 22 and 23

There are a total of 397 hospitality establishments in the town of Stratford-upon-Avon. To estimate the amount of food waste from commercial hospitality establishments in Stratford, the factors shown in the table above were multiplied by the number of businesses in each category. In choosing which Total Waste factor to choose, the median was chosen rather than the mean, as this number is lower and provides a more conservative estimate.

Table 11.4 Production and Composition Factors by Business Type – Stratford-upon-Avon

Business Type	Number of Businesses in Stratford	Total Waste per Business (median) (tonnes/yr)	Food Waste Percentage (%)	Total Food waste (tonnes/yr)
Hotels	14	66	37%	342
Restaurants	104	30	43%	1,641
Fast Food	173	12	48%	996
Pubs	106	43	36%	1,342
Total	**397**			**4,321**

This method of estimation could give a potential total ranging from 4,000-10,000 tpa depending on the waste factors used and business sizes assumed. The low end of the range has been chosen for modelling to avoid overestimation of the waste resource.

Agricultural Manures

Although the town of Stratford-upon-Avon is an urban centre, it is situated within an agricultural region which does have a number of dairy farms and other livestock operations.

Co-digestion of food waste with agricultural waste such as cattle slurry has benefits in improved bio-digestion process stability and better biogas production than from either substrate alone. Estimation of animal manures and slurries from the agricultural sector used the methodology established in a previous study (Banks et al., 2011), and stocking rates and other supporting data from Defra.

According to agricultural census figures (Defra, 2010a), in 2007 Warwickshire had the following:

- 114 farms with less than 10 cows (total 282 animals)
- 12 farms with between 10 and 30 dairy cows (total 168 animals)
- 39 farms with between 70 and 100 dairy cows (total 3173 animals)
- 36 farms with between 100 and 200 dairy cows (total 5231 animals)
- 2-4 farms with over 200 dairy cows (at least 400 animals)

There were a total of 10044 milking head on 224 farms. Each fully mature dairy cow produces 19.4 tonnes of excreta per year (Burton and Turner, 2003). For other cattle in the dairy (calves, heifers etc.) a factor of 11.6 tonnes per year is used (Defra, 2010b).

Table 11.5 shows a typical calculation for a single farm, which could host and provide feedstock for an individual AD plant. The amount that can be collected depends how much time the cattle spend indoors. For a dairy farm in which cattle are kept indoors through the winter (six months) and then let out for grazing during the other half of the year, this gives a factor of 50% for manure collection. The cattle, however, would return to the barn for milking twice per day, for an approximate 2.5 hours per day. This can be estimated to contribute a further 10% for collectable production.

Table 11.5 Estimated manure production from a theoretical farm in Warwickshire

Dairy Cows head	Other Cattle head	Dairy Cow Manure Factor tonnes/head	Other Cattle Manure Factor tonnes/head	Annual Production tonnes/year	Collection Factor %	Annual Collectable Production tonnes/year
145	129	19.4	11.6	4,309	60%	2,586

As shown, a medium-sized dairy farm with 145 milking head could expect to produce approximately 4,300 tonnes per year of cattle slurry, with a collectable amount of 2,600 tonnes per year.

11.2.3 Current Waste Transport and Processing Infrastructure

Food Waste

Domestic Organic Waste
Stratford District Council (SDC) is responsible for collection of household waste from a population of 118,900 covering an area of 976 km^2; this includes the Town of Stratford-upon-Avon with its population of approximately 25,000 and approximately 10,000 residences. Currently, there is a fortnightly kerbside organics collection service - the ‘green wheely bin’ collection (SDC, 2012).
SDC allows for food waste to be placed in the green bin. The Council also holds currently a supply of 2500 kitchen food waste caddies, which are provided free to householders upon request; thus far approximately 500-600 of the caddies have been picked up by householders.

Residents may dispose of their food waste in their green organics bin, or in their residual waste black bin, which is also collected fortnightly, on alternate weeks to the organics bin. It is likely, therefore, that much of the household food waste – and at least 50% - is going into the residual waste bin, as residents tend to dispose of food waste with their residual waste in weeks when garden waste is not collected (WRAP, 2009).

Indeed, it was confirmed in discussions with SDC, and with Warwickshire County Council – the Waste Disposal Authority - that composition studies in the Warwickshire districts have found that only 4-6% of residential food waste is being collected in the green bin organics collection. The balance of the food waste was collected with the residual refuse - and therefore is predominantly landfilled (see below for disposal routes for refuse).

According to WasteDataFlow, the government’s portal for waste reporting by local authorities (www.wastedataflow.org) the total amount of household waste collected by Stratford-on-Avon District Council in 2011 was 27,689 tonnes, of which 30.5% (8,432 tonnes) of organic waste was sent for in-vessel composting (IVC). The bulk of this organic waste is garden waste, as evidenced by the waste composition results. The overall diversion rate in the district for waste in 2011, including recycling and composting, was 59.3%.

Collection and Disposal Contracts for Household Waste

Collection of household organic waste for the District of Stratford-on-Avon is contracted out to a waste services company (Biffa Ltd). The contract was signed in 2008 for a duration of seven years, with an option to extend for a further seven years in 2015; a total of 14 years' duration.

The processing and disposal of waste is the responsibility of Warwickshire County Council (WCC) who has also contracted with private companies for the processing and disposal of waste. The green bin organic waste is processed at an In-Vessel Composting facility near Ufton, owned by Biffa Ltd., on a contract of 15 years duration. As part of an agreement under the Warwickshire Waste Partnership, three of the district councils (including Stratford) are obliged to provide/deliver a minimum annual tonnage to the facility of 35,000 tonnes. The total organic waste delivered to the facility from collections in the County in 2011 exceeded this requirement at 39,000 tonnes.

For domestic residual refuse from Stratford-on-Avon District, two destinations for disposal exist: the Coventry and Solihull Waste Disposal Company energy-from-waste (EFW) plant in Coventry, and the Bubbenhall Wood landfill near Bubbenhall in Warwick District. The County's contract for disposal at the Bubbenhall landfill requires a minimum tonnage of 50,000 tonnes per year, an amount that decreases by 5% per year to encourage the efforts of the County and district councils to divert waste to other streams - and reduce waste generation overall).

The length of these domestic contracts means that possibilities for diverting food waste from its current destinations are limited. Future legislation to ban organic waste from landfill altogether, the increasing gate fees for landfill, and changes to waste collection and treatment legislation may influence changes towards a greater recovery of foodwaste and other biodigestible waste. The Coalition Government recently announced £250 million of funding for councils to support a Weekly Collection Support Scheme - and encourages applications which:

"add a weekly food waste (or organic waste) service to an existing fortnightly collection of residual household waste, where an authority can credibly demonstrate that this represents the preference of local people. This additional service will reduce the amount of biodegradable waste sent to landfill, and reduce the amount of biodegradable food waste that has to be stored in or around the home." (DCLG, 2012)

If the District were to take advantage of this scheme, this could allow the introduction of separate food waste collection for processing by anaerobic digestion.

Commercial Waste Collection

Commercial businesses in Stratford are responsible for management of their own wastes, and this is generally done through contracts with waste collection companies. In contrast to the long timespan of the local authority collection contract, commercial waste collection contracts are generally of one year duration, renewed annually.

11.2.4 Energy Loads

The town of Stratford-upon-Avon has a leisure centre with a swimming pool at its town centre (see Figure 11.1, right side of map). This could be a potential use for heat from a biogas-fired CHP or boiler. Electricity and/or heat could be used by buildings in the town centre adjacent to a local AD plant, depending on the plant's location.

11.3 AD Modelling

The anaerobic digestion model developed at the University of Southampton (Salter, 2010) was used to determine potential outcomes for an anaerobic digester for Stratford-upon-Avon. The model was run three times, using varying inputs of the waste streams available, and assuming a waste transport distance of 10 km. Average monthly temperatures from the town of Pershore, 14 km from Stratford, were used for heat calculations.

Model Run 1 – Domestic Food Waste only
The model was run using the estimated quantities of food waste that could be collected from households in the town. This is a total of 700 tonnes per year of food waste.

Model Run 2 – Domestic and Hospitality Food Waste
The second model run was based on 700 tonnes of household food waste, plus food waste from hospitality establishments, estimated at 4000 tonnes per year.

Model Run 3 – Domestic and Hospitality Food Waste with Cattle Slurry
The third model run was based on the quantities of food waste given above from both domestic and hospitality sources, plus the addition of 2,600 tonnes of cattle slurry, as a potential on-farm digester.

11.4 Results

Tables 11.6 and 11.7 show the outputs and savings that could potentially be associated with an onsite AD plant, depending on the waste stream(s) processed. Table 11.6 shows the results of modelling using a CHP plant for biogas utilisation, while Table 11.7 gives results of modelling using a boiler for biogas utilisation.

Table 11.6 Modelling Outputs for Onsite Anaerobic Digestion at Stratford-upon-Avon – CHP

Energy and material outputs (/year)	Run 1 - Domestic Food Waste only	Run 2 - Domestic & Hospitality Food Waste	Run 3 - Domestic & Hospitality Food Waste + Cattle Slurry	
Digester input	700	4700	7300	tonnes
Digester capacity required	155	1042	1238	m3
Digester retention time	74	74	56	days
Methane produced	64915	435859	471790	m3
Methane available	64266	431501	467072	m3
Biogas (volume)	111923	751481	811366	m3
Biogas (mass)	139	933	1006	tonnes
Digestate	561	3767	6294	tonnes
Electricity produced	806	5410	5856	GJ
	223824	1502821	1626708	kWh
	27	181	195	kW generator
Heat produced	1151	7728	8365	GJ
Upgraded biogas	0	0	0	m3
Waste transport diesel	1747	1747	1747	litres
Total energy output	1957	13138	14221	GJ
Energy inputs required (/year)				
Waste transport	63	63	63	GJ
Digestate transport	63	425	710	GJ
CHP supplied electricity	101	677	714	GJ
Imported electricity	0	0	0	GJ
Boiler/CHP supplied heat	297	1624	2342	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	181	1213	1882	GJ
Total energy input	536	2830	3875	GJ
Energy exports				
Energy in methane produced	2325	15612	16900	GJ
Exported electricity	705	4733	5141	GJ
	196	1315	1428	MWh
Exported heat	854	6104	6023	GJ
	237	1696	1673	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	1559	10837	11165	GJ
Energy Balance	1421	10308	10346	GJ
	2.0	2.2	1.4	GJ/tonne

Table 11.7 Modelling Outputs for Onsite Anaerobic Digestion at Stratford-upon-Avon – Boiler

Energy and material outputs (/year)	Run 1 - Domestic Food Waste only	Run 2 - Domestic & Hospitality Food Waste	Run 3 - Domestic & Hospitality Food Waste + Cattle Slurry	
Digester input	700	4700	7300	tonnes
Digester capacity required	155	1042	1238	m3
Digester retention time	74	74	56	days
Methane produced	64915	435859	471790	m3
Methane available	64266	431501	467072	m3
Biogas (volume)	111923	751481	811366	m3
Biogas (mass)	139	933	1006	tonnes
Digestate	561	3767	6294	tonnes
Electricity produced	0	0	0	GJ
	0	0	0	kWh
	0	0	0	kW generator
Heat produced	1957	13138	14221	GJ
Upgraded biogas	0	0	0	m3
Waste transport diesel	1747	1747	1747	litres
Total energy output	1957	13138	14221	GJ
Energy inputs required (/year)				
Waste transport	63	63	63	GJ
Digestate transport	63	425	710	GJ
CHP supplied electricity	0	0	0	GJ
Imported electricity	101	677	714	GJ
Boiler/CHP supplied heat	297	1624	2342	GJ
Imported gas for heat	0	0	0	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	181	1213	1882	GJ
Total energy input	536	2830	3875	GJ
Energy exports				
Energy in methane produced	2325	15612	16900	GJ
Exported electricity	0	0	0	GJ
	0	0	0	MWh
Exported heat	1660	11514	11879	GJ
	461	3199	3300	MWh
Energy in upgraded CH4	0	0	0	GJ
Exported energy	1660	11514	11879	GJ
Energy Balance	1421	10308	10346	GJ
	2.0	2.2	1.4	GJ/tonne

11.5 Conclusions

An AD plant operating on food waste from the town of Stratford-upon-Avon could potentially produce, depending whether food waste from hospitality establishments and cattle slurry were included, from 196-1,428 MWh of electricity annually and 237-1,673 MWh of heat with a CHP, or 461-3,300 MWh with a boiler.

At an average UK household annual electrical consumption rate of 4,418 kWh (DECC, 2012), this equates to sufficient electricity to power from 45-323 houses. The heat could be used at the leisure centre's swimming pool or pools in schools in the area, or by district heating or other potential heat loads in the area.

Considering that the UK government wishes to encourage community energy schemes as stated in its 'Developing an Anaerobic Digestion Framework' (Defra, 2010c), the Town of Stratford-upon-Avon could be a good candidate for a community-scale AD plant. In practice, the difficulty of securing waste contracts (which are either very short-term for commercial premises, or for domestic wastes are already locked up for the next seven years) could make it difficult to proceed with financing for the plant, without certainty of securing a waste stream. However, if local collection companies were interested in providing their wastes to the plant it could be a feasible proposition.

11.6 Acknowledgements

Thanks to Community Energy Warwickshire for the use of information gathered in the Local Energy Assessment Fund study on Food Waste Anaerobic Digestion for Stratford upon Avon Feasibility Study, March 2012.

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12 Case Study of Veolia St Alban’s depot commercial food waste collection

12.1 Introduction

Collection of food waste from commercial premises in the hospitality sector, such as restaurants, cafes, bars and hotels, is relatively common in some EU countries. One example of such a service is the collection scheme operated by Valorsul in Lisbon (see VALORGAS deliverable D2.4); others are mentioned briefly in deliverable D2.2. Schemes of this type are less common in the UK, however, and there is still a lack of data on the quantities of waste generated in the commercial sector, or even of robust assessment methodologies (Bradley et al., 2008). A recent study by WRAP (2011) has attempted to address this in part, by assessing the options for UK local authorities to offer a food waste collection service to schools and SME businesses in their local areas.

One of the first UK initiatives specifically targeting the commercial hospitality sector was the collection service originally developed by Veolia Environmental Services (UK) Ltd in partnership with Whitbread, the UK's largest hospitality company (Veolia, 2010; Guardian, 2011). Since then the scheme has been rolled out to more Whitbread sites by the client, while Veolia has attracted other commercial sector participants in order to improve the efficiency of service (Veolia, 2011a and b; Whitbread, 2011). The current case study considers a single Veolia depot offering this type of source segregated food waste collection to commercial organisations within the area served, and considers a range of options for operating such a scheme.

12.2 Collection scheme

The commercial food waste collection operating out of Veolia's St Albans depot currently serves 54 premises. Each separates its produced food waste into 240- or 360-litre bins or Euro bag cornstarch sacks for collection once or twice a week, depending on quantity. The location of the collection sites is shown in Figure 1: it can be seen that the depot is roughly in the centre of the collection area. The food waste is collected by 11 standard single-compartment refuse collection vehicles (RCV), with a gross vehicle weight of 26 tonnes and around 12.8 tonnes payload (WRATE, N.D., Dennis Eagle LTD, N.D.). Once collected it is transported to the Westwood AD plant, using the same vehicles. The Westwood plant is owned by BiogenGreenfinch (www.biogen.co.uk) and is located at a distance of 80 km from the St Alban’s depot in Rushden, Northamptonshire (Figure 2).

Detailed daily records on the distance travelled, tonnage collected, fuel usage and other key collection parameters for a 12-month period from 1 June 2010 to 31 May 2011 were provided by Veolia, and are summarised in Table 12.1. Data for the vehicles with registration numbers KP54 EXR, Y588 HHP and the Hire RCV appears incomplete, due to the recording system used. As the number of lifts made by these vehicles was relatively small (17, 26 and 50 lifts in one year respectively, out of a total of 12187 lifts) it was assumed that the effect of any missing or inconsistent data was minor and could be ignored. In the study period the collection vehicles covered a total distance of 48,423 km (including travel to Westwood AD plant), consumed 23,156 litres of diesel fuel and collected 579.77 tonnes of food waste.

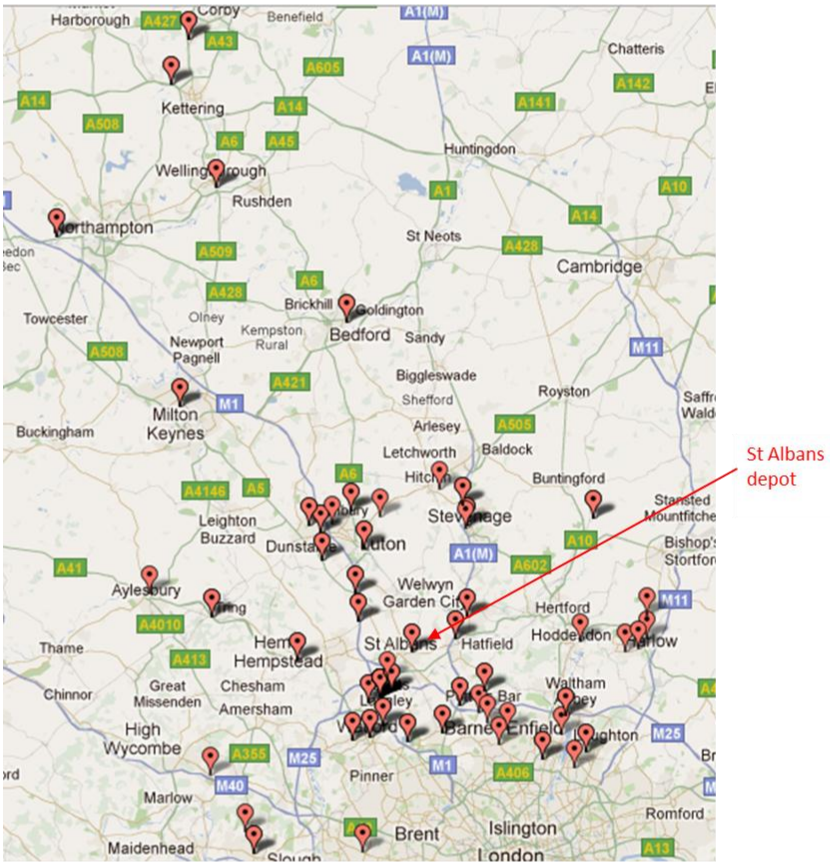

Figure 12.1. Location of commercial food waste collection points served by the St Albans depot. (Google maps © 2012).

Figure 12.2. Locations of St Albans depot and Westwood AD plant (Google maps © 2012).

Table 12.1. Summary of food waste collection data for the period 1 July 2010 to 30 June 2011

Vehicle registration	Hours worked	Distance (km)	Fuel (litres)	No. of Lifts	Weight collected (tonnes)	Distance / Lift (km)	Time / Lift (min)	Weight / Lift (kg)	Fuel (litres / 100km)	Fuel (litres / tonne)	Distance (km / tonne)
HIRE RCV	0	-	-	50	-	0	0	-	-	-	-
KX03 RUJ	1082.38	32093	15549	8009	391.55	4.01	8.1	48.9	48.45	12.20	82.0
PK51 LLM	230.67	7216	3149	1504	70.92	4.80	9.2	47.2	43.64	9.83	101.7
PF57 DHZ	93.1	2825	1263	864	43.86	3.27	6.5	50.8	44.71	15.53	64.4
Y664 OAC	94.33	2459	1417	889	33.94	2.77	6.4	38.2	57.63	13.80	72.5
PN05 NJU	64.5	1806	822	327	20.38	5.52	11.8	62.3	45.51	11.28	88.6
DA60 DKL	14.25	299	173	315	7.36	0.95	2.7	23.4	57.86	24.62	40.6
DK58 FCG	19.5	702	286	82	5.64	8.56	14.3	68.8	40.74	8.03	124.5
DK57 AZW	19	995	497	104	5.3	9.57	11.0	51.0	49.95	5.33	187.7
KP54 EXR	-	-	-	17	0.42	-	-	24.7	-	-	-
Y588 HHP	4.25	28	-	26	0.4	1.08	9.8	15.4	-	14.29	70.0
TOTAL	1622	48423	23156	12187	579.77	-	-	-	-	-	-
Average	-	-	-	-	-	3.97	8.0	47.6	47.82	39.94	83.5

12.3 AD modelling

Four scenarios were considered in the AD modelling.

Scenario 1 - Existing case
This scenario modelled the collection scheme using the existing conditions as described above. At the Westwood AD plant the biogas produced during digestion is consumed in a CHP unit to provide electricity and heat. The CHP unit is assumed to convert the energy in the methane to electricity with an efficiency of 35% and heat with an efficiency of 50%. Digestate is applied to fields adjacent to the AD plant, at an average distance of 0.6 km (Personal communication, BiogenGreenfinch). It is assumed that the digestate is transported using a rigid body lorry (small tanker) between 7.5 and 17 tonnes with a fuel consumption of 0.156 l $tonne^{-1}$ km^{-1}. No embodied energy is attributed to the digester as it already exists, and the input volume from this commercial collection service is small compared to the plant's total input.

Scenario 2 - Weekly deliveries to AD plant
As the amounts of food waste collected per round are relatively small (0.24 to 10.54 tonnes) it would be possible to collect the food waste at a central point and deliver to the AD plant once a week, thus reducing the transport fuel requirement.

In order to determine the number of journeys currently made, any round with a distance travelled of over 220 km was assumed to include a delivery to the AD plant. This corresponded to a total of 121 journeys. In order to reduce the annual transport distance, it was assumed the collected food waste could be stored at the St Albans depot and delivered once a week (total 52 deliveries). The transport distance is thus 8320 km (a reduction of 11040 km) with a maximum weekly load of 25 tonnes of food waste. The transport is thus assumed to take place using an articulated lorry of >33 tonne gross consuming 0.352 l km^{-1} diesel when loaded at 50%, allowing for 100% load on the way there and empty on the way back (AEA 2010).

Scenario 3 - AD plant at transfer station
If an AD plant was established at the depot the fuel used for transportation would be further reduced. In this case it was assumed that 121 journeys of 160 km were no longer undertaken, reducing the overall distance travelled by 19360 km. The digester size was determined based on an input of FW from this collection only, at a loading rate of 3 kg VS_{added} m^{-3} day^{-1}. Efficiency of the CHP was assumed to be the same as for the previous cases. It was assumed that the digestate would need to be transported an average of 5 km from the AD plant to fields for land application, based on local land use.

Scenario 4 - Biomethane production
An alternative to using the biogas to produce electricity via CHP is to upgrade it to biomethane, which can then be used as vehicle fuel or injected into the gas grid. This provides a more carbon neutral approach to collection and transportation of the food waste. In this analysis it was assumed that a digester is located at the depot and that some of the biogas is consumed in a CHP unit large enough to provide only the required parasitic electricity for operating the AD plant and for upgrading and compressing the biogas to biomethane. For biogas upgrading the energy requirement can be divided into two parts, upgrading to remove the impurities and compression if the upgraded gas is to be used for vehicle fuel. The energy requirement is in the form of electricity for pumps and the compressor. Values for upgrading

vary from 0.3 to 0.67 kWh/m^3 biogas (Electrigaz Technologies Inc, 2008) and between 3 to 6% energy in upgraded gas (Persson, 2003). Total energy for upgrading and compression has been given as 0.5 kWh/m^3 upgraded gas (Kalmari, H, pers comm. Aug 2008) and 0.75 kWh/m^3 upgraded gas (Murphy *et al.*, 2004). The values taken here will be 0.3 kWh/m^3 biogas for the upgrading and 0.3 kWh/m^3 gas for compression (Nijaguna, 2002).

Scenario 5 – Increase in collected waste

As noted, the service based at St Alban's depot was set up by Veolia in response to a request from a large client and thus was initially designed to serve this customer's premises: other customers who happened to be located near to a collection round were then added to the scheme. As a result of this, the distance travelled to each collection point and the fuel used per tonne of waste collected is high in comparison with values for a typical source segregated domestic collection scheme, where the distance between properties is much smaller (see VALORGAS deliverable D2.7: Results from LCA and energy footprint modelling for optimisation of collection methods and equipment). In addition, the average amount per lift is only 47.6 kg (Table 12.1). The quantity of food waste collected could be significantly increased, without exceeding the vehicle's capacity, if more customers were identified on or close to the collection routes. It is also likely that this could be achieved without major increases in distance travelled, fuel consumed or even time spent, especially if the routes could be optimised for these greater numbers. As a simplified simulation, this scenario takes the conditions used in scenario 3 as a basis for the calculations but assumes that twice as much food waste is collected on each round without any change in fuel consumption.

12.4 Results and discussion

12.4.1 Energy outputs

Scenario 1 - Existing case

The results for analysis of this scenario are shown in Table 12.2. If only electricity is considered, the net energy balance is -237 GJ indicating that more energy is used in collection and delivery of the food waste than is produced as electricity. If the heat produced in the CHP is also used then the energy balance is +475 GJ. At least 64% of the potential heat must be used in order to make this energy balance zero according to the system boundaries and components considered. It should be remembered, however, that not all of the energy used in collection is avoidable: the food waste will anyway have to be collected and transported e.g. to a landfill or incinerator, and it is therefore only the energy requirement for source segregated collection that represents an additional demand.

Table 12.2. Existing case

	unit	value
Food waste	tonnes	580
Diesel fuel	litres	23156
Total distance travelled	km	48423
Average fuel consumption	km l^{-1}	2.09
Energy value of diesel fuel used	GJ	827.4
Potential biogas yield	m^3	92736
Potential methane yield	m^3	53787
Digestate transport	GJ	1.6
Surplus electricity produced	GJ	590.5
Surplus heat produced	GJ	711.5

Scenario 2 - Weekly deliveries to AD plant

The results for this scenario are shown in Table 12.3. In this scenario, electricity-only production leads to an energy balance of -12.4 GJ, and electricity plus heat to an energy balance of 699.6 GJ. Utilisation of just 2% of the potential heat is needed to make this scenario energy neutral.

One issue for this option would be the need to store the material at the depot. Many of the commercial collections are carried out at weekly intervals, and storage for a longer interval may not be acceptable, especially in summer.

Table 12.3. Reduced number of deliveries

	unit	value
Food waste	tonnes	580
Total distance travelled	km	37383
Diesel fuel	litres	16829
Energy value of diesel fuel used	GJ	601.3
Potential biogas yield	m^3	92736
Potential methane yield	m^3	53787
Digestate transport and application	GJ	1.6
Surplus electricity produced	GJ	590.5
Surplus heat produced	GJ	711.5

Scenario 3 - AD plant at transfer station

The results for Scenario 3 are shown in Table 12.4.In this case the net energy balance (electricity only) is +70.4 GJ which increases to 781.9 GJ if it is possible to utilise all of the heat produced. This scenario is energy positive, even without use of the heat.

The total capacity required for the digester is only 129 m^3. In practice the infrastructure costs for this plant would be as high as for one considerably larger and it is likely that a bigger digester would be constructed and more feedstock brought in, either by identifying additional sources of commercial food waste or by accepting material from household collections . At present domestic food waste is collected together with green waste in the area covered by St Albans City and District Council (see VALORGAS deliverable D2.2), making commercial sources more feasible in the short term.

Table 12.4. AD plant at depot

	unit	value
Food waste	tonnes	580
Total distance travelled	km	29063
Diesel fuel	litres	13898
Energy value of diesel fuel used	GJ	496.6
Digester loading rate	kg VS m^{-3} day^{-1}	3
Digester capacity	m^3	129
Lifespan of plant	years	30
Embodied energy in plant	GJ $year^{-1}$	10.5
Potential biogas yield	m^3	92736
Potential methane yield	m^3	53787
Digestate transport	GJ	13.0
Surplus electricity produced	GJ	590.5
Surplus heat produced	GJ	711.5

Scenario 4 - Biomethane production

In this case there is a net energy balance of 791.6 GJ. Assuming that the collection vehicles have the same energy efficiency running on biomethane as when using diesel, then enough biomethane is produced to replace all of the diesel used in collection and transfer, with an excess of around 815 GJ available for other vehicles at the depot or elsewhere.

Table 12.5. Biomethane production

	unit	value
Food waste	tonnes	580
Total distance travelled	km	29063
Diesel fuel	litres	13898
Energy value of diesel fuel used	GJ	496.6
Embodied energy in plant	GJ $year^{-1}$	10.5
Digestate transport	GJ	13.0
Potential methane yield	m^3	53787
Upgraded and compressed biomethane	m^3 equivalent	36619
Energy value of biomethane	GJ	1311.7

Scenario 5 – Increase in collected waste

Simply doubling the amount of food waste collected on each round makes a large difference to the energy balance when compared with scenario 3. Exporting only electricity leads to an energy export of 643 GJ compared to 70.4 GJ, an increase of 9 times, and considerably more than any expected increase in the amount of diesel consumed. Exporting the heat gives an energy benefit of 2110.3 GJ compared to 781.9 GJ. There is also a small increase in the embodied energy of the digester due to the increase in size from 127 to 257 m^3.

Table 12.6. AD plant at depot - increased waste

	unit	value
Food waste	tonnes	1160
Total distance travelled	km	29063
Diesel fuel	litres	13898
Energy value of diesel fuel used	GJ	496.6
Digester loading rate	kg VS m^{-3} day^{-1}	3
Digester capacity	m^3	257
Lifespan of plant	years	30
Embodied energy in plant	GJ $year^{-1}$	16.5
Potential biogas yield	m^3	185472
Potential methane yield	m^3	107574
Digestate transport	GJ	25.9
Surplus electricity produced	GJ	1182.0
Surplus heat produced	GJ	1467.3

Table 12.7 presents a summary of the energy production and requirements for each scenario.

Table 12.7. Summary of energy balances

		Existing case	Reduced transport	AD plant at depot	Biomethane	AD plant at depot, double food waste
Food waste	tonnes	580	580	580	580	1160
Energy value of diesel used	GJ	829.0	602.9	509.6	509.6	525.5
Surplus electricity produced	GJ	590.5	590.5	590.5		1182
Surplus heat produced	GJ	711.5	711.5	711.5		1467.3
Energy value of biomethane	GJ				1311.7	
energy balance (elec)	GJ	-238.5	-12.4	70.4		643
energy balance (elc + heat)	GJ	473	699.1	781.9		2110.3
energy balance (biomethane)	GJ				791.6	

12.4.2 GHG emissions

If the biomethane replaces the diesel for transport there is a potential GHG saving of 37 tonnes CO_2 eq (assuming the saved diesel is not consumed elsewhere). All scenarios show an improvement in GHG emissions compared to the existing case. Table 12.8 shows the values for greenhouse gas emissions relating to fossil fuel use and replacement.

Table 12.8. Summary of GHG emissions

	Existing case	Reduced transport	AD plant at depot	Biomethane	AD at depot, double waste
Total distance travelled (km)	48423	37383	29063	29063	29063
GHG emissions from diesel fuel used (tonnes CO_2 eq)	61.9	45.0	37.1	37.1	37.1
GHG saving from grid replaced electricity (tonnes CO_2 eq)	74.1	74.1	74.1		148.4
GHG savings from grid replaced natural gas for heat (tonnes CO_2 eq)	40.6	40.6	40.6		83.8
GHG emissions from use of biomethane (tonnes CO_2 eq)					
All				0.14	
Fraction used as diesel replacement				0.05	
GHG balance					
(electricity only)	-12.2	-29.1	-37.0		-111.3
(electricity + heat)	-52.8	-69.7	-77.6		-195.1
Biomethane (replaces diesel use)				-37.0	
(all used as diesel replacement)				-103.74	

All of the scenarios show a decrease in GHG emissions resulting from the replacement of fossil fuel sources used in energy generation. The reduction in fossil fuel diesel use, by relocating the AD plant to the collection depot also makes a significant contribution to the reductions.

12.4.3 Discussion

The results for the current scenario indicate, unsurprisingly, that introducing source segregated food waste collections for commercial customers in this way may not necessarily be the most energy-efficient approach in the early stages: the following scenarios suggest, however, that relatively small changes will alter the energy balance, and in particular that increased uptake of such a service by other clients once it has been established will produce strongly positive results.

The collection service was originally set up by Veolia for primarily commercial reasons, as a major client requested it. From the viewpoint of net energy production, it would clearly be more efficient to operate a commercial collection serving the hospitality sector in conjunction with local authority food waste collections from domestic premises, to maximise yield and minimise fuel consumption within a given area. While the main drivers for introduction of source segregated commercial collections continue to be enlightened commercial practice rather than integrated regional planning of waste management facilities, and while collection charges and gate fees still make a major economic contribution to financing of a plant, this type of scheme is likely to be the most common and practical route for the introduction of anaerobic digestion schemes. Once such a service is introduced, it makes sense to maximise the commercial benefit by seeking other clients and other ways of minimising costs and maximising income.

The option of siting an AD plant at a depot may or may not be practical, depending on planning and other constraints: but in general this type of site is already designated for waste and resource recovery and there may be less difficulty in obtaining the necessary permissions and public acceptance than in other locations, especially if there are potential benefits to the local community such as the potential for local use of waste heat in community buildings or facilities such as swimming pools etc. The choice of a depot or transfer station makes sense in terms of the energy used in transportation, especially if the distance for digestate disposal is not too great; and may also help to minimise the overall number of vehicle movements. The option of producing methane for use in vehicles, such as the refuse collection fleet itself, with any excess used to supply local bus services etc, may be attractive both in energy terms and in terms of the green agenda of the waste management company and its clients.

12.5 Conclusions

The scheme currently produces a yield of 580 tonnes year^{-1} of food waste from 54 participating sites in the hospitality sector within the region served by the depot. It already recovers a significant fraction of the energy used in collection and transport, much of which would still be expended even if the material was collected without source segregation. Modifications in the operation of the scheme could improve the energy balance further. The option of siting a digester at the depot would lead to further gains and could generate biogas as fuel for operation of the collection fleet, with surplus upgraded biomethane available for export especially if the number of participating companies on each route can be further increased. Introduction of a commercial collection in parallel to the domestic service is unlikely to be the most efficient option, in terms of maximising food waste yield and minimising fuel consumption within a given area; but financial and operational considerations may mean this becomes a common way of introducing such schemes in practice.

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13 Case Study of the County of Somerset: Investigating the potential for anaerobic digestion at a county-wide scale

13.1 Introduction

This case study investigates the potential for anaerobic digestion in the English county of Somerset, comparing the transport efficiencies of the current collection scheme and disposal to IVC against the proposed scheme of removal to an AD plant. Both schemes involve a unified collection scheme across the county and are based on use of the existing vehicle fleet.

13.2 County of Somerset

In England and Wales it currently is the responsibility of the local councils to collect waste and the county councils or unitary authorities to dispose of it; this has led to many varied recycling schemes across the country. Somerset is one of the few counties to run a unified collection scheme and is therefore an ideal case study to assess the appropriate scale of AD for the county. The scheme is run by Somerset Waste Partnership (SWP), a consortium of the individual district councils within the county (listed in Table 13.1) using contractors May Gurney.

13.2.1 County Profile

Somerset is a primarily rural county in the south west of England. It is formed of five district local authorities with the number of households per district as shown in Table 13.1.

Table 13.1. Households per district (Mansell 2012)

District	*No. of Households*
Mendip (MDC)	48,520
Sedgemoor (SDC)	50,860
South Somerset (SSDC)	72,850
Taunton Deane (TDBC)	49,230
West Somerset (WSDC)	17,450
SWP Total	238,910

The districts vary considerably in geography, accessibility and population. West Somerset is one of the largest and least accessible, with fewest major roads, and has the lowest population density at 0.5 persons per hectare (SINe, 2010c) compared to a county average of 1.5. Taunton Deane and Sedgemoor have higher than average population densities, at 2.4 (SINe, 2010a) and 1.9 persons per hectare (SINe, 2010b) respectively, and are relatively well connected with motorways and roads linking the major conurbations.

13.2.2 Schemes for comparison

Somerset currently runs a weekly collection of recyclables, with kerbside sorting into stillage vehicles collecting glass, paper, cardboard, food waste, tins, cans, foil, plastic bottles, car batteries, shoes, clothes and textiles. There are also separate fortnightly residual waste and green waste collections.

Although food waste collection has been running since 2004 in some districts, it is only since October 2011 that the system has become county-wide. In 2011 around 17,275 tonnes of food waste was collected (Mansell, 2012) and sent predominantly to in-vessel composting (IVC) at Dimmer near Castle Cary, with the excess leaving the county and being processed in nearby counties such as Dorset and Devon (SCC, 2011a, p10).

IVC is not viewed as a particularly effective way of dealing with food waste, and Somerset is now constructing an anaerobic digestion (AD) plant at the Walpole landfill site near Bridgwater. The new AD plants is scheduled for completion in the summer of 2013. It will be funded, built and run by Viridor Waste Management, and have a capacity of 30,000 tonnes/year (SCC, 2011c, p32) with up to 21,000 tonnes/year available for SWP (Waste Management World, 2011). Viridor will source the rest of the waste to fill the plant from the commercial and industrial sector. SWP has chosen the Walpole site as it already has gas engines to turn the produced gas into electricity. The gas engines were installed for the landfill gases and are therefore suited to this application. SWP is also very interested in direct injection into the grid and conversion of biogas to fuels for transport, to save money and further decrease its carbon foot-print.

13.2.3 Data Sources

Two sources of data have been used for this report: SWP and May Gurney. The SWP records county and district monthly waste totals, broken down into collection type and collection material. Data from April 2010 - January 2012 was provided for analysis (Mansell, 2012). May Gurney records daily vehicle round data including: weight collected, round mileage, hours worked, delivery location and waste origin by district, and provided data covering April - December 2011 for Taunton, Colley Lane and Evercreech Depot and April - October 2011 for Williton (Cowdell, 2012a). Combining these data allowed analysis of the transportation requirements of collection, in terms of miles travelled, estimated fuel used and emissions per tonne of food waste collected.

13.2.4 Depots

Currently the county has five depots that receive and sort the county's waste and recycling for processing. Of these, four run recycling stillage vehicles: Taunton, Colley Lane Bridgwater, Williton and Evercreech. The districts served by each depot are shown in Table 13.2.

Table 13.2 Districts served by depots for recycling collections

Depot	***District served***
Colley Lane	**Sedgemoor** and Taunton Deane
Evercreech	**Mendip**, **South Somerset** and Sedgemoor
Taunton	**Taunton Deane** and **South Somerset**
Williton	**West Somerset**

The amount of recycling sent to each depot varies significantly, with most depots receiving significant amounts of waste only from the districts in bold. The location of the depots and processing centres within the county are shown in Figure 13.1.

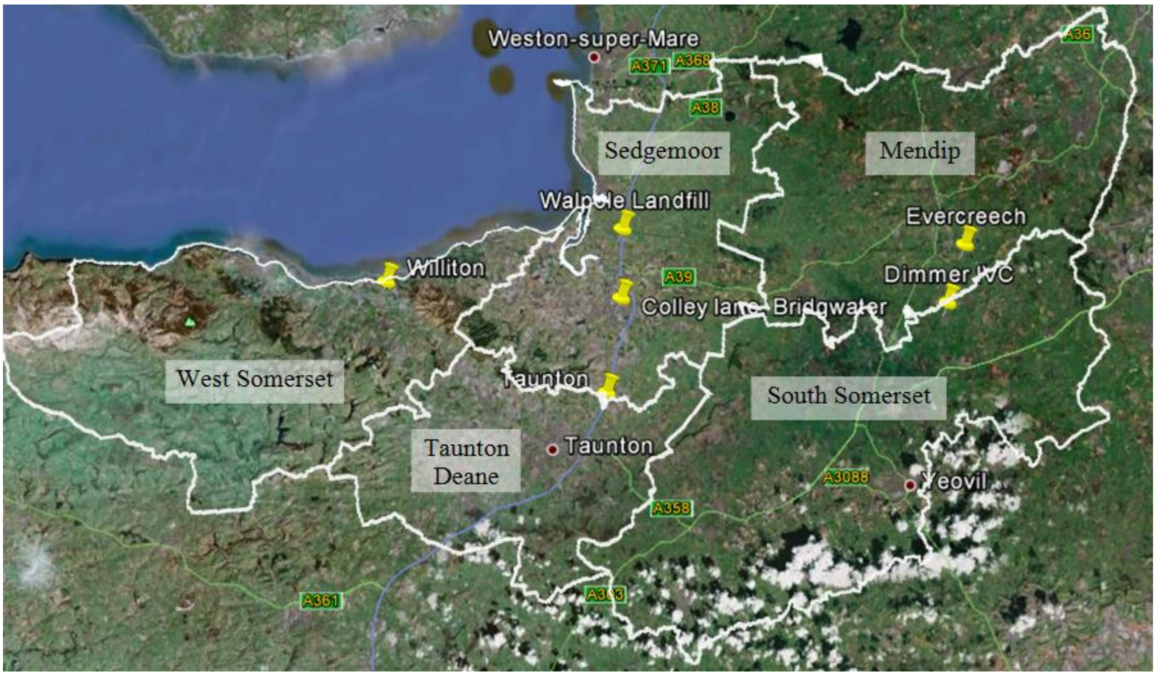

Figure 13.1 Map of districts, county depots and food processing centre locations (Google Earth © 2012)

13.2.5 Data Analysis

To allow assessment of the food waste stream alone it was necessary to calculate the proportion of food waste in the stillage vehicle load. This was calculated monthly based on SWP data for each district. Due to the size of each stillage and the volume of different recyclables, vehicles may not always return to the depot equally full of all waste streams, and therefore the percentage yield of food waste may vary between routes and days. Specific records for were not available, however; average values are shown in Table 13.3.

Table 13.3 District food waste yield as percentage of stillage vehicle yield

District	*% of stillage yield which is food waste*
MDC	24.2
SDC	30.2
SSDC	31.1
TDBC	29.6
WSDC	30.0
SWP	28.4

The collection routes and delivery to processing were assessed in accordance with efficiency measures. The first of these is the distance travelled by each tonne of food waste. For collection routes this was calculated from source data from Cowdell (2011a):

$$collection\ efficiency\ (miles\ per\ tonne) = \frac{Length\ of\ route\ (miles)}{weight\ \ collected\ per\ route\ (tonnes)} \qquad (1)$$

For delivery to processing stage Google Maps journey planner was used along with tonnages of food waste leaving the depots (Cowdell 2011b). The distance and journey time from each of the depots to processing at Dimmer and Walpole are shown in Table 13.4. These values were also used to calculate fuel consumption using an emissions formula (EEA, 2009).

Table 13.4 Journey information for delivery of food waste to processing

	Distance (miles)		*Time (minutes)*	
	Walpole AD	**Dimmer IVC**	**Walpole AD**	**Dimmer IVC**
Colley lane (Bridgwater)	5.3	25	17	54
Williton	21.8	41.9	54	93
Taunton	13	36.5	28	56
Evercreech	28	4.5	46	12
Total	68.1	107.9	145	215

13.2.6 Energy Requirement Calculation

The EEA fuel consumption equations (EEA, 2009) were used to calculate the fuel used during collection based on vehicle type, mileage and hours worked. This information was used to estimate the energy requirements and GHG emissions of the collection scheme. The calculations took into account the three journeys involved in delivery to processing; route collection, full vehicle from depot to processing, empty vehicle returning to depot. Other assumptions made were:

- Vehicle type is consistent across the districts and routes.
- The collection vehicle is half full, representing an average for a journey where the vehicle starts empty and ends full. This is based on a further assumption that each route fills the vehicle.
- The gradient of all routes averages out to be flat. As specific route mapping was not readily available due to changes in recording and route planning it was not possible to look at the course of the vehicles. Therefore equations with zero gradient were used.
- The density of diesel is 835kg/m^3 (Finance Act 1998), to convert the fuel consumption from kilograms to m^3.

Collection. The vehicles used during collection are operated by May Gurney and comprise a range of 7.5-12 tonne vehicles (SWP, 2007) with a similar stillage arrangement throughout the fleet, and as such equation 2 is used:

$$y = \frac{1}{cx^2 + bx + a} \qquad (2)$$

Where:
y = fuel consumption (g/km)
x = vehicle speed (km/hour)
a = 0.00170
b = 0.00019
c = -0.000002
in accordance with Euro-V vehicle (EEA 2009).

Operation. During kerbside collection the stillages are hand-filled by operatives and there is no compaction; fuel consumption during the round is thus exclusively due to the vehicle engine. As the vehicle is generally left idling while being loaded on collection routes, the fuel consumption is not solely related to miles travelled. Nguyen and Wilson (2010) calculated up to 25.1% of fuel during collection can be used when idling. Assuming 88% of the time is associated with the collection round, based on 12% for journey to and from round (WRAP, 2009a), this increases fuel consumption by 0.88*0.251=22.1%. At the depot the compartments are removed and emptied into relevant sections by forklift. Food waste is then driven to processing.

Delivery to Processing. Currently the majority of food waste, over 70% (SCC, 2011a), is sent to IVC at Dimmer with the remainder transported to processing in Devon and Dorset. For this report it was assumed, however, that all food waste was sent to Dimmer as delivery routes for depots were unavailable.

This delivery distance is a main factor in the location of a new AD and it is undesirable to increase the energy required for transporting waste if relocated to Walpole.

Currently the fleet used for delivery to processing includes both rigid and articulated HGVs. To allow for this a mid range vehicle was selected, a rigid trailer 28-32t. Each vehicle makes two journeys: the outward journey from the depot full, and the return journey back to the depot empty. As with the collection round, the gradient is assumed flat and equation 3 is used:

$$y = e + (a \cdot e^{-bx}) + (c \cdot e^{-dx}) \qquad (3)$$

Where:

	Full	Empty
a =	500.1444	502.3551
b =	0.032799	0.060047
c =	18756.01	8995.975
d =	0.925878	0.743233
e =	228.0233	189.4883

in accordance with Euro-V vehicle (EEA, 2009).

For this journey the tonnage for each trip is the average tonnage recorded leaving the depot (Cowdell, 2012b). Journey time and distance are shown in Table 13.3.

13.2.7 Collection Efficiency Measures

Once the daily fuel consumptions have been calculated, they are then divided by the recycling yield on that day to calculate the fuel consumption per tonne of recycling collected. These values are averaged and multiplied by the yield percentage of food waste to calculate the average monthly fuel consumption per tonne of food waste collected. Monthly totals are used, for ease of comparison at later stages and because the percentage of stillage collection represented by food waste is calculated monthly. The energy requirement is proportional to the fuel consumption and is the amount of energy necessary to transport each tonne of food waste in mega joules (MJ) The energy is calculated from the fuel consumption multiplied by the specific energy density of diesel, taken as 36 MJ/litre (Biomass Energy Centre, N/A).

Carbon dioxide emissions are similarly proportional to fuel and calculated by multiplying fuel consumption by 2.6413 to get kg/tonne. Total GHG emissions of transport are calculated in kg CO_2 equivalent, and are calculated by multiplying fuel consumption by 3.1787 (AEA, 2010). GHG combines direct emissions of carbon dioxide, methane, nitrous oxide and indirect emissions due to fuel production of 0.5067 kg/tonne.

13.2.8 AD Modelling

To complete the energy balance for the system the AD energy model (Salter, 2011) was used to calculate the predicted energy output of the plant proposed at Walpole. Ambient temperatures were taken for the city of Bath. The model was run assuming different uses of the biogas: firstly in a CHP; secondly with upgrading of the gas for direct use; and thirdly, upgrading and compression of the gas.

13.3 Results and Discussion

13.3.1 Household yield

The average yield of food waste collected per household is shown in Figure 13.2 below. These figures are based on recorded data from 2011 for each district disregarding the effect of participation or set-out rates. West Somerset data is only an average of November 2011 to January 2012 as the scheme was only started in October.

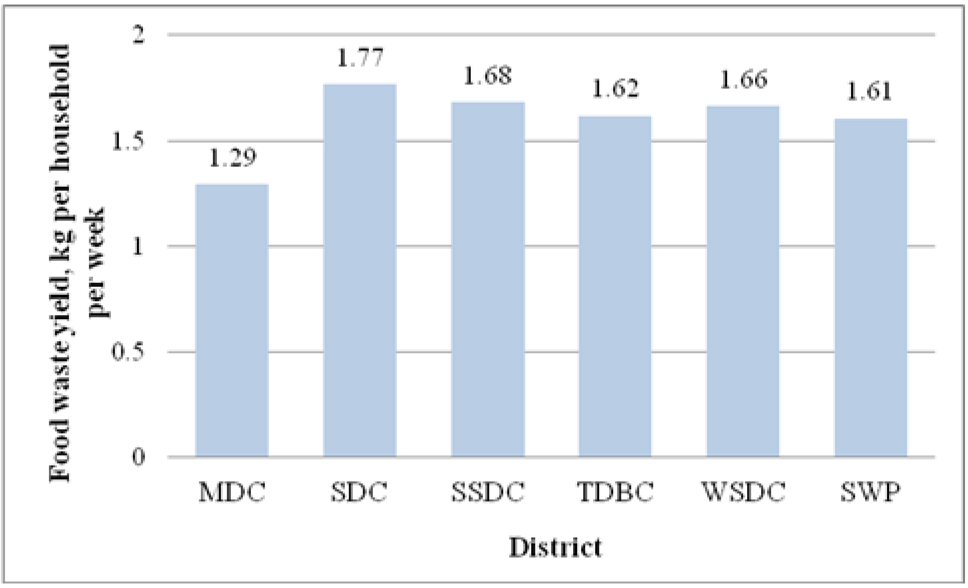

Figure 13.2 Average food waste yields per household per week

The graph illustrates that SDC has the highest yield in the county per household, and MDC the lowest. MDC has the lowest percentage of food waste in recycling collections and a lower household yield correlates with this, and suggests that other forms of recycling are more prevalent. It is useful to note that West Somerset yields have quickly increased to match the rest of the county although previous schemes have shown that initial yields are sometimes greater than the average over time (WRAP, 2009).

The districts perform well when compared to WRAP trials (WRAP, 2009) where the average food waste yield was 1.5 kg/week for fortnightly collections. However if trial participation rates are considered WRAP recorded an average collection of 2.5 kg/week suggesting there is not full participation in the county or that there is less food waste recycled per household.

The trend in food waste yields from April 2010 is illustrated in Figure 13.3 over the full 22 months. It can be seen that there is a significant fluctuation throughout the year in yields, with similar trends for each district throughout the recording period, showing peaks in winter likely linked to the holidays and lower yields in the summer.

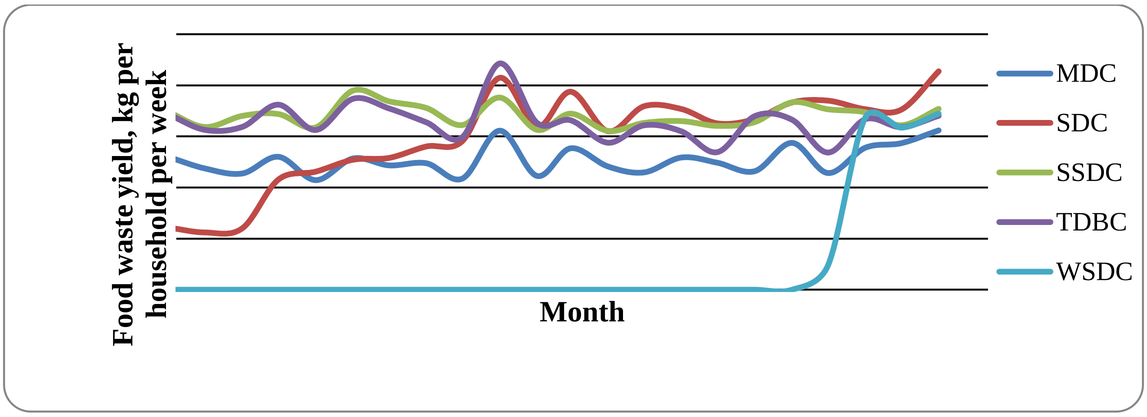

Figure 13.2 Trends in food waste yields per household during the collection period

There is no significant trend in yield over time for the whole county as the WSDC scheme is new and SDC yield has increased significantly. Over the collection period for each district the trend for household yield has: increased in Sedgemoor, West Somerset and Mendip districts, decreased in Taunton Deane and remained relatively steady within South Somerset.

13.3.1 Collection Efficiency

For each district the route data was used to calculate the average mileage each tonne of food waste travelled. From Table 13.5 it can be seen that recycling collected by WSDC travels the furthest during collection. This is unsurprising as the district has very few major towns and has the lowest population density. At the other end of the scale travel distance within Taunton Deane and Sedgemoor is considerably lower. Both are well connected to depots and have higher than average population densities.

Table 13.5 Collection efficiency (miles per tonne)

	Distance travelled (miles/ tonne of recycling)					
Month	**MDC**	**SDC**	**SSDC (EV)**	**SSDC (TA)**	**TDBC**	**WSDC**
Apr-11	30.39	19.23	33.21	44.73	20.16	60.61
May-11	34.10	19.51	38.50	45.82	23.02	66.06
Jun-11	29.54	22.16	32.32	51.07	24.39	59.47
Jul-11	26.89	25.30	30.13	46.21	18.58	60.89
Aug-11	20.79	21.06	23.04	49.42	19.02	60.58
Sep-11	23.32	20.39	27.15	50.42	22.70	59.49
Oct-11	26.50	22.39	30.83	56.29	21.61	216.92
Nov-11	23.74	20.13	26.89	43.98	19.45	0.00
Dec-11	25.82	19.46	31.30	45.54	19.63	0.00
Average	26.79	21.07	30.37	48.16	20.95	64.89
				(Apr-Sep average)		61

South Somerset sends recycling to both Evercreech (EV) and Taunton (TA) depots, with Taunton routes consistently less efficient. South Somerset is the biggest county and its outer extents are some of the furthest points from any depots, which means that although collection round itself maybe short, distance to depot is likely quite large and it will be difficult to improve efficiency. This is of particular relevance when considering its largest conurbation Yeovil, which is the furthest major population centre from a depot.

Although other districts record some waste going to more than one depot, the data were limited and have not been processed. In these cases there were few rounds going to these depots and they have therefore been omitted. When adjusted for food waste yield similar trends can be seen between the counties, shown in Table 13.6.

Table 13.6 Collection efficiency (miles per tonne of food waste)

	Distance travelled (miles/per tonne of food waste recycling)					
Month	**MDC**	**SDC**	**SSDC (EV)**	**SSDC (TA)**	**TDBC**	**WSDC**
Apr-11	7.31	5.93	10.16	13.68	6.79	0.00
May-11	7.33	6.06	11.89	14.15	5.87	0.00
Jun-11	7.25	6.28	9.77	15.44	7.80	0.00
Jul-11	6.67	8.53	9.32	14.29	4.92	0.00
Aug-11	4.44	5.52	6.90	14.80	5.57	0.00
Sep-11	5.89	6.10	8.87	16.47	6.70	0.00
Oct-11	6.04	7.00	10.36	18.92	6.23	19.03
Nov-11	6.95	5.83	8.42	13.77	6.10	0.00
Dec-11	6.38	6.50	9.27	13.49	6.12	0.00
Average	6.47	6.42	9.44	15.00	6.23	19.03

The most notable differences between Tables 13.5 and 13.6 is that MDC records more similar values to SDC. However MDC had the lowest yield for food waste and it represents a smaller percentage of the stillage vehicle, so its efficiency for food waste collection is good, though slightly misleading. If the proportion of food waste as a percentage of total recycling collected increased then the FC assigned would increase and district performance may in fact worsen. However if yields increase proportionally between recyclables then their route efficiency will remain good.

Data for West Somerset are currently very limited, with only one recorded month of food waste collection at the time of data gathering. In addition routes may not be finalised yet, as when food waste collection was added in October average distance travelled increased significantly, as shown in Table 13.4. As West Somerset is the most rural district, however, it may be expected to have higher distances.

Emissions and Energy Calculation

Fuel consumption of the collection routes was calculated using equation 2 (EEA, 2009), increased by 22.1% to accommodate for fuel consumed while idling. These were then multiplied by food waste yield percentage to calculate the FC required to collect a tonne of food waste recycling in each district (Table 13.7). To obtain the energy consumption the FC is then multiplied by the specific energy of diesel to calculate the energy used in collection (Table 13.8). GHG emissions are also proportional to fuel consumption (Table 13.9).

These results show significant variability within the county, with TDBC requiring just over 50% of the energy required to collect food waste within SSDC and send it to Taunton. Table 13.7 also shows that energy requirements for most districts, particularly MDC and SSDC (EV), are generally falling over time, suggesting that the schemes are becoming more efficient. However as there are only nine months of data this could be due to annual variation and a similar pattern could be observed cyclically if more data is analysed. For example, as

December has a higher yield per household (Figure 13.3), individual rounds become shorter as more waste is collected. This is dependent on round proximity to depot, as the journey to and from the collection round section of the route would become more common, and can lead to increased energy requirements if journeys are long.

Table 13.7 Fuel consumption per tonne of food waste collected

	FC (litres/per tonne of food waste recycling)					
Month	**MDC**	**SDC**	**SSDC (EV)**	**SSDC (TA)**	**TDBC**	**WSDC**
Apr-11	3.17	2.45	4.05	4.24	2.73	0.00
May-11	3.17	2.60	4.80	4.51	2.28	0.00
Jun-11	3.08	2.63	3.94	5.05	3.01	0.00
Jul-11	2.87	3.90	3.91	4.94	2.11	0.00
Aug-11	1.97	2.37	2.95	4.94	2.30	0.00
Sep-11	2.44	2.74	3.42	5.88	2.78	0.00
Oct-11	2.28	2.93	3.72	6.48	2.57	6.89
Nov-11	2.60	2.57	3.06	4.90	2.59	0.00
Dec-11	2.27	2.76	3.14	4.40	2.45	0.00
Average	2.65	2.77	3.66	5.04	2.53	6.89

Table 13.8 Energy requirement to collect a tonne of food waste

	Energy (MJ/per tonne of food waste recycling)					
Month	**MDC**	**SDC**	**SSDC (EV)**	**SSDC (TA)**	**TDBC**	**WSDC**
Apr-11	114.14	88.10	145.87	152.71	98.12	0.00
May-11	114.17	93.62	172.79	162.41	82.07	0.00
Jun-11	110.95	94.80	141.94	181.77	108.28	0.00
Jul-11	103.21	140.32	140.68	177.94	75.89	0.00
Aug-11	71.09	85.42	106.08	177.89	82.93	0.00
Sep-11	88.01	98.77	123.02	211.61	99.98	0.00
Oct-11	82.20	105.57	133.77	233.23	92.54	247.90
Nov-11	93.65	92.38	110.22	176.45	93.28	0.00
Dec-11	81.60	99.27	113.07	158.55	88.23	0.00
Average	95.45	99.81	131.94	181.40	91.26	247.90

Table 13.9 GHG emission per tonne of food waste collected

	GHG (kg CO_2 eq./per tonne of food waste recycling)					
Month	**MDC**	**SDC**	**SSDC (EV)**	**SSDC (TA)**	**TDBC**	**WSDC**
Apr-11	10.08	7.78	12.88	13.48	8.66	0.00
May-11	10.08	8.27	15.26	14.34	7.25	0.00
Jun-11	9.80	8.37	12.53	16.05	9.56	0.00
Jul-11	9.11	12.39	12.42	15.71	6.70	0.00
Aug-11	6.28	7.54	9.37	15.71	7.32	0.00
Sep-11	7.77	8.72	10.86	18.68	8.83	0.00
Oct-11	7.26	9.32	11.81	20.59	8.17	21.89
Nov-11	8.27	8.16	9.73	15.58	8.24	0.00
Dec-11	7.20	8.77	9.98	14.00	7.79	0.00
Average	8.43	8.81	11.65	16.02	8.06	21.89

Using these figures total GHG emissions associated with collection equals around 195 m^3 per annum. If the county food waste rises to 21,000 tonnes with the same efficiency this value will rise to 220 m^3.

Looking at collection efficiency it can be seen that the smaller, more densely populated districts such as Taunton Deane recorded the more favourable results. This is as expected as these districts are closer to, or include depots, and with higher population density travel between households en route is predominantly shorter. The collection rounds are not broken down into journey to and from route and actual collection route time, however so the effect of the journey to collection round is unknown.

Delivery to Processing. Using equation 3 and route data obtained from Google Maps, the fuel consumption of the delivery of food waste to Dimmer IVC and Walpole AD was calculated, as shown in Table 13.9. Two fuel consumptions are identified for each route (to and from location) and then totalled to calculate the overall value. As discussed in the methodology the tonnage of waste for each route is the average of that recorded leaving each depot (Cowdell 2011b).

The weight of food waste recorded suggests that each vehicle may not be full. However vehicles are treated as such for FC equation. The variation in recorded weights leaving the depot is likely variation in level of filling but may be partly due to varying density of food waste depending on source and level of compaction over time.

Table 13.10. Fuel consumption to treatment

		Distance (miles)	Time (minutes)	Average speed (mph)	Average speed (km/h)	FC (g/km)	Per journey		Tonnage per trip (tonnes)	FC (litres/ tonne of food waste)	FC (litres/ tonne of food waste)
							FC (kg)	FC (litres)			
Evercreech	to Walpole	28	46	36.52	58.78	300.8	8.42	10.09	15	1.13	1.13
	from Walpole					204.2	5.72	6.85			
	to Dimmer	4.5	12	22.50	36.21	380.5	1.71	2.05	15	0.23	0.23
	from Dimmer					246.6	1.11	1.33			
Taunton	to Walpole	13	28	27.86	44.83	343.0	4.46	5.34	16.26	0.54	0.54
	from Walpole					223.5	2.91	3.48			
	to Dimmer	36.5	56	39.11	62.94	291.5	10.64	12.74	16.26	1.32	1.32
	from Dimmer					201.0	7.34	8.78			
Williton	to Walpole	21.8	54	24.22	38.98	367.3	8.01	9.59	17.25	0.92	0.92
	from Walpole					237.8	5.18	6.21			
	to Dimmer	41.9	93	27.03	43.50	348.1	14.58	17.47	17.25	1.67	1.67
	from Dimmer					226.3	9.48	11.36			
Colley Lane	to Walpole	5.3	17	18.71	30.10	414.3	2.20	2.63	16.69	0.26	0.26
	from Walpole					271.9	1.44	1.73			
	to Dimmer	25	54	27.78	44.70	343.5	8.59	10.28	16.69	1.02	1.02
	from Dimmer					223.8	5.59	6.70			

From Table 13.9 it is clear that by transporting food waste to AD at Walpole in the future overall journey distance will reduce, with three depots reducing travel distance by around 20 miles per journey (40 miles round trip). The disadvantage is that the journey length has increased for food waste removed from Evercreech, which receives nearly as much recycling as Colley Lane and Taunton depots combined. Therefore energy savings shown in Figure 13.4 are less than expected and a rethink of collection routes may offer more substantial benefits.

Table 13.11 Recorded kerb side collection totals (Cowdell 2012a)

Depot	**Recycling collected**
Evercreech	21,581.31 tonnes
Colley lane	10,788.08 tonnes
Taunton	12,630.01 tonnes
Williton	700.88 tonnes

The yearly energy savings, (**Figure 13.3**) by moving to Walpole was calculated for each district by:

$$\begin{aligned} \textit{Net energy of relocating} \\ &= \textit{Average monthly food waste collected} \\ &\times (\textit{energy required to transport to AD} \times 12 \\ &- \textit{energy required to transport to IVC} \times 12) \end{aligned} \qquad (4)$$

These are then summed to get the county total, SWP.

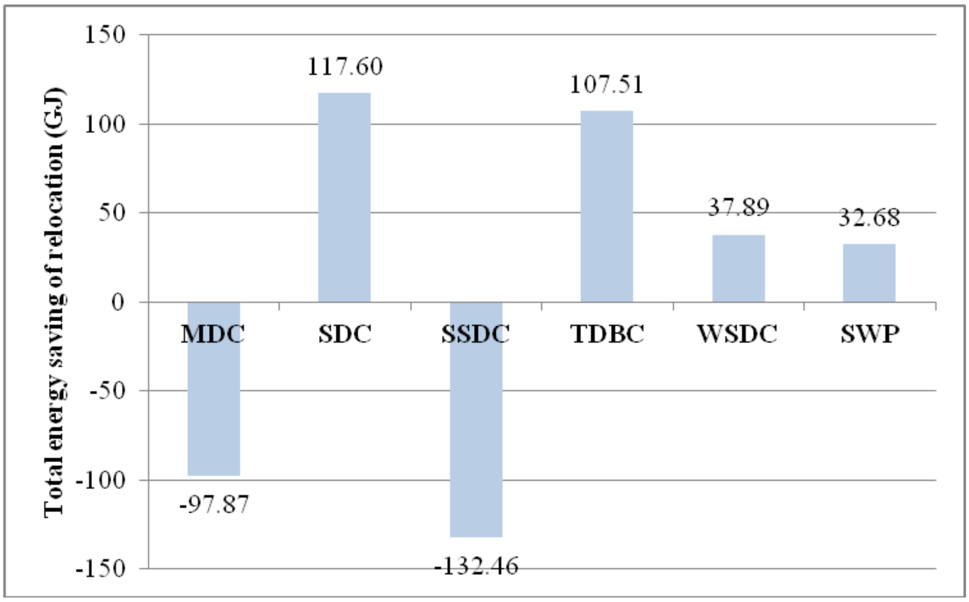

Figure 13.3 Yearly net energy of relocating to Walpole

The biggest energy change is actually an increase in energy required when moving SSDC waste, which is because around 83% of food waste is currently collected and sent to Evercreech. This increases journey length by 74 miles round trip.

Delivering half the waste from the western side of South Somerset to Taunton depot may provide savings with route length not increasing substantially if routes are planned correctly, due to relative proximity of Evercreech and Taunton depots to district. Likewise it may also be worthwhile to run western Mendip collection routes out of Colley Lane depot.

Alternatively it may also be worthwhile maintaining some form of processing at Dimmer, either the existing IVC or another AD plant to process food waste from the east of Somerset. There are disadvantages however as IVC would considerably reduce the gains from energy generation, and the construction of two separate plants would reduce net energy gain due to operating requirements. There is the possibility of using existing AD plants in the county; the best location would be the Wincanton plant, but and its capacity is unlikely to be sufficient.

13.3.2 Projected Energy Requirements

By considering both the collection rounds and the transport stages a full picture of what is required to transport food waste within the current and proposed scheme can be viewed. Table 13.11 shows the current scheme with delivery to Dimmer IVC and Table 13.12 the proposed scheme to Walpole AD. The results are broken down for each district and also show the county average which is weighted according to county yield. Data for SSDC is shown for both depots and the average for the district found by multiplying each depots result by the proportion of waste it receives. Evercreech receives around 83% of SSDC food waste and the results for the district reflect this weighting.

Table13.12 Efficiency of collection scheme, delivery to IVC

District	Measures per tonne of food waste collected				
	Fuel consumption (litres)	Carbon dioxide emissions (kg CO_2)	Total GHG emissions (kg CO_2 e)	Energy requirement (MJ)	collection efficiency (miles)
MDC	2.88	7.60	9.14	103.56	6.77
SDC	3.79	10.01	12.05	136.44	7.91
SSDC	4.30	11.35	13.66	154.74	10.98
TDBC	3.86	10.19	12.27	138.92	8.48
WSDC	8.56	22.60	27.20	308.06	21.46
SWP	4.18	11.04	13.28	150.41	9.85
SSDC (EV)	*3.89*	*10.28*	*12.37*	*140.05*	*9.74*
SSDC (TA)	*6.36*	*16.81*	*20.23*	*229.06*	*17.24*

Table 13.13 Efficiency of collection scheme, delivery to AD

District	Measures per tonne of food waste collected				
	Fuel consumption (litres)	Carbon dioxide emissions (kg CO_2)	Total GHG emissions (kg CO_2 e)	Energy requirement (MJ)	Collection efficiency (km/tonne)
MDC	3.78	9.98	12.02	136.09	8.34
SDC	3.03	8.01	9.64	109.20	6.73
SSDC (av.)	4.92	13.01	15.65	177.26	12.05
TDBC	3.08	8.13	9.78	110.78	7.03
WSDC	7.80	20.61	24.80	280.87	20.30
SWP	4.13	10.91	13.12	148.64	9.78
SSDC (EV)	*4.79*	*12.66*	*15.24*	*172.58*	*11.31*
SSDC (TA)	*5.58*	*14.74*	*17.74*	*200.92*	*15.80*

It can be seen that looking at the county as a whole there is not much difference in the two schemes, saving only 1.77 MJ per tonne collected, and a mileage difference of 0.07miles.

Due to the limited data for WSDC it is unclear if the value obtained for this district is truly representative, which affects the efficiency of the county as a whole. To counter this, efficiency has been calculated omitting WSDC, (Table 13.14). In this case the weighting associated with each depot has been recalculated to exclude WSDC.

Table 13.14 Efficiency of collection scheme, delivery to AD omitting WSDC

District	Measures per tonne of food waste collected				
	Fuel consumption (litres)	Carbon dioxide emissions (kg CO_2)	Total GHG emissions (kg CO_2 e)	Energy requirement (MJ)	Collection efficiency (km/tonne)
To IVC	3.83	10.11	12.17	137.81	8.92
To AD	3.82	10.09	12.14	137.51	8.90

From Table 13.13 there appears to be even less difference in scheme efficiency. However as shown in Figure 13.4 this is a saving of 32.68 GJ a year and ignores any benefit from using the food waste for AD.

In order to calculate the true gains of moving to Walpole the AD benefit must be included. When the digester opens at Walpole, Somerset have projected a provision of 21,000 tonnes and the AD calculations are based on this value, and so the total energy requirement is higher than in Figure 13.4. To accommodate this, current collection yields are increased proportionally to represent the predicted yield of 21,000 tonnes, where:

$$\text{Projected yield per district} = \frac{\text{District monthly yield}}{\text{County monthly yield}} \times \text{projected yield for county of } 21{,}000T \qquad (5)$$

This enables a projected energy requirement of collection to be forecast, Table 13.14, for comparison with AD potential production. The total for SWP is therefore:

$$\sum \text{Projected yield per district tonnes} \times \text{energy per tonne } (MJ) \qquad (6)$$

where energy per tonne is that shown in Table 13.12, for collection and delivery to AD at Walpole. From Table 13.15, the projected energy requirement is 3120 GJ/year.

Table **13.15** Projected energy requirements

District	Average food waste per month (tonnes)	% of total represented by district	Energy required per tonne of waste collected (MJ)	Energy required per month (MJ)	Current Energy required per year (MJ)	Projected tonnage -based of 21000 total (tonnes)	Projected energy (MJ)
MDC	250.7	16.33%	136.09	34,117.76	409,413.16	3429	466,676
SDC	359.81	23.44%	109.2	39,291.25	471,495.02	4922	537,441
SSDC	490.16	31.93%	177.09	86,802.43	1,041,629.21	6705	1,187,316
TDBC	318.45	20.74%	110.78	35,277.89	423,334.69	4356	482,544
WSDC	116.15	7.57%	280.87	32,623.05	391,476.61	1589	446,230
SWP	1535.27	100%	-		2,737,348.69	21000	3,120,207
					Total energy year (GJ) =		3120.2

13.3.3 AD Modelling Results

Table 13.16 shows the results of AD modelling, independent of waste transport.

Table **13.16** Modelling outputs for AD at Walpole Depot, Somerset

Energy and material outputs (/year)	CHP	Gas upgrading	Gas upgrading and compression	
Digester input	21000	21000	21000	tonnes
Digester capacity required	4658	4658	4658	m3
Digester retention time	74	74	74	days
Methane produced	1947456	1947456	1947456	m3
Methane available	1927981	1927981	1927981	m3
Biogas (volume)	3357683	3357683	3357683	m3
Biogas (mass)	4167	4167	4167	tonnes
Digestate	16833	16833	16833	tonnes
Electricity produced	24171	0	0	GJ
	6714733	0	0	kWh
	807	0	0	kW generator
Heat produced	34530	0	0	GJ
Upgraded biogas	0	1927981	1927981	m3
Waste transport diesel	0	0	0	litres
Total energy output	58701	0	0	GJ
Energy inputs required (/year)				
Waste transport	0	0	0	GJ
Digestate transport	1899	1899	1899	GJ
CHP supplied electricity	3024	0	0	GJ
Imported electricity	0	6614	8696	GJ
Boiler/CHP supplied heat	6453	0	0	GJ
Imported gas for heat	0	7591	7591	GJ
Pasteuriser inclusion	pre	pre	pre	digester
Pasteuriser heat	5361	5361	5361	GJ
Total energy input	11485	16214	18296	GJ
Energy exports				
Energy in methane produced	69758	69758	69758	GJ
Exported electricity	21147	0	0	GJ
	5875	0	0	MWh
Exported heat	28078	0	0	GJ
	7800	0	0	MWh
Energy in upgraded CH4	0	69060	69060	GJ
Exported energy	49225	69060	69060	GJ
Energy Balance	47216	52847	50764	GJ
	2.2	2.5	2.4	GJ/tonne

Along with the benefit gained from sending the food waste to a new location the digestion of the food waste provides energy. Although the plant has a planned capacity of 30,000 tonnes, the model was run with the 21,000 tonnes from SWP, to determine the digestion outputs and inputs specifically attributable to waste from SWP. The model shows that depending on whether biogas is used onsite in a CHP or upgraded for direct use, with or without compression, the net energy provided would be between 47,216 to 52,847 GJ, or 2.2 – 2.5 GJ/tonne.

The options for use of the biogas are dependent on need, and use as a fuel will depend on vehicle compatibility with biogas. There may also be increased transport costs associated with this, as vehicles will need to refuel at specific locations, not just any available petrol station. Moreover, to deliver upgraded biogas to depots / refuelling locations would involve transportation, as collection fleet vehicles will not travel to Walpole. However these costs may still enable a net energy gain if efficiently operated.

Furthermore, installing digestate delivery pipe networks to local farms similar to that at Cannington would reduce digestate delivery requirements.

13.4 Conclusions

In accordance with the aims of this study the efficiencies of the current and proposed system have been identified and show that across the county Taunton Deane and Sedgemoor benefit most from the move to AD at Walpole, with energy requirements and journey distances falling most. It can be seen that the energy required to collect food waste across Somerset varies considerably between districts, and that proposed plans to use waste for AD at Walpole leads to considerable energy gains over the current system. These could be further improved through revised route planning to ensure that food waste is sent to depots closer to Walpole, where this doesn't adversely affect collection rounds. This is particularly important in South Somerset where delivery to Evercreech and then onwards is currently the most costly route within the county.

Due to limited information currently available on similar schemes the relative efficiency of Somerset within the UK is unknown but expands existing knowledge on the subject. With further research it is hoped that comparisons can be made with other schemes to evaluate the quality of the scheme.

Inaccuracies may have arisen in calculation. This is predominately due to problems with data collection. All depots provided route collection data, but in some cases information was missing or erroneous that either did not allow use or had to be manipulated to compare with majority of data. Moreover due to the size and age of collection and delivery fleet the vehicles are not all consistent and assumption of consistency may have created inaccuracy. Due to the scale of the area covered, individual routes could not be compared within the limits of this report and although averages for collection are a fair representation detail is limited. The relatively recent start of food waste collection in West Somerset means that there is limited data to process and little conclusion can be drawn apart from food waste yields from this district. In the near future more data will be available and a truer analysis made. Further inaccuracy lies in the operational energy requirements. This report has worked on the assumption that a further 25% of fuel is required when idling, but information on idling fuel consumption for stillage vehicles is currently very limited and any future assessment should ensure that where possible more detailed analysis is used.

This report provides results that offer a fair representation of the county's food waste collection scheme but further analysis is recommended when more route data is available and stillage vehicle operation more accurate. Fuel consumption monitoring during the route may be a useful way of doing this, along with more detailed route breakdown of collection rounds, separating the journey into round and travel to and from round components. This would enable depot use by counties to be reviewed along with energy of the scheme.

13.5 Acknowledgements

Thanks should go to David Mansell at the Somerset Waste Partnership, Michael Cowdell at May Gurney and Wing Chu at the University of Southampton for their cooperation, advice and assistance.

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14 Conclusions

This report has examined case studies for potential anaerobic digestion plants at various scales, from the very small (15 m^3, 68 tonnes/year at Harrogate District Hospital) to a large commercial scale (~4700 m^3, 21000 tonnes/year for the county of Somerset), and for a number of scenarios. As expected, at the smallest scale the plants make only a small contribution to the overall energy consumption of the institution concerned and are unlikely to be constructed for economic reasons (e.g. Harrogate District Hospital; Welbeck College). In this situation the best solution is to join in with a local or municipal collection, where this is possible. In some cases, however, adoption of anaerobic digestion may appear worthwhile due to associated social or environmental benefits (e.g. HMP Hewell); this is especially so if the organisation has the capacity to construct and operate the plant in house (e.g. BMAD). Larger institutions such as universities are equivalent in size to a small town, and on-site AD can be feasible if it fits with existing infrastructure such as CHP plants. The Veolia depot provides an example where commercial considerations may favour the introduction of a scheme where collections are initially not energy-efficient but major improvements are possible. Once the community to be served is the size of a county, AD becomes a practical option and considerations of location and routing of collections become predominant. The simple theoretical study carried out provided a means of assessing the overall energy inputs and outputs from point source and distributed populations, as well as indicating their sensitivity to different factors and assumptions in planning the scheme. The results obtained in this way do not provide a complete energy balance since embodied energy and materials are not included: but the approach provides a means of energy budgeting to determine the feasibility of a scheme and its pay-back period in energy terms.