Assessment of Micro-Scale Anaerobic Digestion for Management of Urban Organic Waste: A Case Study in London, UK[1]

Dr. Mark Walker[1], Helen Theaker[1], Rokiah Yaman[2], Dr. Davide Poggio[3], Dr. William Nimmo[1], Angela Bywater[4], Prof. Mohamed Pourkashanian[1]

[1] Department of Mechanical Engineering, the University of Sheffield, Sheffield, S1 3JD, UK. hftheaker1@sheffield.ac.uk mark.walker@sheffield.ac.uk, d.poggio@surrey.ac.uk, w.nimmo@sheffield.ac.uk, m.pourkashanian@sheffield.ac.uk

[2] Camley Street Natural Park, 12 Camley Street, London, Greater London, N1C 4PW, UK. info@communitybydesign.co.uk

[3] Centre for Research in Social Simulation (CRESS), Department of Sociology, Faculty of Arts and Human Sciences, University of Surrey, Guildford, GU2 7XH, UK. d.poggio@surrey.ac.uk.

[4] University of Southampton, University Road, Southampton SO17 1BJ, UK, a.m.bywater@soton.ac.uk

Corresponding author: Mark Walker, Energy Building, Department of Mechanical Engineering, The University of Sheffield, Sheffield, S1 3JD, UK. mark.walker@sheffield.ac.uk, +44 114 2157242

Abstract

This paper describes the analysis of an AD plant that is novel in that it is located in an urban environment, built on a micro-scale, fed on food and catering waste, and operates as a purposeful system. The plant was built in 2013 and continues to operate to date, processing urban food waste and generating biogas for use in a community café. The plant was monitored for a period of 319 days during 2014, during which the operational parameters, biological stability and energy requirements of the plant were assessed. The plant processed 4574 kg of food waste during this time, producing 1008 m^3 of biogas at average 60.6 % methane. The results showed that the plant was capable of stable operation despite large fluctuations in the rate and type of feed. Another innovative aspect of the plant was that it was equipped with a pre-digester tank and automated feeding, which reduced the effect of

[1] Article available at http://dx.doi.org/10.1016/j.wasman.2017.01.036. Please note that access to the full text of this article will depend on your personal or institutional entitlements. This article can already be cited using the year of online availability and the DOI as follows: Walker *et al* (2017). Assessment of Micro-Scale Anaerobic Digestion for Management of Urban Organic Waste: A Case Study in London, UK. Waste Management (Preprint). j.wasman.2017.01.036.

feedstock variations on the digestion process. Towards the end of the testing period, a rise in the concentration of volatile fatty acids and ammonia was detected in the digestate, indicating biological instability, and this was successfully remedied by adding trace elements. The energy balance and coefficient of performance (COP) of the system were calculated, which concluded that the system used 49% less heat energy by being housed in a greenhouse, achieved a net positive energy balance and potential COP of 3.16 and 5.55 based on electrical and heat energy, respectively. Greenhouse gas emissions analysis concluded that the most important contribution of the plant to the mitigation of greenhouse gases was the avoidance of on-site fossil fuel use, followed by the diversion of food waste from landfill and that the plant could result in carbon reduction of 2.95 kg CO_{2eq} kWh^{-1} electricity production or 0.741 kg CO_{2eq} kg^{-1} waste treated.

Highlights

- A micro-scale AD plant was built and operated reliably in London, UK
- The system produced 0.596 m^3 CH_4 kg^{-1} VS from locally-collected mixed organic waste
- GHG reduction of the system was 0.741 kg CO_{2eq} kg^{-1} waste treated cf. landfilling
- The system advantageously included a pre-digestion tank to buffer the feed variations
- Biological ammonia inhibition was mitigated by trace element supplementation

Keywords: Anaerobic digestion, Biogas, Food waste, Urban organic waste, Ammonia inhibition, Micro-scale

Abbreviations

AD	Anaerobic Digestion
COD	Chemical Oxygen Demand
COP	Coefficient of performance
GHG	Greenhouse gas
HRT	Hydraulic retention time
kW_e	Kilowatts of electrical output
LCV	Lower calorific value
OLR	Organic loading rate
TPA	Tonnes per annum
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids

1 Introduction

Anaerobic Digestion (AD) in the UK and Europe has enjoyed a wide uptake in the past 20 years, due to governments' introduction of feed-in tariffs and renewable heat incentives improving its economic viability (Edwards et al., 2015). However, although there has been much development at scales over 125 kW_e electrical output, there has been very limited uptake of the technology at the micro scale (5-15kW_e or equivalent) (NNFCC, 2016).

The use of AD on a micro-scale is used mainly in developing countries, with an estimated 5 million household scale digesters across India and China alone, as it provides a convenient way of processing and sanitising local waste such as animal slurries (Lansing et al., 2008), as well as producing biogas. However, in the developed world, AD is generally restricted to larger scale plants. There are currently 316 non-sewage-based AD plants operating in the UK, with a total installed capacity of 290MW (average of 918 kW per plant) (NNFCC, 2016). These AD plants are fed on a variety of feedstocks, including energy crops, dairy effluent, food waste and animal slurries and manures.

However, across the UK there is now a growing introduction of source segregated food waste collections and a need to reduce waste and emissions wherever possible to achieve climate change targets. Micro-AD plants in an urban environment could offer support for these issues in the form of non-centralised (i.e. distributed) organic waste management. There are a number of challenges specific to the urban environment that AD can address (Stoknes et al., 2016).

Micro-scale AD applications have the potential to deliver a variety of advantages relative to conventional AD plants including; reduced transport requirements, potential for community involvement, and the fostering of a circular economy by means of creating a 'biorefinery' that will dispose of local waste, utilise its energy potential, and also produce a natural fertiliser that can be used in urban agriculture, horticulture and hydroponics. The demonstration of small-scale AD will also make the technology more familiar and accessible, which could potentially increase its uptake by adding understanding of the field and capturing feedstocks from sources that are out of the catchment area of larger plants.
This paper describes a monitoring study of a novel micro-AD system, with an innovative process design and unusual setting, implemented in a community wildlife park in London in the UK. The paper includes a system description, and performance, energy and carbon evaluations with the purpose of presenting and assessing the concept of micro-AD in the urban environment.

2 Materials and Methods

2.1 Site description

The pilot system was designed and installed by a consortium of companies and researchers in 2013, and the monitoring took place from October 2013 to November 2014. The plant was built within the grounds of the Camley Street Natural Park in London, UK and the site was used to convert locally produced, commercial organic waste, collected by cargo bicycle, into biogas for cooking, heating and electricity.

The following is a list of the key components installed as part of the micro-AD system:

- 2m^3 anaerobic digester (Methanogen UK Ltd., UK) containing an automated mechanical mixer and heated by an internal water heat exchanger
- Pre-feed system consisting of a chopper mill, a 0.65 m^3 mixed 'pre-feed' tank on load cells and a feeding pump (Guy Blanch Bio Development Ltd, UK)
- Hydrogen sulphide scrubber filled with activated carbon pellets
- 1 m^3 floating gasometer for biogas storage
- 0.46 m^3 digestate sedimentation tank
- 0.2 m^3 digestate liquor storage tank
- Purpose built automated biogas boiler
- Biogas hob
- A data logging system and a suite of sensors for online monitoring

A full schematic of the system is shown in Figure 1.

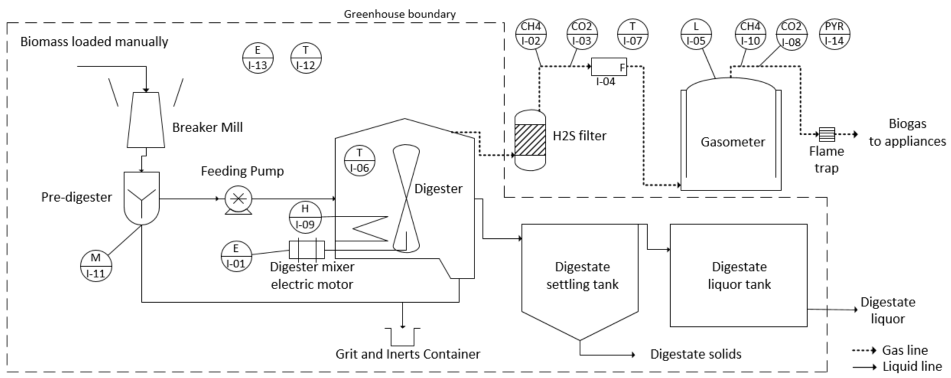

Figure 1: Schematic of equipment at the micro-AD site[2]

---

[2] Sensor abbreviation M – Mass, E – Electricity, T – temperature, H – heat, CH4 – methane %, CO2 – carbon dioxide %, F – Gas flow, L – Level, PYR – Incident solar radiation

2.2 System operation

The system was commissioned and began operating on the 16/10/2013 and continues to operate into 2017. The main feedstocks being added to the pre-digester tank during the monitoring period can be separated into four phases:

Phase 1: Day 1 to 15: apple pomace, catering waste, café waste, oats, tea leaves, water
Phase 2: Day 16 to 107: catering waste, café waste, tea leaves, water
Phase 3: Day 108 to 294: catering waste, soaked oats, soaked paper bin liners, water
Phase 4: Day 295 to 399: predominantly catering waste with some soaked paper bin liners, water

The phases are illustrated in Figure 2, which shows that both the type of feedstock and the quantity were very variable, due to variances in the collections sources over time. The system was designed with a pre-digester to smooth out these variations.

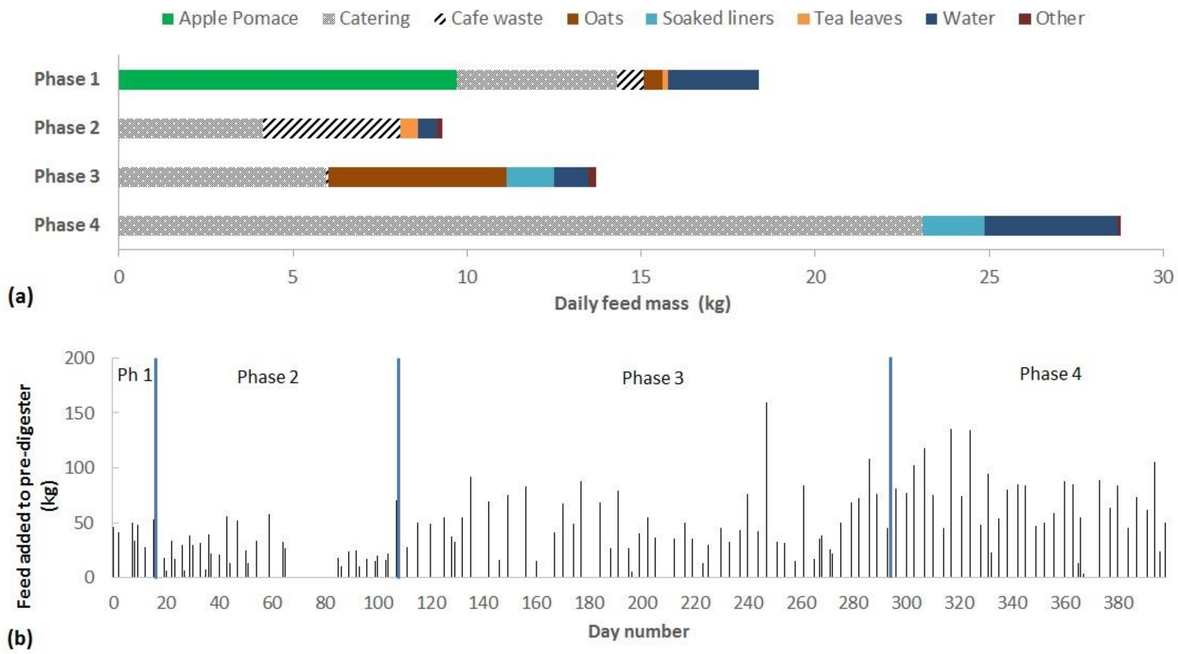

Figure 2: (a) Feedstocks added to the pre-digester in each phase and (b) mass of feed added to the pre-digester on each day.

The digester feed was expected to be in the range of 15-20 kg day^{-1}, although the average feed during the course of the experiment was lower than this, at 14.3 kg day^{-1}, due to commissioning and operational issues. The pre-digester tank was loaded manually, through a breaker mill, twice a week. From day 1 to 190, feeding was not automated, so the feedstock pump was operated by hand 4-5 times per week to pump the entire feed for the day from the pre-digester tank into the digester (i.e. 20 kg). After day 190, the feeding was automated and feed was automatically pumped into the digester at the rate of 2 kg every two hours. The plant was operated and tested by volunteers and staff, and the biogas was used on a gas hob in the site's café. A 1 kW_e CHP Stirling engine (Ecogen, UK) was planned for the site but this was installed after the monitoring period.

2.3 Project monitoring

The project monitoring period began on 3/1/14 (day 80) and data collection continued until 19/11/2014 (day 399) although some digestate samples were taken and analysed after this date up until 13/07/2015 (day 635). Three forms of monitoring were used: daily readings taken by the operators, automatic sampling, and laboratory-based ("off-line") sample testing.

2.3.1 Operator monitoring

Data collection was performed by the plant operator. During each loading operation, manual records were made of the type and amount of feedstock added to the pre-digester tank, including the addition of water, contamination, operational time taken, and notes about any problems or issues. Alongside this, manual measurements were taken of the cumulative biogas flow and digester temperature.

2.3.2 Automatic monitoring using sensors and cloud-based logging software

The system was also automatically monitored in real time by a suite of sensors connected to data acquisition hardware. These sensors measured the following: biogas production (Elster BK-G2.5 Diaphragm gas flow meter), methane and carbon dioxide content of the biogas at both the digester outlet and at the system outlet (Dynament NDIR CH_4 sensor, Dynament NDIR CO_2 sensor), temperatures of the digester, greenhouse and outside ambient (Atlas Scientific ENV-TEMP thermistor), electrical consumption of the site (ISKRAEMECO ME162 electricity meter) and digester (Finder 7E.13 electricity meter), heat consumption of the digester (Superstatic 449 heat meter) and incident solar radiation on the greenhouse (APOGEE CS-300 Pyrometer). In addition, biogas oxygen (ITG-103 electrochemical sensor) and hydrogen sulphide (ITG I-46 electrochemical sensor) composition were measured intermittently but these sensors did not operate reliably over the monitoring period.

Calibration of the biogas composition sensors was done using a calibration gas containing 35 % carbon dioxide, 1 % oxygen, 50 ppm hydrogen sulphide and the balance being methane. Recalibration was performed approximately every two months over the monitoring period. All other sensors were pre-calibrated from the factory.

The customised PC data logging software was developed using DAQFactory software and data was made available online through the DAQConnect website, for data sharing amongst the larger project team.

2.3.3 Offline analyses – laboratory-based testing of pre-digester and digestate

Samples from both the pre-digester tank and the digester output (digestate) were taken by the operator. TS and VS were measured as per standard methods (APHA, 1998), pH was measured with a Hach pH meter and probe. VFAs were measured using an Agilent 7890A gas chromatograph, with a DB-FFAP column of high polarity designed for the analysis of VFAs, as per the manufacturer's guidelines. Elemental content was determined using an elemental analyser (Flash EA2000, CE Instruments) equipped with a flame photometric detector (Flash EA 1112 FPD, CE Instruments). Alkalinity was measured by titration using endpoints of 5.75 (partial) and 4.3 (total) with intermediate alkalinity being the difference between the partial and total alkalinities. Anion and cation concentrations were measured using a Metrohm 940 ProfIC Vario Ion Chromatography system. Theoretical COD (Chemical Oxygen Demand) was calculated using the method of Baker et al. (1999).

3 Results and Discussion

3.1 System overview

3.1.1 Operational Key performance indicators for comparison

The data collected allowed the calculation of total feed and water added to the AD system over its operational period, hydraulic retention time (HRT), total biogas production and average overall, specific and volumetric biogas production. These are summarised in Table 1.

Table 1: Key performance statistics for the micro-AD plant from day 80 to day 399

Measurements	Value	Unit
Average daily feed amount	14.3	kg day^{-1}
Average daily VS added	3.22	kg day^{-1}
Average OLR	1.6	kg VS m^{-3} day^{-1}
Average water added	2.3	kg day^{-1}
Average daily biogas production	3.15	m^3 day^{-1}
Volumetric daily biogas production	1.57	m^3_{biogas} $m^{-3}_{digester}$ day^{-1}
Total mass of food added	4574	kg
Specific biogas yield	220	m^3 $tonne^{-1}$ fresh matter
Specific methane yield	595.5	m^3 CH_4 $tonne^{-1}$ VS
Average biogas methane content	60.6	%
Average HRT	127.2	days
Operational period	319	days
Average digester temperature	35.7	˚C

3.1.2 Feedstock and pre-digester tank characterisation

The volumes of each waste feedstock type added to the pre-digester tank are shown in Figure 2. It can be seen that food waste (from small catering businesses) was the largest category with over 52% of the total waste added to the AD system, with waste oats also representing a large fraction of the feed (17%).

By combining a mixed tank model with the data collected by the operator, it is possible to approximate the composition of the waste being fed into the digester at any moment. Figure 3 shows (a) the total waste and its composition in the pre-digester tank and (b) percentage of each category being fed to the digester each day.

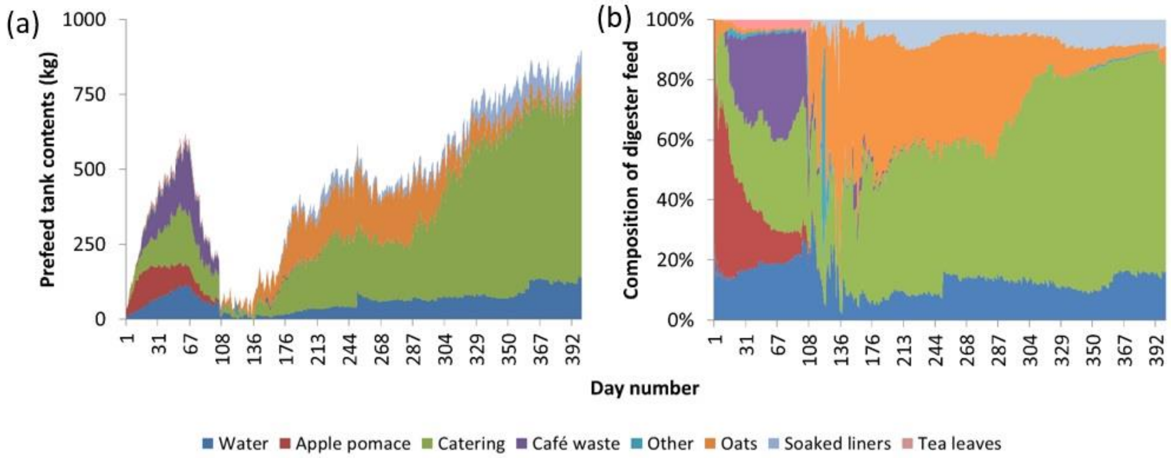

Figure 3: Content of the pre-digester tank, (a) by weight and (b) by percentage composition.

As demonstrated in Figure 2 and Figure 3, the combination of disruptions to the feeding schedule and a pre-digester tank make it very difficult to ascertain the exact composition of the feed going into the digester.

3.1.3 Operational observations

Anecdotal evidence given by operators stated that although representing an additional workload, collection of the daily readings enabled the site staff to engage more effectively with the workings of the plant and learn more about the processes involved.

Key lessons learned during the testing period were as follows:

- Space: due to its location, the site had a very limited space available for the installation and this led to very little room for maintenance and 'housekeeping'. This made the operation of the plant unnecessarily difficult so should be avoided if possible.
- Pre-digester: the pre-digester tank provided very useful storage, which enabled the operators to add feedstock when it became available, usually twice a week.

- Odour: Odour was a problem with some feedstocks, which was improved by better sealing of the pre-digester tank. Operators noted that odour seemed to improve when oats were added and became worse during periods of heavy feeding.
- Noise: Noise is of particular concern in an urban area. The main source of noise pollution was the milling machinery.
- Biogas use: Biogas was initially used in a biogas hob for making hot drinks but later in the project a custom-built automated biogas boiler was installed. There are no type-approved ‘off-the-shelf’ heating appliances for biogas currently available in the UK. Later in the project a CHP Stirling engine was installed.
- Digestate: Although it is a very valuable resource, demand for the digestate was limited and caused issues throughout the testing period. This was due to a number of reasons, including lack of appropriate regulation at this scale and lack of scientific data to provide confidence in its safety to potential users for urban horticultural use. Careful consideration should be given before a plant is built to identify a reliable outlet for the digestate.

3.1.4 Economic analysis

A brief economic analysis of the plant (details are provided in Appendix 1) shows a higher than predicted capital cost, mainly due to the need for an expensive logging system, a bespoke biogas boiler and CHP. Operational costs were lower than expected but not by a significant amount. Revenue from the plant was lower than expected, because the plant processed less feedstock than was predicted. The system was able to cover some of its operational costs by generating revenue from waste disposal and energy production but required grant funding for its installation. In future systems, it is expected that there are significant savings to be made from capital costs by increasing production volume and reducing monitoring requirements.

The economics of this project are not favourable compared to an established plant with proven technology. At this early stage of development, rather than financial return, the main drivers behind investment in this plant were the proof of concept, promotion of the technology and education around the subject. In future applications, the economics of such a system would need to be more favourable for investment.

3.2 Analysis of the pre-digester tank

As shown in Figure 3, the potential effect of the pre-digester tank can be observed in that waste loading events (waste added to the pre-digester tank) were decoupled from the feeding events (into the digester) by the dilution of the loaded feedstock in the existing contents of the pre-digester tank. This effect can last several months as can be seen clearly in the ‘washout’ behaviour of apple pomace, which despite only being added to the pre-digester tank during phase 1 (days 1 to 15), it is still being added to the digester at day 130, during phase 3. The small size of the installation means that it is possible to have a relatively large pre-digester tank (compared with the main digester). This means that the period of 'feed buffering' is relatively long compared with a conventional large-scale AD plant, where building such a large pre-digester tank would be uneconomical. In this case, the volume ratio was 1:3 (pre-digester: digester). As food waste is known to be a highly variable feedstock (Fisgativa et al., 2016), this represents a useful advantage to the micro-scale application.

The type of feedstock added to the pre-digester can be related to the measured TS and VS concentrations in the pre-digester, shown in Figure 4(a). During the period of oats being fed into in the pre-digester tank (phase 3, days 108 to 294) the TS of the pre-digester rose from 22% to 37%, and then fell during phase 4, when predominantly food waste was added to the pre-digester tank.

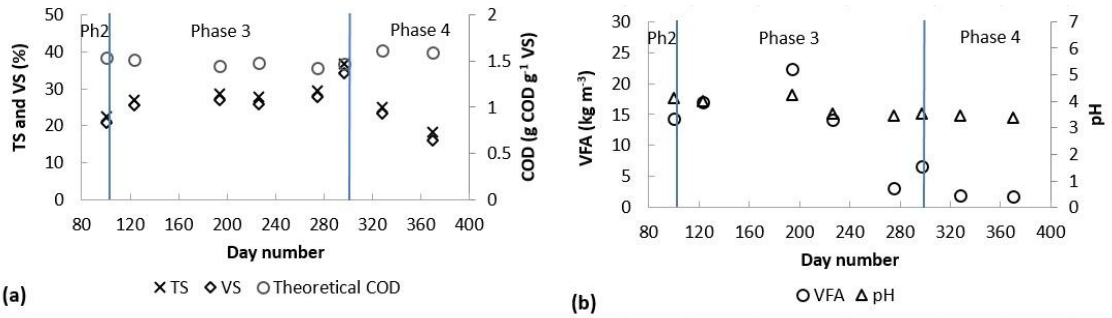

Figure 4: Laboratory analysis of the pre-digester tank showing (a) TS, VS and theoretical COD, and (b) VFA and pH

The variation in TS and VS is important, as these concentrations have a large impact on the potential biogas production of the feedstock. The VS has a large variation (from 16% to 34%), however the theoretical COD, calculated from the elemental composition, shows very little variation during the testing period since it is specific to the solids material.

The VFA concentration in the pre-digester tank is an indicator of the amount of hydrolysis and fermentation taking place. This peaked in phase 3 at around 22.4 kg m^{-3}. After this point, a reduction in the VFA concentration is observed, likely to be a consequence of the decrease in pH leading to an inhibition of fermentation, analogous to ensiling. The low pH environment in the pre-digester tank is such that the formation of methane by methanogenic organisms can be ruled out since these organisms cannot grow under these conditions (Angelidaki et al., 2003).

The average elemental composition of the feedstock was 49.0, 34.8, 6.2 and 2.92 (% by mass of TS) of C, H, O and N, respectively, i.e. a C:N of 14.4.

3.3 Digestate characterisation

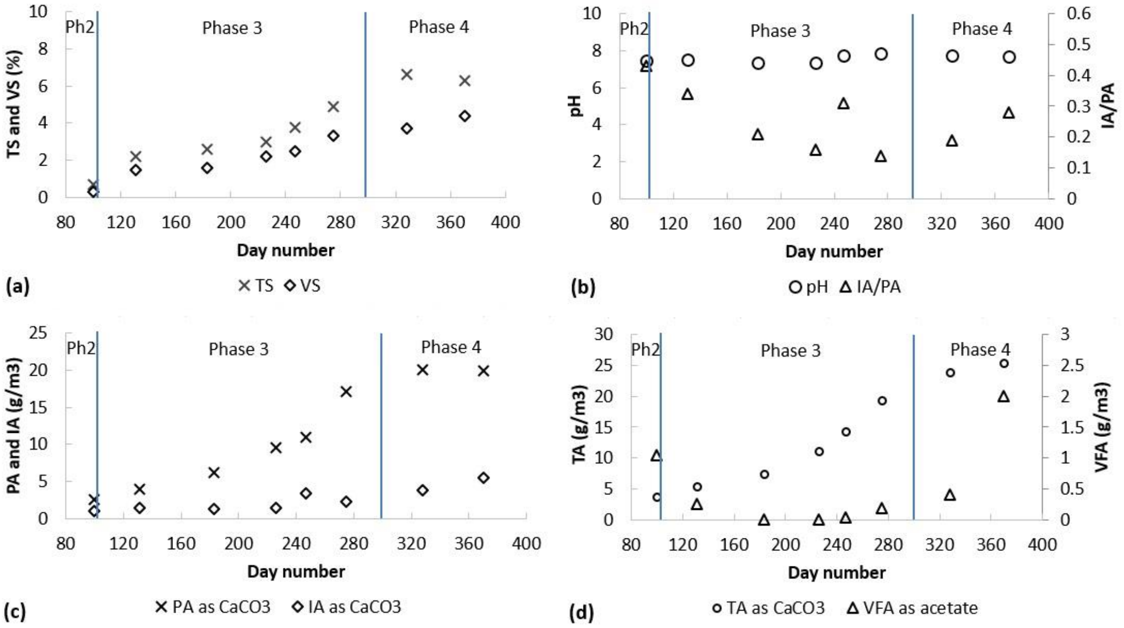

Figure 5: Laboratory analysis of the digestate showing (a) TS and VS, (b) pH and IA/PA, (c) PA and IA, and (d) TA and VFA.

A summary of the laboratory analysis of the digestate is shown in Figure 5. A general increasing trend in TS and VS was observed as the initial inoculum (diluted digestate and cattle slurry) was replaced with the mixed waste feedstock. The trend appears to have levelled off by the end of the testing period, indicating the arrival at a pseudo steady state of the system in terms of mass balance, albeit dependent on the input moisture content and added water. The digestion process appears healthy throughout the testing period. The process is characterised by; stable pH (well within the optimum range for the growth of methanogens) (Gujer and Zehnder, 1983); a gradual increase in partial and total alkalinity and generally low (<500 mg l^{-1}) VFA concentrations after the initial acclimatisation period. The average temperature of the digester during the testing period was 35.7 °C and stayed within ±1 °C of this. The greenhouse had a positive effect on the temperatures and energy requirements of the system, as described in section 3.6.1.

The digestate was tested off-line and found to contain negligible amounts of pathogens (E.Coli and Salmonella). Operator experience was that it was stable and had minimal odour. The average retention time for the feed in the digester was 127 days.

3.3.1 Ion analysis

Average digestate anion concentrations were 0.84, 0.24, 3.72, 1.67, 0.05 g l^{-1} for Na^+, Ca^{2+}, NH_4^+, K^+ and Mg^{2+}, cation concentrations were 1.52, 0.09 and 0.22 g l^{-1} of Cl^-, Br^- and PO_4^{2-} respectively. The NPK, presented as is conventional for fertilisers, of the mature digestate (the sample taken on day 370) on a dry basis is 16.2:1:9.6 which is similar to that reported by WRAP for food waste digestate (15.3;1;3.8)(WRAP, 2011).

3.4 Biogas production

There were variations in biogas production per unit feed over the project period, caused predominantly by variations in the composition and amount of feedstock added to the system.

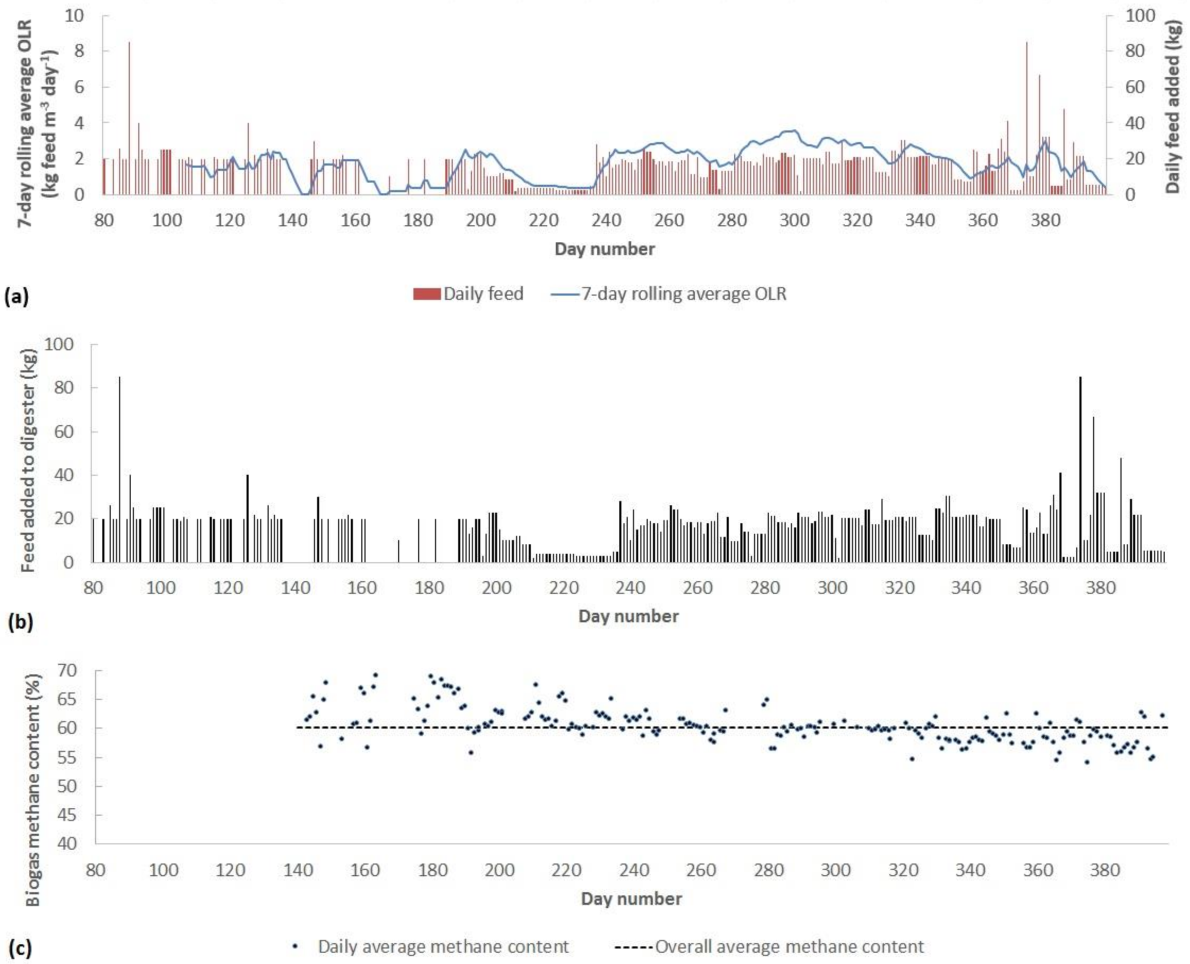

Figure 6: (a) Digester OLR and feed added to the digester (I-11), (b) biogas production (I-04) and (c) biogas methane content (I-02) during the test period.

The biogas production of the system is highly variable from day to day, as shown in Figure 6, whereas a weekly trend showed a gradual increase reaching around 4-5 m^3 day^{-1} up to day 289, after which there was a gradual decrease in the biogas production from the system. The quality of the biogas, as shown in Figure 6(c), shows less daily variation but over the course of the project the trend was a gradual decrease in the methane composition of the biogas from around 65% to around 57%. The hydrogen sulphide was not measured regularly but spot measurements gave an average pre-treatment H_2S reading of > 200 ppm (out of range of the sensor used) and an average post- treatment reading of 178 ppm. To understand the reason for the downward trend in methane composition, further analysis would be required; it is possible that the change in the feedstock composition led to a natural reduction in the biogas composition, but it could also be an early sign of process instability (Lv et al., 2014); this is discussed further in section 3.5. The decrease in biogas production volume was not caused by a reduction in the OLR (which remained fairly constant from around day 235 onwards, at around 2.2 kg m^{-3} day^{-1}, shown in Figure 6(a)) but a reduction in the VS concentration of the mixed biomass in the pre-digester tank, which decreased from around day 297 onwards, as shown in Figure 4. This would also contribute to the reducing biogas production, and was likely due to a change in feedstock from waste oats to food waste.

3.5 Ammonia inhibition and trace element dosage

The last sample of digestate analysed (on day 370) indicated potential instability, through high VFA and decreasing methane concentration in the biogas (shown in Figure 7). For this reason, further samples of the digestate were taken for analysis beyond the official testing period.

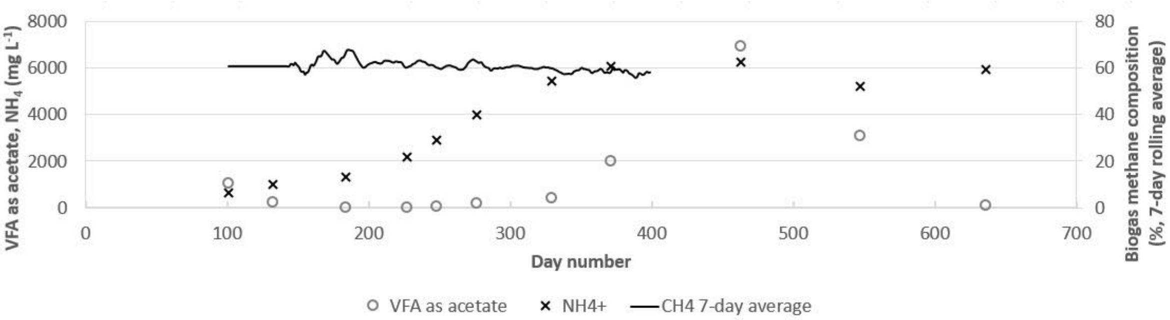

Figure 7: Digestate VFA and ammonia concentration, and methane content of the biogas.

Figure 7 shows a rise in ammonia concentration and a subsequent rise in VFA concentration and drop in methane content in the biogas. The feedstock being supplied to the digester at this point was mainly food waste, and this feedstock type was fed in from day 294 (the start of phase 4). The IA/PA ratio was also measured in the digestate samples, and this stayed low throughout the whole monitoring period indicating process stability (Ripley et al., 1986). This type of behaviour has been noted in food waste digesters previously and can be the initial signs of a long term (>1 year) failure of the process, caused by a combination of ammonia inhibition of acetoclastic methanogens along with deficiencies in certain trace elements blocking both propionate oxidation and syntrophic hydrogenotrophic methanogenesis (Banks et al., 2012). Acting on the theory that this situation could be resolved by addition of trace nutrients to the system, the required addition of trace elements was calculated, as shown in Table 2.

Table 2: Trace element addition for other sites and this site.

Element		Mo	Ni	W	Se	Co
Suggested by Banks et al. (2012)	mg L^{-1} wet	0.2	1	0.2	0.2	1
Banks et al. (2012) based on TS = 23.7%	mg kg^{-1} TS	0.8	4.2	0.8	0.8	4.2
Average added by (Facchin et al., 2013)	mg kg^{-1} TS	6	10	1	1	10
Values adopted at micro-AD site	mg kg^{-1} TS	4	5	1	1	5
One-off dose to pre-digester	g	1.2	1	0.2	0.2	1
One-off dose to digester	g	0.72	0.6	0.12	0.12	0.6
Dosage every 2 months	g	1.73	1.44	0.29	0.29	1.44
Source compound		$(NH_4)6Mo7O_{24}4H_2O$	$NiCl_2.6H_2O$	$Na_2WO_4.2H_2O$	Na_2SeO_3	$CoCl_26H_2O$
Target element by weight	%	54	25	56	46	25

A dose of trace elements solution was added to the digester on day 476, followed by doses at two-monthly intervals afterwards. Following the addition, the VFA concentration in the digester dropped to 112 mg/l on day 636, which is well within the acceptable range (Wang et al., 2009). As expected, the ammonia concentration did not drop as a consequence of the trace element addition, but instead there was a decrease in VFA. This appeared to indicate that the inhibition of the VFA metabolism pathway was reduced when the correct proportions of trace elements were added, in agreement with the results of Banks et al. (2012).

3.6 Energy consumption of the plant

3.6.1 Heat consumption

The internal temperature of the digester was maintained by a hot water heat exchanger. The heat demand was measured by a heat meter, shown in Table 3 along with the average temperatures in the system and had an average value of 80W over the logging period. This table also shows the average incident solar radiation on the greenhouse.

Table 3: Heat consumption and temperature data.

Measurement	Value	Figure 1 reference
Digester temperature (˚C)	32.9	I-06
Greenhouse temperature (˚C)	23.7	I-12
External temperature (˚C)	15.0	I-07
Heat input to digester (W)	79.7	I-09
Incident solar radiation (W m^{-2})	43.3	I-14

Temperature data collected by the logging system can be used to analyse the bulk heat transfer characteristics of the micro-AD system. Because the temperature of the digester was approximately constant throughout the project, the heat loss from the digester can be equated to its heat input. The heat loss has conductive, convective and radiative elements although for this analysis they are simply grouped together to give an overall heat loss value and overall heat transfer coefficient.

Using monthly data for temperature and heat use on the heat meter, the heat transfer coefficient (K) can be calculated using the equation $\dot{Q} = K\Delta T$, where $\dot{Q}$ is the heat loss (W), K is the overall heat transfer coefficient (W ˚C^{-1}) and ΔT is the temperature difference (˚C). This equation can be used with the average temperature difference between digester and greenhouse to give the digester overall effective heat transfer coefficient (K_d), and the difference between the digester and ambient to give the overall effective heat transfer coefficient for both the digester and greenhouse together (K_b).

K_d had an average of 8.7 W ˚C^{-1} (8.0-9.5 with 95% confidence) giving the digester a U-value of approximately 0.85 W m^{-2} ˚C^{-1}. The heat demand varies in the range 39.1-111.5 W over the logging period, although given the mild winter conditions, this could be expected to increase to around 121 W with an average ambient winter temperature of around 4.4 ˚C and higher in severe winter conditions. K_b was estimated at 4.2 W ˚C^{-1} (3.5-5.0 with 95% confidence). Using both of these average heat transfer coefficients, an approximation can be made of the energy savings given by housing the digester in the greenhouse.

To assess the heating effect of the greenhouse, the calculations for heat demand above can be repeated, instead using the difference between the digester temperature and the ambient temperature.

The measured heat demand, calculated heat demand, and calculated heat demand without the greenhouse are shown in Figure 8. Based on this analysis, the overall heat savings of putting the digester inside a greenhouse are an average of 49% (of the projected heat demand without housing) or 76.6 W.

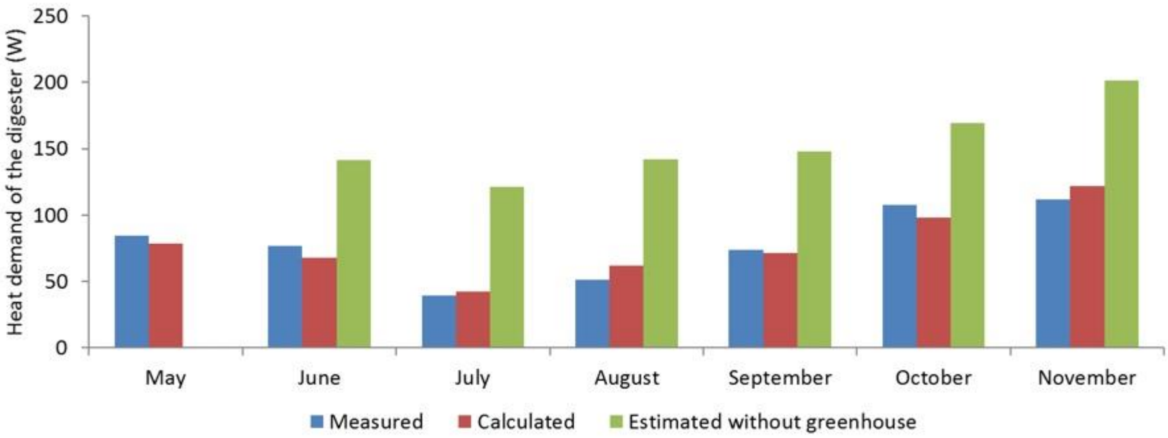

Figure 8: Temperature and heat demand of the digester during the testing period[3].

3.6.2 Electrical consumption

The system had two electrical meters, M1 and M2, I-01 and I-13 on Figure 1 respectively. M1 measured only the energy consumed by the digester mixing motor. M2 measured the complete consumption of the site, including the digester mixing motor, the pre-digester system (feedstock mill, pre-digester tank mixing motor, feeding pump), the logging system (sensors, data acquisition hardware, PC) and in addition a number of other electrical demands for the site that were not associated with the AD system (lighting, power tools, telephone and PC charging, kettle).The energy use was recorded most reliably over a sample period of day 217 to day 394, which is shown with the average power for this period in Table 4.

Table 4: Electrical consumption data for the sample period day 217 to day 394.

Measurement	Energy use (kWh)	Average energy use (kWh day^{-1})	Equivalent average power (W)
M1: Electrical demand of digester	228.5	1.29	53.8
M2: Electrical input to site	638.0	3.60	150.2

To further break down the electrical use of the site, an estimate for the micro-AD system electrical demand has been made based on manual measurements of the separate items in the system. These are shown in Table 5. Note that the logging system power consumption has been calculated as the residual power that was measured by M2 and is not accounted for by other components. The other electricity uses mentioned previously that are outside the plant but are measured by M2, have been assumed to be negligible in order to give the

[3] No estimated data without greenhouse in May as thermistor I-07 not installed yet

worst case estimated power consumption for the plant only. The actual electricity use of the plant will therefore in reality be slightly lower.

Table 5: Estimated electricity demand of AD system based on rated power demand and estimated duty cycle, for the sample period day 217 to day 394.

Component	Power demand cycle	Total energy use (kWh)	Average energy use (kWh day^{-1})	Equivalent average power (W)
Chopper mill	1.5kW, 5 min/24 hr	22.1	0.125	5.21
Pre-digester mixing	0.18kW, 10 min/24 hr	5.3	0.030	1.25
Digester feeding pump	72W, 1 min/2 hrs	2.5	0.014	0.60
Extraction (greenhouse)	25W, 18 min/hr	31.9	0.180	7.50
Extraction (monitoring room)	25W, 12 min/3 hrs	7.1	0.040	1.67
Digester mixing (measured)	N/A measured	228.5	1.291	53.8
Logging system (calculated)	N/A			80.2
Total (Whole site)			**TOTAL**	**150.2**
Total (Plant only)			**TOTAL**	**70.0**

3.6.3 Coefficient of performance

An energetic analysis was performed on the micro-AD system, including the measured energy inputs of heat and electricity and the measured outputs of biogas quantity and methane percentage. In order to add relevance to the results, a hypothetical CHP has been included as the biogas appliance with a low electrical efficiency of 25% and heat recovery efficiency of 50%, both relative to the lower caloric value (LCV) of the methane input, which is realistic for the scale considered. The calculations are set out in Table 6, and the methane production is converted to an average power in watts to give nominal values for net energy output of the CHP and coefficients of performance (COP).

Table 6: Energy mass balance for micro-AD site (based on LCV of methane = 11.1 kWh m^{-3}).

Energy output of micro-AD system	
Methane production (m^3 day^{-1})	1.91
Gross energy production in biogas (kWh$_{th}$ day^{-1})	21.2
Gross power output in biogas (W$_{th}$)	884
CHP outputs	
Electrical power output (W)	221
Heat power output (W)	442
Net output power of AD system	
Electricity (whole site) (W)	70.8
Electricity (plant only) (W)	151.0
Heat (W)	362.3
Coefficients of performance (COP)	
Electricity (whole site)	1.47
Electricity (plant only)	3.16
Heat	5.55
Heat (without greenhouse)	2.72

The results show all COPs are greater than 1, thus indicating a positive energy balance. The plant on its own (without the logging system) has an electrical COP of 3.16 due to its low parasitic electrical requirements. However, when the additional load of the rest of the system is included, this was reduced to 1.47. The relatively high continuous electrical demand of the logging system reduces the electrical COP of the site and it is clear that reduction of this demand would be required, either through optimisation or through minimisation the system components, to allow continuous logging to be feasible on a micro-AD system.

The high COP on a heat basis (5.55) can be attributed to the performance of the insulation of the digester and the effect of housing the digester in a greenhouse. As was calculated in section 3.6.1, the solar gain of the greenhouse reduced the heat demand by 49% and therefore an estimate of the coefficient of performance of the digester without the greenhouse can be calculated as 2.72.

In terms of parasitic loads, the plant uses 31.7% of the total electricity production, whereas the whole site uses 68.0% of the total electricity production, and the heat requirement is 18.0% of the total heat production.

3.6.4 Avoidance of greenhouse gas emissions

Table 7 summarises the carbon emissions balance for the plant. An explanation of the carbon emission categories is as follows:

The annual methane production of 697 m^3 could result in carbon dioxide reduction of 1411 kg yr^{-1} relative to the same consumption of natural gas based on DEFRA/DECC estimates (DECC, 2016).

The diversion of 5.3 TPA of organic waste from landfill could result in a carbon reduction of 2724.5 kg yr^{-1} (WRAP, 2011) based on 500 kg CO_{2eq} $tonne^{-1}$ (DECC, 2016).

Abated waste transport was calculated by assuming the normal route for food waste would be transport of an average 56 km round-trip in an articulated lorry that could hold 40 tonnes based on UK figures from WRAP (2016). This generated a relatively small emissions saving of 13.5 kg yr^{-1}.

Carbon dioxide emissions savings are also made by using digestate instead of conventional inorganic fertilisers. Of the 4574 kg added as feed from day 80 to 399, 1185 kg was lost as biogas. Taking into account the water added, the digestate production was an estimated 4700.7 kg yr^{-1}, which would result in a 141.0 kg yr^{-1} carbon dioxide emissions saving (WRAP, 2012).

Using the AD system electrical and heat demand, the consumption of 613.4 kWh yr^{-1} of electricity and 698 kWh yr^{-1} of heat can be associated with emissions of 251.2 and 160.1 kg yr^{-1} (DECC, 2016) of carbon dioxide respectively.

The net carbon reduction of the AD system was 3878.7 kg yr^{-1}, 2.95 kg CO_{2eq} kWh^{-1} electricity production or 0.741 kg CO_{2eq} kg^{-1} waste treated.

Other authors have studied the GHG reduction potential of AD compared with other treatment methods for MSW (Baldasano and Soriano, 2000, Liu et al., 2012, Møller et al., 2009, Masse et al., 2011) and farm residues such as cattle slurry (Masse et al., 2011), but no previous studies have calculated the GHG reduction from source segregated food waste as per this paper. In comparison to digestion of food waste, the GHG reduction from the AD of MSW compared with landfilling will vary. This is because the waste has different characteristics and different treatment is required for the MSW digestate since it cannot be used as a fertilizer due to high levels of contamination. Studies report values of 0.114 (Liu et al., 2012) 0.375 (Møller et al., 2009) and 0.55- 0.78 (Baldasano and Soriano, 2000) kg CO_{2eq} kg^{-1} waste treated for MSW. The AD of source segregated food waste produces a high quality digestate with minimal contamination that can be used as a fertiliser and displace the use of mineral fertiliser, resulting in additional GHG reductions.

Table 7: Greenhouse gas balance for the plant.

Item	Associated CO_2 emissions	Reference	CO_2 saving kg yr^{-1}
Methane produced, for use in CHP	2.0245 kg CO_{2eq} m^{-3}	(DECC, 2016)	1411.0
Diversion of waste from landfill	500 kg CO_{2eq} $tonne^{-1}$	(DECC/DEFRA, 2011)	2724.5
Reduction in transport	2.7 kg CO_{2eq} $tonne^{-1}$ waste	(GOV.UK, 2015)	13.5
Displacement of artificial fertilisers	30 kg CO_{2eq} $tonne^{-1}$ digestate	(WRAP, 2012)	141.0
Use of electricity	0.40957 kg CO_{2eq} kWh^{-1}	(DECC, 2016)	- 251.2
Heating the digester	0.20405 kg CO_{2eq} kWh^{-1}	(DECC, 2016)	- 160.1
NET CARBON EMISSIONS AVOIDANCE		**3878.7**	**kg CO_{2eq} yr^{-1}**

3.7 Comparison with a large-scale AD plant

Published data (Banks et al., 2011) from a 900 m^3 commercial anaerobic digestion system fed on food and green waste allows a comparison of some of the performance outputs of micro-AD with large scale AD. Values either directly taken from or derived from the data presented in the paper, are shown, and compared with equivalent values for the micro-AD site in Table 8.

Results for volumetric biogas yield and biogas composition are broadly similar for both systems, thus demonstrating a similar level of performance in terms of biomethane output when compared with the size of the system. The average specific methane yield from the feedstock was much lower in the large scale system, which could indicate a performance difference. However, in consideration of the other available data on the monitoring of the large scale plant, it is thought that this can probably be attributed to an actual reduced biogas potential of the feedstock due to addition of green waste and the feeding of less fresh food waste into the system. In comparison, the micro-AD digester was fed predominantly food waste and oats, which both have a high specific methane potential. The variation in weekly biogas flow was greater in the micro-AD system especially during the manual feeding period, but was more comparable with the large-scale system once the automatic feeding was implemented.

The parasitic requirement of the large-scale system (31.4 %) is similar to that of the micro-AD system (31.7 %) and the parasitic heat requirement is much greater in the large system which can be attributed to the pasteurisation heat (no pasteurisation was performed at the micro-AD site).

Using the data available, it appears that the performance of the micro-AD is either comparable or slightly better than the large scale AD system. However, it is likely that the choice of appropriate scale would be made based on factors external to the system (e.g.

collections, waste quantities and distribution of production, digestate use) or based on an economic analysis. A full comparative life-cycle analysis (LCA) between the two sizes of plant would greatly improve this study but is outside of the scope of this project.

Table 8: Comparison of key performance indicators of large scale AD and micro-AD plants.

Performance parameter	Large scale AD (Banks et al., 2011)	Micro-AD
Average specific biogas yield (m^3 $tonne^{-1}$ wet)	156	220
Average specific methane yield (m^3 $tonne^{-1}$ VS)	402	595
Average methane composition of biogas (%)	62.6	60.6
Average volumetric biogas yield (m^3_{biogas} $m^3_{digester}$ day^{-1})	1.59	1.57
Variation in weekly biogas production (+/- % of average)	32.8	61.6 (manual) 38.6 (auto)
Average parasitic electrical demand (% of elec. output)	31.4	31.7
Average parasitic heat demand (% of recoverable heat)	30.3	18.0
Digestate nitrogen (kg N $tonne^{-1}$)	5.6	4.7
Digestate phosphorus (kg P $tonne^{-1}$)	0.4	0.2
Digestate potassium (kg K $tonne^{-1}$)	2.3	2.3

4 Conclusion

The novelty of this plant lies in its size and location, and from the results obtained and the long-term operation of the plant it can be concluded that it is a viable technology with the potential to help to solve the problem of food waste processing in the urban environment. The operational performance parameters of the plant were very similar to a large-scale AD plant treating source segregated food waste in terms of main outputs and parasitic energy requirements. The plant processed 5.23 TPA of urban organic waste producing an average of 595 m^3 CH_4 per tonne of VS destroyed with an average 60.6 % methane content in the biogas produced. The results showed that the plant was capable of stable operation despite large fluctuations in the rate and type of the feed waste biomass.

After initial signs of ammonia inhibition trace elements were supplemented to the system as per literature data and the biological system exhibited symptoms of recovery with a reduction in VFA concentration.

The system achieved a net positive energy balance and potential COP of 3.16 and 5.55 based on electrical and heat energy inputs and outputs respectively. Greenhouse gas emissions analysis concluded plant could result in carbon dioxide reduction 3878.7 kg yr^{-1} which was equivalent to carbon reductions of 2.95 kg CO_{2eq} kWh^{-1} electricity production or 0.741 kg CO_{2eq} kg^{-1} waste treated.

5 Acknowledgments

The authors would like to acknowledge WRAP DIAD II for funding the construction and operation of the AD plant (full copy of the project report available from www.wrap.org.uk) and the School of Process Engineering at the University of Leeds for access to their laboratories and analytical equipment. Thanks go to the LEAP consortium, which included Community by Design, James Murcott and Angela Bywater at Methanogen UK Ltd, Guy Blanch Bio Development, Dr David Neylan, Clive Andrews at Aleka Designs and Cath Kibbler at the Community Composting Network. The generous contributions of the voluntary Community by Design site staff; Marco Fanasca, Panteha Ahmadi and Tasos Torounidis, are also acknowledged.

6 References

Angelidaki, I., Ellegaard, L. & Ahring, B. 2003. Applications of the anaerobic digestion process. *Biomethanation II*, 1-33.

Apha 1998. *Standard methods for the examination of water and wastewater,* Washington, DC, American Public Health Association.

Baker, J. R., Milke, M. W. & Mihelcic, J. R. 1999. Relationship between chemical and theoretical oxygen demand for specific classes of organic chemicals. *Water Research,* 33**,** 327-334.

Baldasano, J. & Soriano, C. 2000. Emission of greenhouse gases from anaerobic digestion processes: comparison with other municipal solid waste treatments. *In:* BALDASANO, J., MATA-ALVAREZ, J., CECCHI, F. & TILCHE, A. (eds.).

Banks, C. J., Chesshire, M., Heaven, S. & Arnold, R. 2011. Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. *Bioresource Technology,* 102**,** 612-620.

Banks, C. J., Zhang, Y., Jiang, Y. & Heaven, S. 2012. Trace element requirements for stable food waste digestion at elevated ammonia concentrations. *Bioresource Technology,* 104**,** 127-135.

Decc. 2016. *Greenhouse gas reporting - conversion factors 2016* [Online]. Available: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2016 [Accessed 10th August 2016].

Decc/Defra 2011. Anaerobic Digestion Strategy and Action Plan.

Edwards, J., Othman, M. & Burn, S. 2015. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. *Renewable and Sustainable Energy Reviews,* 52**,** 815-828.

Facchin, V., Cavinato, C., Fatone, F., Pavan, P., Cecchi, F. & Bolzonella, D. 2013. Effect of trace element supplementation on the mesophilic anaerobic digestion of foodwaste in batch trials: The influence of inoculum origin. *Biochemical Engineering Journal,* 70**,** 71-77.

Fisgativa, H., Tremier, A. & Dabert, P. 2016. Characterizing the variability of food waste quality: A need for efficient valorisation through anaerobic digestion. *Waste Management,* 50**,** 264-274.
Gov.Uk. 2015. *Average heavy goods vehicle fuel consumption: Great Britain* [Online]. Available: https://www.gov.uk/government/statistical-data-sets/env01-fuel-consumption [Accessed 17th August 2016].
Gujer, W. & Zehnder, A. J. B. 1983. Conversion Processes in Anaerobic Digestion. *Water Science and Technology,* 15**,** 127-167.
Lansing, S., Botero, R. B. & Martin, J. F. 2008. Waste treatment and biogas quality in small-scale agricultural digesters. *Bioresource Technology,* 99**,** 5881-5890.
Liu, X., Gao, X., Wang, W., Zheng, L., Zhou, Y. & Sun, Y. 2012. Pilot-scale anaerobic co-digestion of municipal biomass waste: Focusing on biogas production and GHG reduction. *Renewable Energy,* 44**,** 463-468.
Lv, Z., Hu, M., Harms, H., Richnow, H. H., Liebetrau, J. & Nikolausz, M. 2014. Stable isotope composition of biogas allows early warning of complete process failure as a result of ammonia inhibition in anaerobic digesters. *Bioresource Technology,* 167**,** 251-259.
Masse, D. I., Talbot, G. & Gilbert, Y. 2011. On farm biogas production: A method to reduce GHG emissions and develop more sustainable livestock operations. *Animal Feed Science and Technology,* 166-67**,** 436-445.
Møller, J., Boldrin, A. & Christensen, T. H. 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. *Waste Management & Research,* 27**,** 813-824.
Nnfcc. 2016. *Biogas Map* [Online]. Available: http://www.biogas-info.co.uk/resources/biogas-map/ [Accessed 15th August 2016].
Ripley, L. E., Boyle, W. C. & Converse, J. C. 1986. Improved Alkalimetric Monitoring for Anaerobic Digestion of High-Strength Wastes. *Journal (Water Pollution Control Federation),* 58**,** 406-411.
Stoknes, K., Scholwin, F., Krzesiński, W., Wojciechowska, E. & Jasińska, A. 2016. Efficiency of a novel "Food to waste to food" system including anaerobic digestion of food waste and cultivation of vegetables on digestate in a bubble-insulated greenhouse. *Waste Management*.
Wang, Y., Zhang, Y., Wang, J. & Meng, L. 2009. Effects of volatile fatty acid concentrations on methane yield and methanogenic bacteria. *Biomass and Bioenergy,* 33**,** 848-853.
Wrap 2011. Digestates: Realising the fertiliser benefits for crops and grassland. Banbury: WRAP.
Wrap 2012. Digestate Action Plan. Banbury: WRAP.
Wrap 2016. Household food waste collections guide. Banbury: WRAP.

Appendix 1. Economic analysis

This section provides an economic analysis of the system, which is split into capital costs, operational costs and revenue (tables A1, A2 and A3 respectively).

Table A1: Predicted and actual capital costs (GBP to Euro October 2013 exchange rate = 1.1815).

Capital cost	**Predicted**	**Actual**
Monitoring system	€3385	€3385
Pre-feed system	€6262	€5848
Digester	€7266	€7266
Gas holder	€1477	€1477
Ancillaries	€2741	€2741
Gas use	€1595	€11224
Infrastructure	€1772	
Commissioning	€1181	€1181
TOTAL CAPITAL COST	**€25680**	**€33123**

Table A2: Predicted and actual operational costs (GBP to Euro October 2013 exchange rate = 1.1815).

Operational costs	**Predicted**	**Actual**
Labour cost for prediction (€ hour^{1})	9.5	
Wages for operation (€ year^{-1})	1725	1474
Parts (€ year^{-1})	478	478
Maintenance (€ year^{-1})	47	47
Total operational costs (€ year^{-1})	2251	2000
Electricity cost		
Electricity cost (€ kWh^{-1})	0.118	0.118
Electricity use digester (€ year^{-1})	217.3	138.7
Electricity use for feed mill/mixing (€ year^{-1})	20.1	7.3
Electricity use for extraction (€ year^{-1})		9.5
Electricity use for monitoring (€ year^{-1})		107.8
Total Electricity Use (€ year^{-1})	237.4	263.3
TOTAL ANNUAL COSTS (€ year^{-1})	**2488.14**	**2263.53**

Table A3: Predicted and actual revenue (*based on calorific value of heavy fuel oil of 41.2 MJ L^{-1}).

Revenue	**Predicted**	**Actual**
Feedstock		
Feedstock (food waste) handled (kg day^{-1})	40	18.8
Feedstock (food waste) handled (kg $year^{-1}$)	14,600	5,317
Methane production		
Cost of heating oil (€ L^{-1})	0.74	0.74
Methane to fuel oil conversion (L)*	1,292	813
Savings in fuel oil (€ $year^{-1}$)	962.04	605.68
Digestate		
Standard value (from WRAP) (€ $tonne^{-1}$)	5.27	5.27
Fertiliser savings (€ $year^{-1}$)	76.94	28.01
Gate Fees		
Number of caddies collected	1,142.40	416
Caddy charge (€)	3.25	3.25
Total caddy income (€ $year^{-1}$)	3711.80	1651.64
Landfill tax savings		
Landfill tax (€ $tonne^{-1}$)	94.52	94.52
Diversion from landfill (€ $year^{-1)}$	1380.00	502.52
TOTAL REVENUE (€ $year^{-1}$)	**6130.77**	**2487.85**