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Energetic and environmental benefits of co-digestion of food waste and cattle slurry: a preliminary assessment

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Abstract

The research evaluated the feasibility of centralised pre-processing and pasteurisation of source-separated domestic food waste followed by transport to farms for anaerobic co-digestion with dairy cattle slurry. Data from long-term experiments on the co-digestion of these two substrates was used to predict gross energy yields; net yields were then derived from full system analysis using an energy modelling tool. The ratio of cattle slurry to food waste in the co-digestion was based on the nutrient requirements of the dairy farm and was modelled using both nitrogen and phosphorous as the limiting factor. The model was run for both medium-size and large farms in which the cattle were housed either all year round or for only 50% of the year. The results showed that the addition of food waste improved energy yields per of digester unit volume, with a corresponding increased potential for improving farm income by as much as 50%. Data for dairy farms in the county of Hampshire UK, which has a low density of dairy cattle and a large population, was used as a stringent test case to verify the applicability of the concept. In this particular case the nutrient requirements of the larger farms could be satisfied, and further benefits were gained from the reduction in greenhouse gas emissions avoided through improved manure management and fertiliser imports. The results indicated that this approach offered major advantages in terms of resource conservation and pollution abatement when compared to either centralised anaerobic digestion of food waste or energy recovery from thermal treatment.

Keywords: Anaerobic digestion, food waste, cattle slurry, greenhouse gas, renewable energy, nutrient management.

1 Introduction

Sustainable management of biowastes is currently a major issue in Europe (European Commission, 2010). One of the primary drivers for this is the requirement under the Landfill directive (99/31/EC) for diversion of biodegradable wastes, due to their potential for greenhouse gas emissions. There is, however, increasing awareness of the resource recovery potential of these wastes, and of the economic benefits in managing them through the anaerobic digestion route. The European Commission estimates that about one third of the EU's 2020 target for renewable energy in transport could be met using biogas produced from biowaste, while around 2% of the EU's overall renewable energy target could be met if all biowaste was converted to energy, with economic gains estimated at between €1.5 and €7 billion depending on the scale and effectiveness of recycling and waste prevention policies (European Commission, 2010).

Of the biowaste available for anaerobic digestion, food wastes have recently attracted most attention in the UK (Defra, 2009, 2010a), and a small number of digesters have already been built specifically for the reception and conversion of this material. This follows a successful demonstration of the technology in a project at Ludlow, UK funded by the UK Government's Department of Environment, Food and Rural Affairs (Defra) and Advantage West Midlands. Over a 14-month monitoring period 615,472 m^3 of biogas was produced from the 3936 tonnes of source segregated domestic food waste added to the Ludlow digester, with an overall methane yield of 98 m^3 $tonne^{-1}$ wet weight (WW). Descriptions of the plant and the results of monitoring and evaluation are given in Arnold et al. (2009) and Banks et al. (2011).

The concept of a centralised anaerobic digester receiving and treating biowastes is well understood, and the potential financial returns of this approach may be enhanced by economies of scale. It does, however, rely upon the availability of an agricultural land base for application of the digestate and on the willingness of farmers to participate in reuse. This may be limited when the only benefit to the farm is from the nutrients contained in the digestate. In a centralised system income from both gate fees and energy generation (including any renewable energy premium) goes to the plant owner or operator. At present farmers are usually asked to accept digestates without any fee, although spreading of the material may be done at no additional cost. It is easy to envisage that this may not always be the case, with increases in digestion capacity leading to reduction of gate fees and competition for the available land area from anaerobically digested wastewater sludges. It is therefore interesting to look at other models that may offer greater robustness based on alternative distribution of economic gains, and may contribute more effectively to nutrient management as well as renewable energy production and greenhouse gas (GHG) emissions reduction by taking into account a greater proportion of the available biomass resource.

Household food waste, estimated to be around 8.3 million tonnes $year^{-1}$ in the UK (WRAP, 2009a), makes up only a small part of the available biowaste. By far the largest tonnage of organic waste in Europe is animal slurry and manure, with annual UK production estimated at around 100 million tonnes WW. The biogas potential of this material is relatively low, with typical values for slurry from dairy cows of only ~20 m^3 $tonne^{-1}$ WW. This low energy potential means that anaerobic digestion of manures and slurries from dairy herds has never been economically attractive in Europe, as confirmed by the very small number of digesters found on farms of this type. There are, however, significant environmental benefits from digesting cattle slurry which can make a major contribution to EU and UK government targets for GHG emissions (Banks et al., 2007). Greenhouse gas emissions from manure management in the EU 27 in 2008 were estimated as 50.26 million tonnes CO_2 equivalent, of which dairy cattle contributed 21% (EEA, 2010). Digestion of this material may also improve its fertiliser properties and assist in nutrient management (Al-Seadi, 2008; Lukehurst et al., 2010). There are therefore strong arguments for stimulating the uptake of digestion to treat animal manures by promoting co-digestion with other energy-rich substrates, and examples of this approach already exist in Europe. Denmark has had a very successful programme since the 1970s, and in 2006 digested 1.51 million tonnes of animal manure with 340000 tonnes of alternative biomass primarily derived from food manufacture in 19 centralised co-digestion plants and 56 farm scale plants (Al-Seadi, 2000; Winterberg et al., 2006). Both Austria and Germany have developed successful digestion programmes incorporating the use of animal manures for energy production. In these cases the biogas yield of the digesters is enhanced mainly by the addition of energy crops (Braun et al., 2010). Although wastes are available they are not commonly used as co-substrates as this results in reduction of the price paid for electricity generated: both countries have adopted the principle that the polluter should pay for the treatment of waste and this should not be subsidised through a higher renewable energy tariff.

The obvious place for co-digestion of food wastes and animal slurries is on the farm, where both the majority of the material and the land base for application are located; but there are also obstacles to this approach. Recovery of food waste through anaerobic digestion is subject to the Animal By-products Regulation (ABPR) (EC 1774/2002), which is designed to protect both animal and human health by preventing the spread of animal disease. For the purposes of treating ABPR category III material, this involves a size reduction step to ensure that material entering the digester measures less than 12 mm in one plane; and a pasteurisation step where the temperature of the feed or the digestate is raised to 70 ^{o}C for one hour for pathogen removal. When dealing only with category III catering wastes other conditions can be substituted provided they can be shown to offer the same level of biosecurity (EC 1774/2002). These ABPR requirements add a further level of complexity to the design of an anaerobic digestion plant that significantly increases the capital cost of the installation, making it less attractive for smaller-scale applications. The requirement for heat treatment of feedstock or digestate also reduces the net energy gain from the process, and tends to favour the use of combined heat and power (CHP) where the heat generated can be used for this purpose. This may again restrict the installation of digesters on farms, where suitable electricity grid connections may not be available and the cost of upgrading the connection to allow electricity export is often prohibitive. The above circumstances, combined with UK waste management infrastructure, logistics and contractual arrangements, and regulatory requirements all work against the installation of smaller-scale co-digestion plant on farms (Banks et al., 2007). Yet without the input of a high-energy waste material, the volumetric gas productivity of farm-based digesters fed solely on manures and slurry is unlikely to be economically viable, and the energy potential and environmental benefits of digesting these substrates will be lost.

The paper proposes a solution that could increase energy returns, reduce GHG emissions and promote better nutrient management through combining centralised pre-processing of source-segregated food waste with subsequent on-farm co-digestion, as shown in Figure 1. An additional benefit is that co-digestion can improve the process, since using food waste as a sole feedstock can lead to longer-term stability problems (Banks and Zhang, 2010). The paper makes use of results from laboratory trials to determine the optimum digestion ratio of food waste and cattle slurry and looks at the potential impacts on energy production, nutrient management and GHG emissions obtained by combining the two. A case study examines the implications of using different ratios of cattle slurry to food waste and the resulting potential for energy and nutrient replacement on dairy farms in the county of Hampshire, UK.

2 Materials and methods

Co-digestion of food waste and dairy cattle slurry is considered in terms of energy production and impact on emissions. This is achieved by defining a boundary for inputs to and outputs from the farm in order to allow direct comparison of alternative scenarios. Calculation of the energy and nutrient balances and impact on GHG emissions was carried out using the model and methods described in Salter et al. (2007) and Salter and Banks (2009). Specific details concerning these balances are outlined in the following sections.

Where gas volumes and masses are used, values have been converted to standard temperature and pressure (STP) of 273.15 K and 101.325 kPa.

2.1 Data sources and modelling parameters

2.1.1 Estimation of source segregated domestic food waste.

UK households are assumed to generate an average of 180 kg of food waste household^{-1} year^{-1} (WRAP, 2009b).

2.1.2 Estimation of cattle slurry quantities

A dairy cow produces approximately 19.3 tonnes year^{-1} of excreta (Burton and Turner, 2003; Defra, 2010d). Some of this is deposited in the field when the cattle are grazing, and some on the hard standing of the dairy when cattle are brought in for milking, or on the floor of housing. The amount of material collected is proportional to the amount of time the cattle spend housed and being milked; the volume may also be influenced by dilution with wash waters. As well as dairy cattle a farm will also have a number of other cattle, consisting of calves, and cows not producing milk or too young for milk production. These animals spend the majority of their time in the field and return excreta directly to the land.

2.1.3 Estimation of fertiliser use

Dairy farms have grazing and also grow forage crops or grass that is harvested as hay or silage and used to feed housed cattle through the winter period. Each crop grown has a recommended fertiliser application rate (Defra 2010d). In this study it was assumed that the farms are located in a nitrogen vulnerable zone (NVZ) (Defra, 2009b) which limits the permissible application of nitrogen to 250 kg ha^{-1} year^{-1}. The recommended application rates for N, P_2O_5 and K_2O assuming soil nutrient status is low (level l) are shown in Table 2 below. In meeting these recommended application rates it is assumed that the nutrients in excreta deposited by cattle during grazing, or collected in the form of slurry whilst cows are housed or being milked, are returned to the land; and any additional requirement is made up through the use of mineral fertilisers. Typical figures for N, P and K contained in cattle excreta are given in The RB209 Fertiliser Manual (Defra 2010d) and are shown in Table 1. Where slurry is digested, the digestate produced is assumed to contain all of the nutrients originally present in the undigested material.

2.1.4 GHG emissions

GHG emitted from manures and slurries were calculated using the IPCC methodology (IPCC, 2006). The methane emission factor (EF) is obtained from the formula

$$EF = (VS_{(d)} * 365) * (B_o * 0.716 * \Sigma\ MCF_{(s)}/100 * MS_{(s)}/100) \qquad (1)$$

where $VS_{(d)}$ is the daily volatile solids production per animal, B_o is the maximum methane producing capacity, $MCF_{(s)}$ are the methane conversion factors for each part of the manure management system, $MS_{(s)}$ are the fractions of livestock manure produced in each part of the management system, 0.716 is the conversion factor for m^3 CH_4 to kg CH_4 at 273.25 K and 101.325 kPa, and 365 is the number of days in a year. Methane emissions were converted to CO_2 equivalent by multiplying by 25 (IPCC, 2007)

GHG emissions for mineral fertiliser production are based on those reported by Mortimer et al. (2003) of 6.81, 1.74 and 1.81 kg CO_2 equivalent kg^{-1} product for N, P_2O_5 and K_2O respectively.

The value for GHG emissions from the generation of grid based electricity is taken as 0.168 kg CO_2 equivalent MJ^{-1} for all fuel sources (DECC, 2009).

2.1.5 Indirect energy use

Energy usage in fertiliser production varies considerably depending on the process (Wood and Cowie, 2004). The values taken here of 40.3, 3.4 and 7.3 MJ kg^{-1} for N, P_2O_5 and K_2O respectively are averages from European producers (Kongshaug, 1998); it is assumed this energy was derived from fossil fuels. Energy for packaging and transport of mineral fertilisers is taken as 2.6 MJ kg^{-1} product (Mortimer et al., 2003).

2.1.6 Estimation of biogas yield

Data was taken from laboratory trials conducted to determine biogas yields and methane content at ratios of food waste to cattle slurry of 4:1, 3:2 and 2:3 on a wet weight basis (Banks and Zhang, 2010). These trials used continuously stirred digesters maintained at a temperature of 37 °C over a period of approximately 12 month. In all cases the digester volatile solids (VS) loading rate was maintained at 4 kg m^{-3} day^{-1}. The total solids (TS) content of the cattle slurry used was 9.31% indicating some dilution with wash waters. The amount of wash water added was calculated by comparing the measured nitrogen concentration in the slurry (3.3 kg N $tonne^{-1}$ slurry) with a typical average concentration excreted by dairy cattle without dilution (5.2 kg N $tonne^{-1}$ excreta), giving a figure for added wash water of 0.57 m^3 $tonne^{-1}$ excreta. At this loading rate and ratios the specific methane yields contributed by the cattle slurry and food waste components respectively were constant, and the calculated values are shown in Table 1 with the other data used in modelling. Treating the data in this manner allowed different CS:FW ratios to be considered in the scenarios investigated.

Table 1. Data used in modelling scenarios.

	TS (%)	VS (%TS)	CH_4 (m^3 kg^{-1} VS)	CH_4 (%biogas)	N (g kg^{-1} WW)	P (g kg^{-1} WW)	K (g kg^{-1} WW)
cattle slurry	9.31	70.0	0.185	60	3.3	0.8	1.6
source separated food waste	23.74	91.4	0.380	60	8.1	1.3	3.4
dairy cows excreta (RB209)					5.2	0.96	3.3

other cattle excreta (RB209)		5.2	0.9	4.3

2.1.7 Digester size, energy output and nutrients

The working volume of the digester V is determined by the organic loading rate (OLR) according to equation 2

$$V\ [m^3] = \text{daily VS addition}\ [\text{kg VS day}^{-1}]\ /\ \text{OLR}\ [\text{kg VS m}^{-3}\ \text{day}^{-1}] \qquad (2)$$

The average time for which material remains in the digester (the retention time, RT) is calculated from equation 3 assuming that the input materials have a density of 1000 kg m^{-3}.

$$\text{RT [days]} = V\ [m^3]/\text{daily volume addition}\ [m^3\ \text{day}^{-1}]\ (3)$$

It is assumed that biogas is stored in the digester headspace, and a further 10% is added to the working volume to accommodate this. The digester is assumed to be cylindrical in shape with a width to height ratio of 4:1.

Heat required to raise the temperature of the feedstock materials to that of the digester was calculated assuming a specific heat capacity similar to that of water at 4.18 kJ kg^{-1} K^{-1}, and assuming the material was at ambient temperature when added to the digester. The pasteuriser was assumed to run on waste heat from a separate source (see below).

The energy required to maintain the digester at its operating temperature was calculated using average monthly air and soil temperatures in the study area and a typical heat transfer coefficient for digester surfaces of 0.7 W m^{-2} K^{-1}. The potential energy output from the digester is calculated based on predicted biogas production. For the purposes of this study it was assumed that the biogas is used in a combined heat and power (CHP) unit with an electrical efficiency of 35% based on the lower calorific value of its methane content, taken as 35.82 MJ m^{-3} CH_4. The size of the CHP was determined from the total available electrical output divided by the number of operating hours (in this case taken as 8322 hours $year^{-1}$ to allow for maintenance). Electricity required for digester operation, calculated using a value of 33 MJ $tonne^{-1}$ of fresh material processed (Berglund and Börjesson, 2006), is assumed to be supplied by the CHP unit and all remaining generated electricity is then exported to the national grid. Heat for the digester is assumed to be supplied by the CHP unit, and any excess heat is given no monetary value.

2.2 Local data

2.2.1 Hampshire dairy farms

The Farm Business Survey (FBS) indicates that a typical large dairy farm has 174.3 dairy cows (Defra, 2010c). In addition to grazing, it also uses part of its land for production of other crops, including fodder and grass for silage, as shown in Table 2. The proportion of grazed grass to that ensiled changes depending on the amount of time the cattle spend housed, and the fodder crop grown may vary. This data was used to predict the land areas and crops grown on an average medium-size (100-200 dairy cows) and average large dairy farm (> 200 dairy cows) in Hampshire. Data for 2007 (Defra, 2010b) showed there were 303 dairy farms in Hampshire, of which 34 were large and 38 medium. The average number of cows for each of these cases is shown in Table 2. For the current study, it was assumed that kale would be used as the fodder crop. Table 2 also gives the recommended application rates for N, P_2O_5, and K_2O.

Table 2. Stocking rates, crop areas and recommended nutrient application rates.

	Typical large dairy farm - FBS Data	Average Hampshire medium-size farm	Average Hampshire large farm	recommended nutrient application kg ha^{-1} (N, P_2O_5, K_2O)
dairy cows	174.3	141	294	
other cattle	155.6	126	263	
area of farm (ha)	167.5	135.5	282.5	
grass (ha)	117.2	94.8	197.7	250 - 105 - 290 (silage)[a] 250 - 40 - 30 (grazed)[a]
winter wheat (ha)	10.1	8.3	17	220 - 90 - 95
winter barley (ha)	4	3.2	6.7	180 - 90 - 95
spring barley (ha)	1.6	1.3	2.7	150 - 75 - 83
Oilseed rape (ha)	1.3	1.1	2.2	220 - 65 - 75
peas and beans (ha)	0.6	0.5	1	0 - 60 - 65
fallow & fodder (ha)	21.8	17.6	36.8	170 - 75 - 225
uncropped (ha)	10.9	8.8	18.4	

[a] Nitrogen application limited by assumed NVZ status

2.2.2 Population statistics and waste infrastructure

Hampshire is situated in the south of the UK and occupies an area of 3769 km^2 with densely populated areas along the south coast and around Basingstoke which is situated 48 km inland. There were an estimated 707,772 households in Hampshire in 2009, based on the county's population (ONS, 2010) and assuming the same household size as in the 2001 census (Census, 2001). These generate approximately 785,000 tonnes of household waste annually of which 628,000 tonnes is kerbside collected (Hampshire County Council, 2009). If 60% of the available food waste was captured in source segregated collection schemes this would give rise to 76,434 tonnes year^{-1} of food waste and increase the overall recycling percentage by 12%.

Currently, non-recyclable waste arising from domestic properties is taken to a transfer station, of which there are 8 in the county, and then compacted and shipped to one of the county's three energy-from-waste (EfW) plants which have a total annual capacity of 420,000 tonnes year^{-1}. In the current study it was assumed that food waste would be co-collected either with residual waste or with kerbside-collected recyclables in a dual-purpose vehicle and taken to a transfer station; no additional vehicle movements are therefore required. It was also assumed that a centralised pre-processing unit to reduce the food waste particle size, homogenise and pasteurise it, would be located on the site of each EfW plant and could take advantage of excess process heat after economic recovery for use in power generation. This prepared feedstock would then be supplied to farms without any further processing. The average distance over which the waste is transferred to the farms is assumed to be 20 km, based on the area of the county and assuming approximately one-third is served by each plant. Pre-treated waste is transported in road tankers, the emissions of which are based on a fuel consumption of 2.73 MJ tonne^{-1} km^{-1} (AEA, 2010), assuming 25-tonne loads delivered at regular intervals throughout the year.

3 Results

3.1 Nutrient balance

The model output can be used to optimise any of a number of parameters, but in the present study the first aim was to determine the amount of food waste that could be imported without exceeding a farm's nutrient requirements or the limit for nitrogen application in a NVZ. Results are presented for 4 different scenarios: a medium-sized farm (141 dairy cows) with the animals housed either i) 50 or ii) 100% of the time; and a large farm (294 dairy cows) housed iii) 50 or iv) 100% of the time. All other cows on the farm are assumed to be on un-housed grazing and to deposit nutrients directly back to the field. The total nutrient requirements, in addition to any deposited by grazing cattle, for the four scenarios are shown in Table 3. The co-digested cattle slurry and food waste can provide a proportion of these, and the amount of food waste that can be imported is calculated based on the nitrogen required after taking into account the contribution from the slurry. Because the proportions of nutrients in the cattle slurry and food waste do not completely match the crop requirements, the application of some P and K in mineral form is also required.

Table 3. Nutrient requirements for scenarios 1-4.

Scenario	1	2	3	4
dairy cows	141	141	294	294
housed (% year)	50	100	50	100
wash water (tonnes)	776	1551	1617	3234
other cattle	126	126	262	262
grass grazing area (ha)	80.7	45.4	167.7	94.2
grass silage area (ha)	14.2	49.4	30	103.5
N required (kg)	14301	21069	25303	25328
P required (kg P_2O_5)	3813	7533	4846	5361
K required (kg K_2O)	7189	17453	11099	25689
food waste required to replace N (tonne year^{-1})	1176	1492	2453	3115

3.2 Energy potential

The selected loading rate of 4 kgVS m^{-3} d^{-1} gives a required digester capacity of between 259 and 788 m^3 depending on farm size and the period for which the animals are housed. Where cattle are housed for only 50% of the time the amount of slurry fed to the digester is reduced, with a corresponding reduction in CS:FW ratio as seen in Table 4. For all farm sizes the digester retention time is between 22 and 26 days and the power output varies between 47 and 136 kW. A typical large dairy farm where the dairy cows were housed for 50% of the year would require 2453 tonnes year^{-1} of food waste, and a medium-sized farm 1176 tonnes year^{-1}. Given the 76434 tonnes of food waste available, this would be enough to supply 31 of the large farms or 13 of the large and all 38 medium-size farms. The results for each scenario are summarised in Table 4.

Table 4. Energy production potential of scenarios 1-4.

Scenario	1	2	3	4
% housed	50	100	50	100
slurry produced (tonnes year^{-1})	2138	4272	4454	8908

CS:FW in digester feed	1.8	2.9	1.8	2.9
food waste (tonnes year^{-1})	1176	1492	2453	3115
loading rate (kg VS m^{-3} day^{-1})	4			
digester capacity (including 10% gas space) (m^{3})	259	378	540	788
retention time (days)	26	22	26	22
biogas (m^{3} year^{-1})	188950	259717	394107	542090
methane (m^{3} year^{-1})	113370	155830	236464	325254
CHP (continuous electrical output) (kW)	47	65	99	136
generated (kWh year^{-1})	394843	542722	823553	1132788

Scenario 3 with the food waste processed at 31 large farms uses 76,042 tonnes of food waste and gives a potential electrical output of 3069 kW continuous. If the same amount of food waste was processed in an EfW plant would give a potential yield of 1808 kW continuous assuming an electrical conversion efficiency of 25% (Porteous, 1998) and a lower heat value of 3.0 MJ kg^{-1} WW for this food waste (Banks and Zhang 2010). Anaerobic co-digestion thus offers a 70% increase in electrical energy potential due both to the increased conversion efficiency and to the additional energy yield from the cattle slurry. Removal of the food waste component is also likely to increase the calorific value of the residual waste fed to the EfW plant, and thus improve its thermal conversion efficiency.

As a further comparison, the energy output from a digester on one of the large farms with 50% housing which received slurry only would be 14 kW continuous and the required digester volume to maintain a minimum retention time of 20 days would be 268 m^{3}, only 50% less than the volume required for co-digestion. To produce the same energy yield as the co-digestion of food waste the farmer could add 2048 tonnes year^{-1} of maize, requiring an area of 58.5 ha (assuming a yield of 35 tonnes ha^{-1}) which would then not be available for food production.

3.3 GHG emissions

In the current study potential reductions in GHG emissions due to anaerobic digestion of the collected slurries can be taken into account, as this gas is captured and utilised during the digestion process. Emissions are also avoided from the replacement of mineral fertilisers by digestate. Potential emissions savings from these sources are shown in Table 5.

Table 5. Potential annual GHG emission savings for scenarios 1-4 (tonnes CO_2 equivalent farm^{-1} year^{-1})

Scenario	1	2	3	4
Avoided CH_4 emissions from manure	60.5	120.9	126.1	252.1
Replacement of grid electricity	181.1	243.4	377.8	508.2
Replacement of mineral fertiliser	65.4	82.9	136.3	173.1
Total	307.0	447.2	640.2	933.4

Assuming scenario 3 based on utilising 31 large farms in Hampshire with 50% housing of dairy cattle, the total GHG emissions savings would be 19846 tonnes CO_2 equivalent year^{-1}. This compares to 7873 tonnes CO_2 equivalent year^{-1} savings from the replacement of grid supplied electricity generated by the EfW plants from the same amount of food waste. For scenario 4 (100% housing) on 24 farms the saving would be 22401 tonnes CO_2 equivalent year^{-1}.

3.4 Equipment costs and income

The current study did not include a detailed economic evaluation of the scenarios, which would involve consideration of capital investment and financing as well as operating costs. The following outline costs for equipment and estimates for income are provided as a basis for assessment of the potential economic feasibility.

3.4.1 Collection and pre-processing

Assuming equal amounts of food waste are sent to each EfW plant in Hampshire, each facility would need to treat 25478 tonnes year^{-1} or 509 tonnes week^{-1} based on 50 weeks of operation a year. In a 5-day working week this material could be dealt with as 4 batches per day in a 30 m^3 pasteurisation unit. The cost of supply of a unit of this size is around £54K; a shredder to ensure compliance with ABPR particle size requirements could cost £30k; installation on an existing site with connections to services is site-dependent but could be as low as £50K on an existing EfW plant with existing vehicle facilities and tipping areas. Assuming heat can be reclaimed from the EfW plant, the capital costs of this installation are roughly equivalent to the revenue that could be raised in six weeks of operation, based on a typical gate fee of £40 tonne^{-1} of food waste received for processing (WRAP, 2009a). The gate fee for food waste reception would also have to cover the distribution of the pre-treated feedstock to the participating farms; but these costs are equivalent to those for transport of digestate from a centralised anaerobic digester if the material is sent to dairy farms for application at the same soil nutrient loading rates.

3.4.2 Co-digestion

Each participating farm would need to install a digester and CHP unit. Income would be gained from the sale of electricity to the grid or by offsetting grid electricity use. Savings would also be made in the purchase of fertiliser by using digestate in its place. The electrical demand to run the digester is subtracted from the total generated to give that available for sale. In the UK's Feed-in Tariff scheme electricity has a value of £0.115 kWh^{-1} when generated from anaerobic digestion in CHP units under 500 kW, plus £0.03 kWh^{-1} when exported to the grid (DECC, 2010b). The capital costs for a digester vary according to size: costs in the range £2k to £7k kW^{-1} electricity installed have been suggested (MREC, 2008; Redman, 2008). These costs do not include connection to the national grid, planning or permitting. The outline costs and incomes for the different scenarios are shown in Table 6.

Table 6. Digester costs and incomes for scenario 1-4.

Scenario	1	2	3	4
CHP (kW)	47	65	99	136
Capital cost (£ kW^{-1})	5000	4500	4000	4000
Total capital cost (£)	235000	292500	396000	544000
Income from electricity (£ year^{-1})	66827	73267	139363	152915

With regard to fertiliser replacement, in November 2010 blended fertiliser cost between £294 and £317 tonne^{-1} delivered (DairyCo, 2011). The mineral nitrogen requirement for the scenario 3 farm without using the food waste is 19869 kg, potentially provided by 100 tonnes of 20-10-10 fertiliser (%N, %P_2O_5, %K_2O). This equates to a cost saving of approximately

£30,000 through use of the digestate produced from co-digesting food waste. Fertiliser costs vary with oil price and were valued at £457 per tonne of 20-10-10 in 2008 (Nix, 2008), equivalent to a saving of approximately £45700.

4 Discussion

The present example uses localised data from the county of Hampshire in the UK, but the general principles are applicable to many situations in Europe, particularly those countries with high population densities and a well-developed waste management infrastructure. Hampshire is in a densely populated region of the country and represents an area where dairy farming is not very intense: it can therefore be regarded as being a fairly stringent test of the proposed approach. The average density of cattle in the county is 25.5 km^{-2} compared to an average for England of 42.5 km^{-2}, with stocking rates in the neighbouring counties of Somerset and Dorset at 74 km^{-2} (Defra, 2008). Even so, there were sufficient dairy farms of medium to large scale within Hampshire to match the county's anticipated food waste arisings, and a sufficient land base within these farms to benefit from the additional nutrients recycled from the food waste.

Taken across the UK, the 8.3 million tonnes of potentially available food waste (WRAP, 2009a) would be enough to supply the nitrogen requirements for all of the 1494 farms with over 200 dairy cows and 2444 out of the 6307 farms with between 100 and 200 dairy farms in the UK. This assumes that the dairy cows are housed for approximately 50% of the time, typical of UK farming conditions.

Ideally the digestate produced should be used on the farm where the digester is located: if this is not the case then under current UK regulations there is a requirement to pasteurise either the cattle slurry prior to digestion or the digestate before export from the farm (BSI, 2010). An on-farm pasteurisation unit would involve additional process complexity and energy usage, and require a longer capital pay-back period. In an area such as Hampshire, with a large proportion of agricultural land under cereal cultivation, this option may be worth considering. In the case presented the potential GHG emissions savings from digestion of food waste alone in a centralised facility are 5216 tonnes CO_2 equivalent year^{-1}, achieved through displaced mineral fertiliser use across the study area; whereas co-digestion on farms where cattle are housed 50% of the time would save 8111 tonnes CO_2 equivalent year^{-1}, and on farms with 100% housing of cattle 10173 tonnes CO_2 equivalent year^{-1}, through displaced mineral fertiliser use and reduced emissions from slurries.

The work presented is a preliminary overview, and a more detailed one would be needed for accurate quantification e.g. of the energy requirements and GHG emissions from transport of surplus digestate to specific farms; but co-digestion of food waste with cattle slurry rather than alone clearly offers a valuable means of mitigating GHG emissions.

The current study was based on replacing all the farm's requirement for additional nitrogen with co-digested food waste. The nutrient composition of the slurries and food waste means however that the requirement for P_2O_5 is over-supplied by 25 - 60%. Running the same scenarios based on replacement of 100% of P_2O_5 would require participation of 31 of the large and 24 of the medium-sized farms under 100% housing. Additional nitrogen would also be required to offset the reduced application rate, although this demand could be met through nitrogen fixation by the use of grass/clover combinations. The study also assumed that all nutrients in the original feedstock are present in the digestate: in practice nutrients may be partitioned into different digestate fractions or even retained in the digester as precipitates, e.g. struvite. A recent study of a food waste digester found only 33% of phosphorus entering the system over a 14-month period could be accounted for in the digestate (Banks et al., 2011).

In general the preferred option in the UK is likely to be to maintain each farm as a contained unit, giving exemption from the need to pasteurise the cattle slurry under section 7.2.4 of PAS 110 and allowing the digestate to be used without further waste management controls (BSI, 2010). Standard Rule SR2010No16 concerning on-farm anaerobic digestion is presently out for its sixth consultation: its current form allows for the import of waste onto farms but does not include domestic food waste. An SR exists for the small-scale (< 500 tonne) composting of biodegradable waste both on and off farms, including unpasteurised ABPR Category III material (SR2011No14_500t). It is reasonable to assume that similar conditions to these would be required by the Environment Agency, which is the competent authority for regulatory matters; this coupled with the requirements of PAS 110 (BSI, 2010) would simplify the regulatory position.

Pasteurisation of the food waste component is essential for biosecurity, and centralisation of this step offers several advantages. It is easier to guarantee achievement of the required process conditions in a single large unit operated routinely on a daily basis by staff with specific waste management training than when sending the same material to a number of small farm units. Centralised pasteurisation also reduces the biosecurity risks during transportation and offloading: transfer can be carried out from tanker to tank by hose, simplifying the requirement for 'clean' and 'dirty' sides of the AD plant and significantly reducing construction costs. The UK is perhaps especially sensitive about the issue of on-farm biosecurity and food waste due to the major Foot and Mouth outbreak in 2001, and for this reason waste management companies may even wish to consider autoclaving rather than pasteurisation as a pre-treatment step.

Centralised pre-processing of the food waste, including the heat treatment step, has implications for the energy balance of the process as this stage often takes advantage of excess heat produced by a CHP unit. Where the CHP unit is remote from the pre-processing plant this is of course not possible. In the current example, heat for this purpose is obtained from EfW plants. Co-location at these plants is efficient as they already act as waste collection centres thus minimising any additional transportation requirements. While these plants are common in most of Europe, Hampshire is relatively unusual in the UK in having 3 of them: for a number of reasons landfill remains a more common UK waste disposal option. The heat required, however, could equally come from a landfill gas engine or a decentralised power plant, both of which produce surplus low-grade heat for which commercial uses are often difficult to find. Decoupling the heat treatment from the AD plant potentially has other advantages as it may allow alternative uses of the biogas, for example as transportation fuel for rural communities as already occurs in Sweden and increasingly in Germany, Austria and Switzerland (Braun et al, 2010). There will always be a requirement for digester heating: with on-site pasteurisation some of the heat is usually recovered for this purpose, but this can also be achieved by using a proportion of the biogas in a simple boiler system. Depending on local requirements for electricity e.g. in the dairy the biogas may be proportionally split between CHP and other uses, in which case excess heat will be available. The most efficient option depends on site-specific circumstances and can be determined in a more detailed assessment of the overall energy balance. In calculating heat requirements it was also assumed that the specific heat capacity of food waste is similar to that of water: this is a conservative assumption and use of real values may further improve the energy balance as the specific heat capacity of most food materials and slurries is lower than 4.18 kJ kg^{-1} K^{-1}.

For the proposed approach to offer a robust solution, the farmer must be a beneficiary. On a medium-size UK farm with a dairy herd of 120 cows the net farm income in 2008 was £76,800 with the average gross margin per cow being £696 (Clothier, 2009). For this type of farm with cows housed 50% of the time the additional income from energy sales would be £52,850 and the savings from fertiliser use £14,293. The scheme could therefore increase farm incomes by more than 50% once capital investment has been repaid. The size of the digester needed is relatively modest even for the large dairy farm and the range of 200-600m^3 is at a scale where factory pre-fabrication to a standard design is possible. This would greatly reduce capital costs from those for current one-off designs and allow uniformity in servicing and repair of the equipment. In 2010 grant aid for construction of digesters on farms was available from the European Union under axis 3 of its rural development policy, making the on-farm option more attractive from the financial viewpoint in comparison with centralised AD. If this type of aid continues through European, national or local schemes capital payback periods would be further reduced.

A major consideration for farmers is a consistent and guaranteed supply of digester feedstock, at least for the period of any loan agreement and preferably extending past this to guarantee future income. Across Europe the trend is for a fall in the number of waste management companies and an increase in their size (Hall, 2010); in the UK there is also a tendency for the contract period between waste management contractors and local authorities to reduce, with 10-year contracts now more typical than the 25-year agreement reached in 1996 for Hampshire's Project Integra (Lisney, 2001). One consequence of this is that medium size and even large-scale dairy farms are too small to deal with large waste management companies and vice versa, and groups of farmers may need to form cooperatives for the purposes of securing the supply of waste. This may have advantages, however, as the waste contractor can be guaranteed an outlet for the food waste when individual digesters are out of commission for servicing/repair by building this capacity into the contract. Dealing as a cooperative would also allow participating farms to negotiate finance for digester construction as a single body, making the investment more attractive to larger financial institutions. Working in this way a group of farms could jointly employ an operative to maintain and service their digesters, thus providing reliable and experienced support, reducing operating costs, and creating skilled rural employment. Similar arrangements could be adopted for service contracts on equipment.

The proposed approach also has some advantages for the waste management contractor. The company loses the income from electricity generation, which under current UK tariffs is highly attractive (Banks et al., 2009); but is left operating a much simpler process with no requirement for major capital investment in a centralised digestion plant. A pre-processing plant can be installed at a fraction of the cost with a very short pay-back period. Transport requirements to take the pre-treated food waste to receiving farms are no greater than those of transporting digestate from a centralised AD plant. The costs to the waste management contractor may be reduced as there is no requirement to spread the material onto the farmers' land, in turn reducing hire costs or the number of vehicle-types needed in the fleet. The contractor can be confident of making long-term agreements with farmers as he is providing a product that directly increases income rather than depending on the farmer to accept digestate in competition with other suppliers of both organic and mineral fertiliser. The heavy administrative requirement to secure the necessary land base for digestate reuse is thus reduced. The contractor may be able to operate at a lower gate fee than is currently accepted as capital costs for digestion equipment are passed onto the farms, and the system may thus be more robust in the longer term as it is more stable and less dependent on energy and fertiliser prices in a rapidly-changing market.

In the case of Hampshire, separate collection and treatment of food waste would have the benefit of reducing the quantity of this type of material, which has a low net calorific value, for processing by the thermal EfW route, thus increasing process efficiency and freeing capacity to receive more suitable wastes. This may provide an attractive alternative to the installation of further thermal EfW capacity. From the viewpoint of regional and national government amongst the most important advantages of this type of approach are the environmental and rural development benefits. Guaranteeing a larger income to farms through revenues from energy sales will reduce the dependency of dairy farms on a fixed price and quota for milk. Adopting an approach based on farm nutrient requirements links the urban waste and agricultural productivity cycles by returning some of the nutrients exported to towns and cities in farm products back onto the farm as imported food wastes.

5 Conclusions

Centralised pre-processing of food waste followed by on-farm co-digestion with dairy cattle slurry was shown to offer an effective approach for management of both of these biowastes. The digestion of cattle slurry becomes economically feasible under the current UK system of feed-in tariffs and results in substantially increased farm incomes, as well as contributing to overall renewable energy production targets and mitigating GHG emissions from manure management. Centralised pre-processing of food wastes guarantees biosecurity while providing a basis for robust and stable long-term relationships between the parties involved in waste management and nutrient recovery. The approach also helps to close the urban - rural nutrient cycle by returning food nutrients directly to the farm, thereby contributing to increased sustainability of agricultural production.

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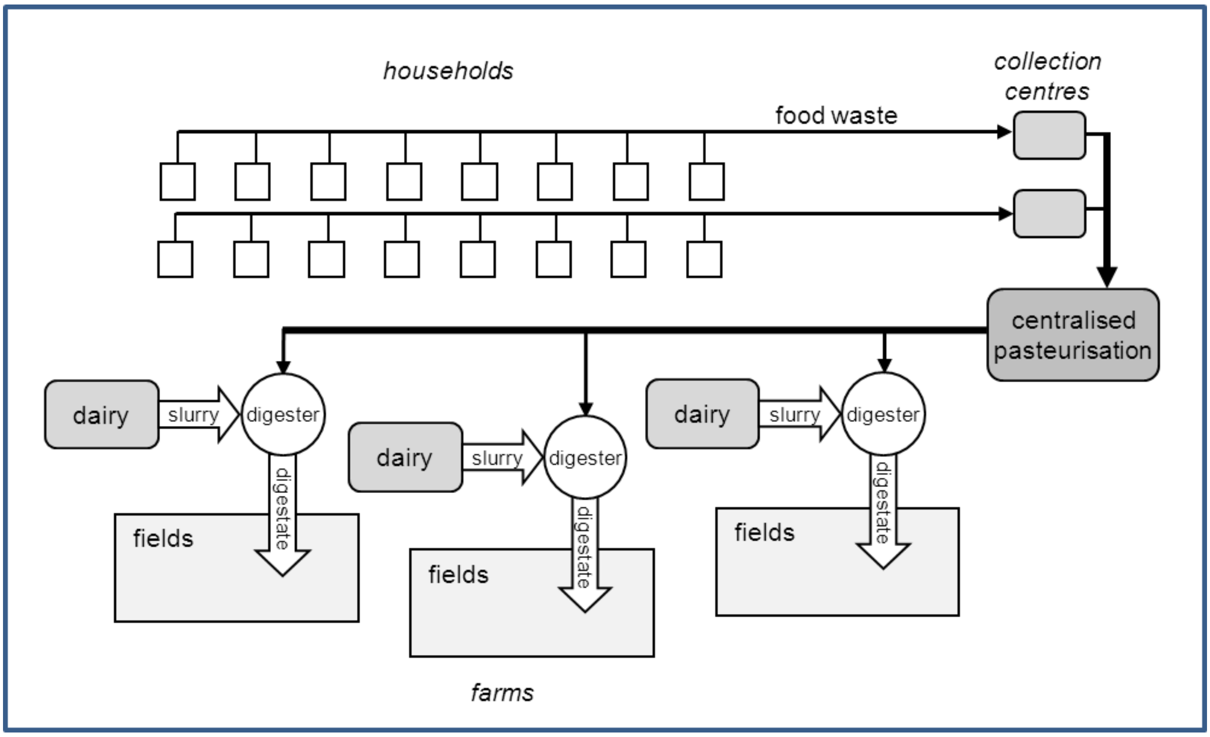

Figure 1. Proposed scheme for centralised pre-processing and pasteurisation followed by on-farm co-digestion.