

Purdy A, Pathare PB, Wang YD, Roskilly AP, Huang Y. [Towards sustainable farming: Feasibility study into energy recovery from bio-wastes on a small-scale dairy farm](#). *Journal of Cleaner Production* 2017. DOI: [10.1016/j.jclepro.2017.11.018](https://doi.org/10.1016/j.jclepro.2017.11.018)

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**DOI link to article:**

<https://doi.org/10.1016/j.jclepro.2017.11.018>

**Date deposited:**

07/11/2017

**Embargo release date:**

05 November 2018



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# **Towards sustainable farming: Feasibility study into energy recovery from bio-wastes on a small-scale dairy farm**

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## **Abstract**

Anaerobic digestion (AD) of farm biomass is growing importance as it offers environmental benefits and the biogas produced from AD which can be used as fuel for co-generation of heat and electricity. The study aimed to explore the viability of energy recovery from bio-wastes on a small-scale dairy farm to produce biogas using AD and the gas used as biofuel to fuel a combined heat and power (CHP) which generated electrical power and heat for the farm. The AD and the CHP system was designed and simulated using ECLIPSE software. Various ages of cow manure were sampled, analysed and used as an AD feedstock and it was found that as cow manure aged the amount biogas produced from anaerobic digestion was decreased; a reduction in biogas production of 5.76% was found over two months, and in the subsequent two months the reduction rate was found to accelerate, leading to a 16.92% reduction after four months. That means cow manure should be used as an AD feedstock as soon as possible, as carbon lost in the form of methane (CH<sub>4</sub>) occurs naturally in the atmosphere, accelerating over time. Early insertion of fresh manure into an anaerobic digester can significantly increase biogas production and subsequently reduce emissions of CH<sub>4</sub>, which has a global warming potential (GWP) of twenty-five times that of carbon dioxide (CO<sub>2</sub>). The simulation results indicated that enough energy can be recovered from the quantity of cow manure available on the farm to provide the electrical and heating energy demands of the farmyard and the attached dwellings, thus creating a sustainable farming system. In combination with the environmental benefits, it was determined that a substantial annual revenue could be generated from utility bill savings and current favourable incentive rates available to promote renewable energy technologies in farming industry in the UK.

**Keywords:** Farm bio-wastes; combined heat and power; biogas; anaerobic digestion

## 1. Introduction

As global climate change is constantly being driven by ever increasing levels of anthropogenic greenhouse gas (GHG) emissions, the deployment of renewable energy technologies must be accelerated to curtail the combustion of fossil fuels and eventually replace this finite resource. The UK government has set a target of 80% GHG reduction by 2050 compared to baseline of 1990 (UK Government, 2008). The UK must diversify the use of renewable energy technologies in each sector to reduce CHG, including agriculture. A farm requires intensive energy inputs, commonly in the form of fossil fuels and artificial fertilisers. The UK agricultural sector currently accounts for around 10% of the UK's GHG emissions; of which 83.0% come from carbon dioxide (CO<sub>2</sub>), 12.3% from methane (CH<sub>4</sub>) and approximately 6.5% from nitrous oxide (N<sub>2</sub>O) (National Statistics, 2017).

As these challenges are exacerbated by an increasing global population leading to increased demand on fossil fuels, energy insecurity and continuous use of the earth's finite natural resources. Therefore sustainable waste management practises are becoming more important not only to alleviate environmental pollution, but to decrease fossil fuel use and GHG emissions responsible for climate change. Anaerobic digestion (AD) is a biochemical technology for the treatment of organic wastes and the production of biogas, which can be used as a fuel for heating or co-generation of electricity and heat (El-Mashad and Zhang, 2010). In the Anaerobic Digestion Strategy and Action Plan (DEFRA, 2011), it was estimated that the potential for AD deployment for heat and electricity in the UK is between 3 and 5 TWh by 2020. Biogas production from agricultural biomass is of growing importance as it offers considerable environmental benefits and is an additional source of income for farmers (Amon et al., 2007). By AD process the significant methane emission resulting from the uncontrolled anaerobic decomposition of organic waste into atmosphere would be stopped, where methane is over 20 times more effective in trapping heat in the atmosphere than CO<sub>2</sub> (Salam et al., 2015).

Livestock effluents surplus is a very sensitive issue for farmers who have several difficulties to manage them and ensure their safe disposal (Pergola et al., 2017). Intensive dairy farming produces large amount of manure which, when not properly managed, can cause severe environmental problems due to its high organic matter, nitrogen (N) and phosphorous (P) concentrations, such as eutrophication of water receptors (Carpenter et al., 1998), air pollution due to volatilization of ammonia (NH<sub>3</sub>) and other compounds (Ryden et al., 1987) and soil degradation when manure is applied in excess. Manure is the second largest source GHG emissions from dairy farms (Aguirre-Villegas and Larson, 2017). Biogas production from

manure contributes to climate protection by reducing emissions of CO<sub>2</sub> via substitution of fossil fuels and by reducing CH<sub>4</sub> emissions from the manure during storage (Møller et al., 2007). In the UK, the schemes tariffs (FITs) in 2010 and the Renewable Heat Incentive (RHI) in 2011 which pay for electricity and heat generation, respectively were introduced (DECC, 2009). Both schemes were help towards the UK's aim of reducing GHG emissions by 80% by 2050 (Government, 2006) and the amount of waste sent to landfill (DEFRA, 2010). The adoption of sustainable energy technologies is a mitigation strategy that has the potential to reduce emissions by replacing fossil fuel consumption and a number of incentives have been developed to enable this goal to be achieved. Therefore, the aim of this research project was to determine the energy potential of various bio-wastes produced by a traditional UK dairy farm, in order to explore their potential as a renewable fuel within a sustainable farming system.

## **2. Methodology**

A dairy farm in Northern Ireland was selected as a case study, covering approximately 80 ha of flat fertile land and a current herd of 105 Friesian cows. The total annual electricity consumption on Farm was 70,972 kWh. The heating consumption has a maximum daily rating of 11 kWh. Cow manure is the most readily available and practical bio-waste feedstock. It was calculated that Farm produces 6.37 t of fresh manure each day, which offered considerable amount of biowaste for the proposed AD with CHP system.

### ***2.1. Sample Collection***

Sampling was carried out in accordance with the recommended methods of manure analysis (Peters et al., 2003). For each sample, 3 sub-samples were collected to mitigate the effects of an anomalous result. Each sample had an approximate mass of 5 g; and was individually placed in a sealed bag with the air removed. The waste samples are categorised as: COW 2 (Cow manure - fresh); COW 3 – (Cow manure -2 months old); COW 4 – (Cow manure -4 months old). The three sub-samples had an average dry matter (DM) content of 17%; which is in the expected range for fresh cow manure from the work of Pain et al [11]. The varying age of the samples will allow the effect of time on potential biogas production to be determined.

### ***2.2. Modelling and simulation***

A model of the AD process and CHP system was created in ECLIPSE and used to simulate prospective biogas production and subsequent energy from each sample feedstock. The calculated percentages of C, H, N and O may be input into ECLIPSE to model the effects of

various digestion parameters and energy conversion technology, and subsequently determine the biogas yield from the AD; and the power and heat generated from the CHP.

The ECLIPSE package was developed by the Energy Research Centre within the University of Ulster in 1992 as a process simulator for the analysis of coal liquefaction technology (Ulster, 1992; Williams and McMullan, 1996). The package is user friendly and can be used to analyse new as well as established technologies for a range of processes. Processes will be simulated where the quantity of available bio-waste substrate available will be used to calculate the biogas yield (kg/day). A model of the AD process and CHP system was created in ECLIPSE and used to simulate prospective biogas production and subsequent energy from each sample feedstock. The first step required to produce an ECLIPSE simulation is to create a process flow diagram (PFD). Once the PFD has been defined and each compound has been added to the database the process may be simulated and the mass energy balance completed. This is the most time consuming and complex part of the ECLIPSE simulation due to the various parameters that must be defined. Input flow rates must be defined, temperatures and pressures in each stream and module must be realistic and chemical equations must be balanced to achieve a zero elemental balance error.

### **3. Results and discussion**

The testing results of elemental analysis of biomass wastes collected are shown in Table 1; the waste samples are named as 'COW2', 'COW3' and 'COW4'. The first step towards completing a mass energy balance for each sample is to input the sample flow rate into the stream definition under ECLIPSE.

The farm produces 59.21 m<sup>3</sup> of cow manure per week. Fresh manure sample consisted of 83% water; the total flow rate was calculated as 0.0734 kg/s; this value was entered into the feed stream of the mass energy balance for COW 2 (Figure 1). It was calculated that within two months the mass of cow manure available would decrease by 2.67% and within 4 months by 8.43%. In terms of annual reductions, these figures would lead to a loss of 62 kg of manure after 2 months, and 196 kg after 4 months. Therefore the total flow rates of COW 3 and COW 4, were reduced to 0.718 kg/s and 0.675 kg/s respectively.

#### ***3.1. Simulation with biogas as fuel***

The ECLIPSE digester simulation for each bio-waste sample was carried out under mesophilic conditions (25°C), at normal atmospheric pressure (1 bar) with a solid to gas conversion efficiency of 50%, as this was the achievable efficiency of a mesophilic anaerobic digester in practise (OSU, 2013).

It is known that cow manure can produce a maximum of 0.182 m<sup>3</sup> of biogas/kg (Qiao et al., 2011). As the farm produces 2,325 t of cow manure per year; therefore the maximum amount of biogas attainable from cow manure was calculated to be 423,150 m<sup>3</sup>/year, equating to 1,159 m<sup>3</sup>/day.

From Figure 2 it can be seen that the biogas production from each of the sample manure feedstocks is significantly less than the maximum that is theoretically attainable. The mesophilic AD process modelled in ECLIPSE with COW 2 as the feedstock, produced 373 m<sup>3</sup> of biogas/day. Therefore the AD process simulation achieved a conversion efficiency of 32% of the solid available to biogas. The digestion parameters in the model were set to achieve a solid to gas efficiency of 50%, therefore this conversion efficiency is 18% less than expected, and well within the achievable range of a mesophilic anaerobic digester. As the biogas production rates have been used to feed the CHP outputs (see Figure 1), the fact that they are comfortably within the achievable range increases confidence in the energy output calculations, and the subsequent GHG savings calculations.

As the cow manure feedstock ages, a reduction in biogas production is noted. After two months the daily biogas production from cow manure (COW 3) is reduced by 21.5 m<sup>3</sup> or 5.76%. After four months (COW 4) the reduction rate is accelerated and the daily biogas production is decreased by 63.1 m<sup>3</sup> or 16.92%.

The loss in biogas production as the manure ages can be explained by the C reduction rate, which is the rate of loss of C as the manure digests naturally in the atmosphere. The loss of C can be viewed over a four month period from the results of the CHN analysis presented in Table 1. It can be seen that after two months the C lost is equivalent to 1.13% of the manure sample, which leads to a daily biogas production loss of 5.76%. Between two and four months the rate of loss is accelerated and the C lost is equivalent to 3.58% of the manure sample, resulting in a daily biogas production decrease of 16.92%.

In an environment which is low in oxygen (O), the present C combines with hydrogen (H) to form CH<sub>4</sub>. Over time the amount of C and H in the manure samples is decreased and the amount of O is increased. The decrease in C and H suggest that the majority of C is combining

with H to form CH<sub>4</sub>. CH<sub>4</sub> is known GHG with a greenhouse warming potential (GWP) equivalent to twenty five times that of CO<sub>2</sub> (Maeda et al., 2013). Therefore it is essential to use cow manure as a feedstock for AD as soon as possible to increase biogas production and prevent CH<sub>4</sub> from entering the atmosphere.

### **3.2.Simulation of CHP for energy outputs**

The electrical and heat energy outputs are presented in Figure 3; conversion efficiencies of 30 and 50% were used respectively. It is known from the technical data-sheets of Alfagy, 2013 that these are the current efficiencies achievable by a CHP system fuelled by biogas. Total power output achievable by the CHP system decreases with the age of the manure feedstock. To reduce the number of variables between each manure sample, the flow rate of DM was modelled at a constant 17% of the total waste flow available. The total amount of bio-waste available annually was known to be 2,325 t of fresh manure. However due to C and H loss the amount of manure available after two months would be reduced relative to the rate of C loss. It was calculated that after two months of carbon loss the annual manure available would reduce to 2,263 t and after four months to 2,129 t. The loss of C and H from manure leads to a decrease in the mass of manure feedstock available, and subsequently reduces the total power outputs from the CHP system.

Total power output available from COW 2 is 78.6 kW, consisting of an electrical power output of 29.6 kW and combined heating output of 49 kW. As the manure feedstock ages, the loss of electrical and heating power outputs are decreased. The electrical power generation is reduced due to a reduction in the amount of biogas available for combustion; subsequently the amount of recoverable heat from the exhaust and engine cooling system is reduced. Due to this interdependent relationship between the amount of biogas available and total power output from the CHP, the electrical and heating power outputs are reduced at approximately the same ratio.

The CHP system is shown to achieve an electrical generation efficiency of approximately 31%, which is typical of a modern electrical generator. The heat recovery system increases the efficiency of the CHP by a very credible 50%, leading to an overall CHP system efficiency of 81%. It is known from technical datasheets produced by a current CHP manufacturer, Alfagy, that an operating efficiency of 81% is currently achievable by their biogas CHP system.

Therefore the operating efficiencies calculated add confidence to the electrical and heating power output results.

### ***3.3. Electricity and heat energy output***

The electrical and heat energies have been summed to determine the variation of the total energy available from the cow manure feedstocks with age. One tonne of fresh manure can produce 296 kWh of combined energy outputs from the CHP system; after two and four months the combined energy outputs per tonne of feedstock are reduced to 291 kWh and 279 kWh respectively. The loss of energy per tonne of substrate is directly related to the loss of C and H available, reiterating the importance of using fresh manure as a feedstock to increase energy outputs.

The maximum daily electrical rating of 19 kW demanded by Farm can be achieved by all of the sampled manure feedstocks. It is found that by using the COW 2 as the feedstock, the maximum electrical power output exceeds the required amount by 10 kW. As the manure ages the electrical power output is reduced to 28.4 kW after two months and 25.5 kW after four months, due to the C losses and subsequent biogas reductions. The AD and CHP system can produce enough electrical energy to meet the demands of farm. The system can therefore create a revenue stream from the capital saved by substituting the electrical power currently purchased from the national grid, and the additional Feed-in-Tariff (FiT) rate paid.

The maximum heat output exceeds the required amount by 38 kW when COW 2 used as the feedstock which resulted the availability a large amount of excess heating power. As the manure ages the heating power is reduced in correlation within the electrical power, to 46.9 kW after two months and 42.2 kW after four months. The fact that the heat power rating of the CHP system greatly exceeds the current demand on Farm is an extremely positive finding to support the case of the installation of an AD system. The AD and CHP system can produce enough heat energy to substitute the current fossil-fuel based heating demands on Farm. If the heat energy is used for space-heating it also qualifies for the Renewable Heat Incentive (RHI), which will increase annual revenue and help to recover the initial investment.

### ***3.4. Greenhouse gas savings***

Cow manure deposited on fields or stored in tanks produces significant amounts of CH<sub>4</sub> as bacteria which is also excreted from the animal facilitates an anaerobic digestion condition. It is found that the annual amount of cow manure produced on Farm is left to digest uncovered in the atmosphere for two months it will emit 6,909 kg of CH<sub>4</sub>. If the annual manure mass is left



uncovered for four months the rate of emission is increased 3 fold and 21,196 kg of CH<sub>4</sub> will be emitted per year. It is therefore essential to input the cow manure as soon as possible into an AD tank, to reduce the loss of C and the subsequent emissions CH<sub>4</sub>, and hence yield more energy from the system. The rate of loss of H from the manure samples is slower than the loss of C; this is due to the fact that H can be sought externally from the moisture around the sample (H<sub>2</sub>O).

In terms of accounting for the GHG gas savings of an on-farm AD and CHP system, non-fossil fuel CO<sub>2</sub> is considered to be part of the natural carbon balance and therefore not a contributor to atmospheric concentrations of CO<sub>2</sub>. The CO<sub>2</sub> produced from the combustion of biogas is therefore considered as net-zero, however the CH<sub>4</sub> which is used as a bio-fuel and prevented from entering the atmosphere can have a significant impact on CH<sub>4</sub> emission reductions from the agriculture industry. It describes the environmental benefits of AD and energy recovery. It not only prevented CH<sub>4</sub> from entering the atmosphere, but also used as a bio-fuel to displace electrical and heat energy demands, which are currently met by fossil-fuels.

The annual CO<sub>2</sub> displacement achievable by substituting the current electrical and heat energy demands to bio-energy supplied from an AD and CHP system. It was calculated that to meet the annual electrical demand on Farm 22,534 kg of coal is combusted annually, resulting in 63,884 kg of CO<sub>2</sub> being emitted to the atmosphere. It was known that 2,532 kg of kerosene is consumed annually for heating, resulting in 7,891 kg of CO<sub>2</sub> emissions. It is found that by substituting the electrical energy heat energy demand, a total of 71,775 kg of CO<sub>2</sub> may be displaced annually by the installation of an AD and CHP system.

#### **4. Conclusions**

This feasibility study indicated that the AD and CHP technology can extract enough energy from the cow manure produced on a small-scale dairy farm to supply the farms entire electrical and heating demands. It was found that as cow manure aged the amount biogas produced from AD decreased. The loss in biogas production is directly correlates with the loss of C. Therefore it is essential to use cow manure as feedstock for AD as soon as possible, to increase biogas production and reduce CH<sub>4</sub> emissions.

As biogas production was decreased with manure age, the energy produced is also decreased. It equated to an electrical power capacity of 29.6 kW and a heating power capacity of 49.0 kW, leading to combined power output of 78.6 kW achievable from fresh cow manure. As the

manure aged the biogas production was known to decrease and the total power output was reduced by 4.20% after two months and 13.87% after four months.

The electrical power rating of Farm was calculated to be 19 kW, and in all cases the achievable power output exceeded the rated consumption and excess heat may be used for space heating to qualify for the RHI. The electrical and heating power demands of Farm could be met by an AD and CHP system solely fuelled by the cow manure produced on-farm, the annual CO<sub>2</sub> displacement achievable by replacing the current fossil-fuel based electricity and heating power was calculated. It was determined that a total of 71,775 kg of CO<sub>2</sub> could be displaced annually by substituting the current electricity demand of the farm and three dwellings, and the heating demand of the main farmhouse. This study shows that the generation of sufficient energy from farm bio-waste to reduce energy use from fossil fuels, thereby cutting net carbon emissions, can be considered a positive mitigation option towards sustainable farming.

### **Acknowledgments**

The authors gratefully acknowledge the financial support from Engineering and Physical Science Research Council, UK (RE4Food project -EP/L002531/1). Also, this study was partly supported by EPSRC IAA Phase 2 (EP/K503885/1) – ‘Computational fluid dynamics (CFD) enabled optimisation of a hybrid solar dryer for sub-Saharan Africa ; and EPSRC Global Challenges Research Fund Institutional Sponsorship Award 2016 - Institutional Sponsorship Funding, ‘Preparing for GCRF Award: Optimisation of different solar dryers used in Sub-Saharan Africa using computational fluid dynamics (CFD)’.

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