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

Andrew Purdy [a], Pankaj B. Pathare [a, b, *], Yaodong Wang [a], Anthony Paul Roskilly [a], Ye Huang [c]

[a] Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom
[b] Department of Soils, Water and Agricultural Engineering, College of Agricultural & Marine Sciences, Sultan Qaboos University, Oman
[c] School of the Built Environment, Ulster University, Jordanstown, BT37 0QB, UK

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A B S T R A C T

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-waste 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. It was found that 1 t fresh manure as the feedstock produced 58.6 m^3 of biogas. That means cow manure should be used as an AD feedstock as soon as possible, as carbon lost in the form of methane (CH_4) occurs naturally in the atmosphere, accelerating over time. The rate of CH_4 emission is increased by 3 fold (i.e. 21,196 kg per year) if the annual manure mass is left uncovered for four month. Early insertion of fresh manure into an anaerobic digester can significantly increase biogas production and subsequently reduce emissions of CH_4, which has a global warming potential (GWP) of twenty-five times that of carbon dioxide (CO_2). 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.

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_2), 12.3% from methane (CH_4) and approximately 6.5% from nitrous oxide (N_2O) (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

* Corresponding author. Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom.
E-mail addresses: pbpathare@gmail.com, pankaj.pathare@ncl.ac.uk (P.B. Pathare).

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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_2 (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_3) 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_2 via substitution of fossil fuels and by reducing CH_4 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 (UK 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 of 10–20% for fresh cow manure from the work of Pain et al. (1984). 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 (The University of 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 were the quantity of available bio-waste substrate available will be used to calculate the biogas yield (kg per 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^3 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 (Fig. 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 ECLPISE digester simulation for each bio-waste sample was

Table 1
Elemental analysis of biomass wastes in the selected dairy farm.

Biomass waste	Element content (%)			
	C	H	N	O
COW 2	42.33	6.00	2.55	49.12
COW 3	41.20	5.84	2.58	50.38
COW 4	38.76	5.53	2.13	53.58