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Distributed and micro-generation from biogas and agricultural application of sewage sludge: Comparative environmental performance analysis using life cycle approaches

Jhuma Sadhukhan *

Centre for Environmental Strategy, University of Surrey, Guildford GU2 7XH, UK

HIGHLIGHTS

- 180,000 MJ biogas from 15.87 t sewage sludge supply 1 household electricity per year.
- From the highest to the lowest avoided impacts: PEM FC < Micro GT < SOFC.
- Biogas systems have avoided GWP: 0.079–0.12 kg CO_2 eq./MJ compared to natural gas.
- 1 m^3 biogas production from ~3.2 t sewage sludge AD can save 0.92 m^3 natural gas.
- Digested matter causes eutrophication and toxicity potentials.

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ABSTRACT

The Feed-In-Tariff scheme in the UK has generated attractive economics in the investment for anaerobic digestion (AD) to convert sewage sludge into biogas and digested sludge for energy and agricultural applications, respectively. The biogas is a source of biomethane to replace natural gas in the gas grid system. Biogas can be utilised to generate combined heat and power (CHP) on-site, at household micro and distributed or community scales. These biogas CHP generation options can replace the equivalent natural gas based CHP generation options. Digested sludge can be transformed into fertiliser for agricultural application replacing inorganic N:P:K fertiliser. Biogas and digested matter yields are inter-dependent: when one increases, the other decreases. Hence, these various options need to be assessed for avoided life cycle impact potentials, to understand where greatest savings lie and in order to rank these options for informed decision making by water industries. To fill a gap in the information available to industry dealing with wastewater, the avoided emissions by various AD based technologies, in primary impact potentials that make a difference between various systems, have been provided in this paper.

1 m^3 biogas can save 0.92 m^3 natural gas. An average UK household (with a demand of 2 kWe) requires 180,000 MJ or 5000 Nm^3 or 4.76 t biogas per year, from 15.87 t sewage sludge processed through AD. The proton exchange membrane fuel cell (PEM FC) is suitable for building micro-generations; micro gas turbine (Micro GT), solid oxide fuel cell (SOFC) and SOFC-GT hybrid are suitable for distributed generations upto 500 kWe and occasionally over 500 kWe; engine and ignition engine above 1 MWe. These CHP technologies can be ranked from the lowest to the highest impacts per unit energy production: PEM FC is the environmentally most benign option, followed by SOFC, SOFC-GT, Engine or Micro GT and Ignition engine (with the highest impact potential), respectively. In terms of avoided global warming, acidification and photochemical ozone creation potentials, compared to equivalent natural gas based systems, the biogas based PEM FC micro-generation and Micro GT distributed systems achieve the greatest avoided emissions with the most cost-effectiveness. Application of digested sludge as fertiliser has more toxicity impacts, however, has greater avoided emissions in acidification and photochemical ozone creation potentials on the basis of inorganic N:P:K fertiliser, compared to the biogas production for the natural gas grid system.

* Tel.: +44 1483 68 6642; fax: +44 1483 68 6671.
E-mail address: jhumasadhukhan@gmail.com

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1. Introduction

There are economic incentives in sewage sludge utilisation for distributed and micro-generation of combined heat and power (CHP), following the introduction of Feed-In-Tariff (FIT) scheme in the UK [1–3]. The distributed systems at community scale are meant to generate few hundred kilowatts to few megawatts of electricity, while the household micro-generation systems are designed to produce 1–4 kW of electricity [2]. The FIT scheme offers the payment for each unit of renewable electricity generation using the technologies shown in the scheme. Thus the scheme enables reduction in import of electricity by facilitating self-generation and export of additional electricity to the electricity grid system. The various payments under the FIT scheme applicable to sewage sludge utilisation in the UK are shown in Table 1. These payments create economic incentives for water companies to invest in anaerobic digestion (AD) and CHP plant installations in the UK [2]. However, there remains the most important question to be answered for industries: in which sequence the following technologies to invest on, to achieve greatest emission cuts or avoided impact potentials from the plant, biogas to natural gas grid system, on-site biogas based CHP generation and fertiliser production from digested sludge. Additionally, it will be extremely useful to identify most important or sensitive environmental impact categories to evaluate, as LCA is a data intensive exercise. LCA results may be affected by data uncertainty and variability and must be resolved by stochastic Monte Carlo simulations and scenario analysis. This paper answers to these most critical research questions, comprehensively.

A number of studies have been undertaken to find technical solutions for alternative products from solid organic wastes, biogas, cleaner liquid fuel and residual solids for agricultural applications [4–11]. Further, Table 1 shows the CHP technologies for utilising biogas from the AD plant. The FIT rates shown are applicable to the AD plant installations. For CHP plant installations, a separate FIT rate of 11 pence per kilowatt-hour is applied.

Though economic incentives in energy application of sewage sludge through the AD process have been enhanced by such schemes, these solid organics can also be used as fertilisers. Their agricultural application could be environmentally more benign. The latter application however, is associated with some inorganic and heavy metal emissions to soil that eventually are released to the atmosphere and water [12,13].

One driver for alternative energy application of sewage sludge is that their growing quantities in landfills are causing emissions to water and air. Concerns over health and environmental protection are growing as increasing number of contaminants are emitted to water resources previously considered clean. Hence, other usages of sewage sludge, such as energy generation must also be assessed for environmental sustainability. Life cycle costs and primary life cycle assessments (LCA) of various wastewater treatment and biogas production processes have been published [14–20]. However, comparative environmental performance analysis using LCA, in terms of avoided emissions, between biogas based on-site distributed and micro CHP generation technologies has not been published. Also, environmental impact potential tradeoffs between biogas production and digested sludge production from sewage sludge via AD need to be established. Thus the aim of this paper is to prioritise primary impact characterisations that make a difference in the selection of the technologies and thereby rank these technologies according to avoided primary impact potential evaluations. Furthermore, Monte Carlo simulation has been carried out to show the probability distributions of impact characterisations and also to determine the most sensitive primary impact characterisations for the wastewater AD system. All the primary impact potentials, acidification (AP), eutrophication (EP), freshwater aquatic ecotoxicity (FAETP), global warming over 100 years (GWP), human toxicity (HTP), marine aquatic ecotoxicity (MAETP), ozone layer depletion (ODP), photochemical ozone creation (POCP) and terrestrial ecotoxicity (TETP) have been evaluated comprehensively, for recommending the most important ones.

2. Process description

Wastewater is collected by sewer system and transported to a treatment process. The process configuration comprising primary and secondary treatments along with the operating inventory data is shown in Fig. 1. The two main sludge streams collected as a feedstock from the primary and secondary treatment process units are the primary sludge and activated sludge. If there is a large quantity of phosphorous compounds present after the secondary treatment, a tertiary phosphate precipitation process unit is used before releasing water to river or reserve. These process units are common in a wastewater treatment plant and can be excluded from the systems to be analysed for comparative LCA.

The system under consideration shown within the boundary in Fig. 1 is discussed as follows. The sludge feedstocks are taken to an AD process unit, where micro-organisms in the absence oxygen destroy or decompose the nutrients and produce a gas stream rich in methane and a nutrient rich residual stream. Upon scrubbing with water for further removal of impurities from the gas followed by drying, biogas consisting of methane and carbon dioxide as the main components and nutrient rich digested matter are produced. The two most commonly used physical absorption processes, the Rectisol™ and Selexol™ technologies, can be used for the removal of H_2S, COS, HCN, NH_3, nickel and iron carbonyls, mercaptans, naphthalene, organic sulphides, etc. to a trace level in the biogas, before its injection to the gas grid system. The solvent is regenerated at a higher temperature by temperature swing and metallic sulphur is recovered from the sour gas by the Claus process, where hydrogen sulphide rich gases are partially combusted with a limited amount of air to produce sulphur dioxide, so that a reaction between unreacted hydrogen sulphide and sulphur dioxide can take place to form metallic sulphur. Impurities such as hydrocarbons in the feed gas are also combusted and the products of combustion can interact to form gaseous sulphur containing by-products. The gas clean up processes required to maintain the impurity levels to less than ppm level for trouble free operation of the electrodes of the fuel

Table 1
FIT rates in Sterling pence per kWh.

AD plant capacity [2]	CHP technologies	FIT rate in 2010/11 [2]	FIT rate in 2012/13 [2]
⩽ 250 kWe	Proton exchange membrane fuel cell	12.70	14.70
250 kWe <; ⩽ 500 kWe	Micro gas turbine; Solid oxide fuel cell; Solid oxide fuel cell and gas turbine	12.70	13.60
500 kWe <	Solid oxide fuel cell; Solid oxide fuel cell and gas turbine Ignition; Sterling; gas engines	9.90	9.90