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Integration of Power to Methane in a waste water treatment plant – A feasibility study

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ABSTRACT

The integration of a biomethanation system within a wastewater treatment plant for conversion of CO_2 and H_2 to CH_4 has been studied. Results indicate that the CO_2 could be utilised to produce an additional 13,420 m^3/day of CH_4, equivalent to approximately 133,826 kWh of energy. The whole conversion process including electrolysis was found to have an energetic efficiency of 66.2%. The currently un-optimised biomethanation element of the process had a parasitic load of 19.9% of produced energy and strategies to reduce this to $< 5\%$ are identified. The system could provide strategic benefits such as integrated management of electricity and gas networks, energy storage and maximising the deployment and efficiency of renewable energy assets. However, no policy or financial frameworks exist to attribute value to these increasingly important functions.

1. Introduction

Society faces a number of challenges relating to future energy production and transmission as efforts continue to reduce global CO_2 emissions. Whilst deployment of renewable electricity generation technologies has increased significantly in the UK from 6.8% of total generation capacity in 2010 to 24.6% in 2015 (BEIS, 2016), grid constraints (Van den Bergh et al., 2015) and high integration costs (Hirth et al., 2015) may limit the effectiveness of power grids based on high penetration of renewables. These problems are not unique to the UK but are repeated throughout developed countries with a high penetration of renewable electricity production and reduction in fossil energy production. Power to Gas (PtG) is an approach that, if successfully developed and deployed, would allow the inter-operability of electricity and gas grids, maximise the productivity of renewable electricity generation infrastructure, contribute towards the decarbonisation and long term viability of regional or national gas transmission networks, and allow for energy storage within the gas grid. The integration of renewable energy generation, energy storage and waste management operations may also bring additional benefits such as the improved efficiency of waste management processes.

PtG is based around the electrolytic production of hydrogen, and, where this electrolysis is driven by renewable electricity, it offers a route for producing low carbon fuel gases (Jensen et al., 2007, Carmo et al., 2013). Whilst hydrogen may represent a valid fuel vector in the long term, at present in many countries it cannot be added to natural gas infrastructure in significant quantities – for example in the UK current gas quality legislation only permits $< 0.1\%$ hydrogen (UK Government, 1996). The potential for including hydrogen concentrations of 0.5–20% are being considered (HSE, 2015), however, these higher levels may be limited only to some networks, and utilising hydrogen at 20% by volume would deliver only 6% of the energy of the same volume of methane. Conversion to high hydrogen percentages is likely to be focused on urban populations and will require significant changes to the gas network infrastructure and end use appliances (Leeds City Gate, 2016). Approaches that utilise low carbon hydrogen to produce low carbon synthetic methane, which is fully compatible with current gas grid infrastructures and regulations, therefore have the potential for short to medium term deployment i.e. over the next few decades, and could contribute to long term viability of more spatially distributed networks serving lower population densities. The Sabatier process thermo-chemically reacts H_2 with CO_2 to produce CH_4 (Jurgensen et al., 2015), however the process operates at high temperatures (> 250 °C) and pressures (> 10 bar) and can be difficult to control, utilises expensive metal catalysts, and is not compatible with the intermittency of renewable energy supplies. Alternatively, several

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microbial species (hydrogenotrophic methanogens) have the ability to utilise hydrogen in combination with carbon dioxide to produce methane and water e.g. (Savvas et al., 2017a), as summarised in the Eq. (1).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O. \quad (1)$$

Another two stage anaerobic microbial pathway could also catalyse this conversion through a combination of homoacetogenesis and acetotrophic methanogenesis (Savvas et al., 2017b).

Whilst the biomethanation process is still at early stage research and development, the approach offers a means of potentially achieving high conversion efficiencies at low temperatures and pressures and is tolerant of contaminants typically found in biologically produced gases or flue gases.

Previous research has conceptualised several applications and configurations for such a biological process, including the production of high methane content biogas from anaerobic digestion plants (Luo et al., 2012, Bensmann et al., 2014), the operation of standalone hydrogenotrophic reactors (Luo and Angelidaki, 2012, Bassani et al., 2015), using single strain microbial populations (Martin et al., 2013) and mixed culture approaches (Savvas et al., 2017a). More recently, some research has been undertaken to evaluate the potential for actually deploying such technology at industrial scale, and quantifying the environmental burdens/benefits that this might bring. Götz et al. (2016) undertook a techno-economic assessment of various Power to Methane (P2M) approaches and concluded that biological methanation, whilst easier to control than chemical catalytic approaches, was limited in effectiveness by poor H_2 mass transfer to the liquid phase. This was also a topic of discussion by Savvas et al., (2017b) and further improvements were achieved by the development of a novel biofilm plugflow reactor capitalising on lower energy requirements of gas to gas (reduced liquid layer) transfers. By undertaking a regional mathematical modeling approach, Zoss et al. (2016) concluded that wind resources in the Baltic states would be insufficient to generate enough H_2 to utilise the CO_2 produced in the regions' biogas plants, but recognised the important grid balancing role that such an approach would make. In assessing the life cycle burdens of P2M and Power to Syngas compared to fossil fuel reference cases, Sternberg and Bardow (2016) concluded that where availability of renewable electricity was limited, syngas production from fossil sources had lower environmental burdens than other options, highlighting the importance of renewable electricity in the viability of P2G systems. The importance of utilising a high proportion of renewable electricity to drive a Power to Gas process was also stated by Reiter and Lindorfer (2015) in their assessment of life cycle Global Warming Impacts of PtG options. Walker et al. (2016) concluded that PtG (in this case hydrogen) could be cost competitive with fossil reference processes providing that the low carbon nature of the hydrogen and the function of providing an energy storage mechanism is reflected in the pricing structure. Gutiérrez-Martín and Rodríguez-Antón (2016) evaluated the technical and economic feasibility of Power to Methane for energy storage based on a thermo-chemical catalytic methanation stage. Vo et al. (2017) assessed the feasibility of matching curtailed wind electricity in Ireland with CO_2 produced in biogas plants to biologically produce methane for transport fuel use, and concluded that predicted 2020 curtailed electricity would be sufficient to utilise 28.4% of CO_2 available in biogas plants.

1.1. Study aims

This study aims to evaluate the feasibility of integrating a novel biomethanation system at a waste water treatment plant (WWTP) incorporating sludge digestion, biogas production, biogas upgrading and gas grid injection. This application was chosen as a potential early adopter of PtG/biomethanation technology as it has an abundant supply of CO_2 and is likely to have on site uses for process products including oxygen (in the aeration processes) and methane (in on site CHP or gas grid injection facilities), and the water industry is familiar with the operation of industrial biological processes. A number of water companies are also investing in the deployment of other renewable energy generation assets near WWTPs. Study conditions, industrial practice and regulatory frameworks are based on those found in the UK, but are broadly applicable in other developed countries. If integration is feasible, wastewater treatment plants could provide novel and increasingly strategic roles within society by delivering the following functions; (i) treatment of wastewater, (ii) recovery of nutrients, (iii) production of biogas, (iv) recycling of CO_2 (via biomethanation), (v) balancing/integration of power and gas grids (via biomethanation).

This is the first time that this approach to biomethanation has been evaluated for full scale deployment in an industrial waste water treatment plant.

The scope of this study covers the following points:

1. To numerically scale up a laboratory based biomethanation process to investigate the configuration and integration of such a process into a waste water treatment/sludge digestion process.
2. To quantify the broad operating parameters of such a system based on current knowledge and experience, in particular the energetic requirements of the system. This is undertaken by considering current operating parameters of both the WWTP and the PtG/biomethanation system and by calculating the major material flows and energetic requirements.

2. Methods

2.1. System boundary

The boundary of the system studied is shown in Fig. 1. The energy requirement of the integrated process is evaluated by quantifying primary energy input to electrolysers (hydrogen production), the biomethanation process, the energy available through methane production, excess thermal energy and, where appropriate, energy savings from utilisation of co-products (i.e. oxygen). As CO_2 for the biomethanation process is sourced from biogas, the existing biogas production and upgrading facilities are included in the overall integration evaluation.

2.2. Primary elements of WWTP

The WWTP considered in this study is consistent with a large conventional sewage treatment plant treating municipal wastewater generated by a population equivalent of approximately 900,000 and treating approximately 65.7 million m^3 of sewage per year. The primary elements of the WWTP are shown in Fig. 2. Of specific interest is the presence of secondary treatment methods that rely on the aeration of mixed liquors in both the activated sludge plant and sequencing batch reactors that currently utilise air as the oxygenating agent. The integration of PtG/biomethanation into such a process has the potential to supply pure oxygen that could be utilised in a modified aeration system, therefore potentially reducing operational energy consumption. In the context of this study, aeration of wastewater is assumed to be required to achieve a reduction in BOD from 220 mg/l to 20 mg/l, and a reduction in Nitrogen from 40 mg/l to 20 mg/l.

In addition, the presence of sludge digestion facilities and the generation of biogas provide a large source of biogenic CO_2. The volume of biogas produced from the digestion of sewage sludge is approximately 40,000 m^3/d. Given an average methane content of 62.5%, this gives an approximate CO_2 production of 14,720 m^3/d. Off gas from the biogas upgrading plant (based on water scrubbing) typically comprises of approximately 90% CO_2 and 8.2% CH_4, with the remaining 1.8% being made up of low concentrations of N_2, H_2, CO, H_2S and O_2 (Malmberg Water AB, 2015) and is therefore considered as a viable feed gas for biomethanation.