Bioresource Technology 131 (2013) 235–245

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Life cycle assessment of biohydrogen and biomethane production and utilisation as a vehicle fuel

Tim Patterson *, Sandra Esteves, Richard Dinsdale, Alan Guwy, Jon Maddy

Sustainable Environment Research Centre (SERC), Faculty of Health, Sport and Science, University of Glamorgan, Pontypridd, Wales CF37 1DL, UK

HIGHLIGHTS

- Two phase treatment of wheat feed decreased environmental impact.
- Two stage treatment of food waste decreased energy output.
- Energy production processes must be optimised according to feedstock characteristics.
- Water usage in the two stage process must be reduced to increase process efficiency.
- Benefits of biomethane from wastes are largely associated with diversion from landfill.

ARTICLE INFO

Article history:
Received 25 September 2012
Received in revised form 11 December 2012
Accepted 14 December 2012
Available online 22 December 2012

Keywords:
Anaerobic digestion
Biomethane
Biohydrogen
Transport fuel
Life cycle assessment

ABSTRACT

Environmental burdens for the production and utilisation of biomethane vehicle fuel or a biohydrogen/biomethane blend produced from food waste or wheat feed, based on data from two different laboratory experiments, have been compared. For food waste treated by batch processes the two stage system gave high hydrogen yields (84.2 l H_2 kg^{-1} VS added) but a lower overall energy output than the single stage system. Reduction in environmental burdens compared with diesel was achieved, supported by the diversion of waste from landfill. For wheat feed, the semi continuously fed two stage process gave low hydrogen yields (7.5 l H_2 kg^{-1} VS added) but higher overall energy output. The process delivers reduction in fossil fuel burdens, and improvements in process efficiencies will lead to reduction in CO_2 burdens compared with diesel. The study highlights the importance of understanding and optimising biofuel production parameters according to the feedstock utilised.

1. Introduction

Anaerobic digestion (AD) is a process where organic matter is mineralised primarily to methane and carbon dioxide (biogas) through a series of reactions mediated by several groups of microorganisms in the absence of oxygen. The process is widely used at an industrial scale for the treatment of organic wastes such as sewage sludge and is currently also being employed for the treatment of municipal, commercial and industrial wastes, or for energy generation using energy crops.

The most common model for biogas utilisation in the UK and across much of Europe is still the generation of electricity and heat using a Combined Heat and Power (CHP) plant (Monson et al., 2007). Where a high level of heat utilisation is achieved this is an efficient use of biogas which minimises environmental impacts. However, where only a low proportion of the heat is utilised, or none at all, other biogas end uses provide greater reductions in environmental burdens (Patterson et al., 2011). One such use is as a vehicle fuel where biogas is cleaned and upgraded to biomethane and is combusted in an internal combustion engine. Both fuel production and engine technologies are based on well understood and readily available processes and products with the majority of major car manufacturers producing natural gas fuelled vehicles (e.g. Volkswagen, Volvo, Fiat, Ford). Barriers to large scale implementation are therefore largely economic.

The majority of AD plants are configured such that the consortia of microbes converting the organic material to biogas are present within a single tank, meaning that conditions are necessarily sub-optimal for any groups of bacteria that require different environmental conditions. A variation to AD where trophic groups of microorganisms with differing optimal environmental conditions are separated into two different vessels has been developed, with potential advantages of this process being (i) hydrogen can be liberated from the acid producing first phase, and (ii) methane production in the second stage can be increased compared to the

* Corresponding author. Tel.: +44 (0) 1443 483688; fax: +44 (0) 1443 482285.
E-mail address: tlpatter@glam.ac.uk (T. Patterson).

0960-8524/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2012.12.109

single stage process, giving an overall increase in energy output (Hawkes et al., 2007). A blend of hydrogen and methane gas has been shown to reduce key exhaust emissions compared with methane alone when burned in an internal combustion engine (Wang et al., 2007; Dimopoulos et al., 2008; Graham et al., 2008). Therefore, the ability to biologically produce such blends has an obvious application as a means of producing non-fossil vehicle fuel, and could represent a further transition stage to a gaseous fuel economy.

However, as two stage biohydrogen/biomethane production requires a different process management strategy to single stage biomethane production (anaerobic digestion), it is not clear whether the potential advantages of biohydrogen/biomethane production will lead to real environmental benefits. One way to investigate this is via Life cycle assessment (LCA). There have been several studies focussing on the energy balances and emissions of anaerobic digestion of various feedstocks, most notably studies by Berglund and Börjesson (2006), Börjesson and Berglund (2006), Börjesson and Berglund (2007), Patterson et al. (2008) and Pöschl et al. (2010), with relatively few studies undertaking full Life cycle assessments of AD infrastructure options e.g. Patterson et al. (2011), Poeschl et al. (2012a), Poeschl et al. (2012b). Relatively little environmental assessment work has been completed for two stage biogas production processes. A study by Zielonka et al.(2010) undertook an energy balance for a two stage process for crop digestion, however this was not a hydrogen producing process and did not extend to an LCA. An energy balance of the dark fermentation process has been undertaken by Ruggeri et al. (2010) and a comparative LCA of a dark fermentation and photofermentation biohydrogen production system is described by Njakou Djomo and Blumberga, 2011. Energy consumption and CO_2 emissions for a biohydrogen production process and vehicle fuel utilisation have been quantified by Ferreira et al. (2011) although this is not based on a specific biohydrogen production process but relies on a number of generic assumptions.

This study aims to compare the environmental burdens of a single stage biogas (methane) production system (i.e. anaerobic digestion) and a two stage (hydrogen/methane) production system using two feedstocks with different characteristics and classifications, and to identify future research requirements for improving the environmental performance of the processes. For both production systems the raw biogas produced is upgraded, compressed and utilised as fuel in a passenger vehicle. It is important to note that the assumptions made, the data used, the allocation procedures implemented and the LCIA methodology used, all of which have been described in as much detail as possible, have large effects on the final results generated.

2. Methods

Environmental burdens were calculated using a Life cycle assessment (LCA) approach undertaken in accordance with European guidance (BSi, 2006a; BSi, 2006b). LCA modelling was undertaken using SimaPro v7.3 software (PRè Consultants b.v.). Data relating to the single and two stage treatment of wheat feed was derived from experimental work described in Massanet-Nicolau et al. (2013), whilst data for the treatment of food waste was obtained from separate laboratory work completed as part of this study. Both experiments were undertaken at the Sustainable Environment Research Centre (SERC) at the University of Glamorgan, UK. Where necessary, data has been supplemented with literature values and as a final option the Ecoinvent database v.2.1 (Swiss Centre for Life cycle inventories, 2009) has been utilised. The intended audience for the study is primarily considered to be researchers active in the field of biohydrogen and biomethane production and utilisation.

2.1. Function and functional unit

The product system assessed was the production of either (i) biomethane or (ii) biohydrogen/biomethane vehicle fuel with the primary biogas production process being either (i) single stage mesophilic anaerobic digestion or (ii) dark fermentation followed by mesophilic anaerobic digestion. Feedstocks considered were a laboratory prepared food waste, approximately representative of municipal food waste collected in Wales as described in Wasteworks Ltd and AEA, 2010, and wheat feed, a by-product of the flour milling process that has been found to be appropriate for biohydrogen production (Hawkes et al., 2008). Raw biogas produced from both processes is assumed to be upgraded using Pressure Swing Adsorption (PSA), is compressed to 200 bar and is distributed at a refuelling facility for passenger vehicle fuel use. The functional unit of the study is the production of sufficient fuel to achieve 1 km of passenger vehicle transportation. Impacts are compared with a reference fuel of diesel derived from fossil sources.

2.2. System boundary

The system boundary describing the processes modelled is shown in Fig. 1. Energy requirements, emissions and primary materials for each sub process have been included in the model. Impacts associated with the door to door collection of food waste or the production of wheat feed have not been included. The primary purpose of the study is to compare the biogas production systems themselves. Energy requirements and emissions associated with the decommissioning of the service station, compression, upgrading and dewatering plant are also not included as these are anticipated to have a negligible compared with the energy and material flows associated with the operational phase of the plant (Berglund and Börjesson, 2006).

2.3. Allocation procedures

The production of biogas by both the single and two stage digestion processes is a multi-output process with outputs being (i) 'Biogas', (ii) the service of 'Disposal' of organic waste to a treatment plant (applicable to waste streams only), and (iii) 'Digestate' to agricultural land. Environmental impacts were allocated to each output on an economic basis. Upgraded biogas was assumed to have an economic value of an equivalent volume of diesel (on an energetic basis) which varied between 0.4452 £/m^3 and 0.5196 £/m^3 depending on hydrogen content, in addition to attracting Renewable Transport Fuel Certificates (RTFCs) with a value of 0.208 £ per RTFC (2011 average). Both feedstocks were considered as being derived from waste, residues or non food cellulosic material and therefore attract double RTFCs. A gate fee of £40 per tonne was applied to the disposal of food waste. No gate fee was applied to wheat feed as alternative disposal routes could be applicable in many circumstances (e.g. animal feed) and therefore the output of 'Disposal' does not apply for wheat feed. Digestate value was calculated according to measured nitrogen content in feedstocks and applying a value for purchasing an equivalent mass of mineral fertiliser. At the time of writing mineral fertilisers were commercially available at a cost of £330 per tonne (34.5% N). Allocation was applied in order to compare the environmental burdens of methane or hydrogen/methane fuel (derived from one of the outputs, ''Biogas'', from the multi output process described above) with the reference fuel of mineral diesel (which is itself produced from the multi output process of crude oil refining). However, results for the total process (without diesel comparison) including burdens allocated to all three process outputs (Biogas, Disposal and Digestate) are also provided and allow direct comparison of all