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AN INDICATIVE APPRAISAL OF HYDROGEN PRODUCTION FROM BIOGENIC MUNICIPAL WASTE

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ABSTRACT

An indicative appraisal has been undertaken of a combined *Anaerobic Digestion* (AD) and *Steam Methane Reforming* (SMR) process to produce hydrogen (H_2) from organic waste. The AD plant was based on the plant in Tilburg (The Netherlands), and was modelled from the kerbside organic waste collections through to methane production. The technical feasibility of H_2 production of this combined process was assessed based on biogenic waste collected in *Bath and North East Somerset* (*B&NES*); a municipal area in the South West of England (UK). The *B&NES* collection trials yielded data that could be used to estimate the catchment area for an AD plant on a commercial scale. A thermodynamic evaluation of the combined process included energy and exergy analysis in order to determine the efficiency of each process, as well as to identify the areas that lead to inefficiencies. The main energy losses were associated with compressor inefficiencies. In contrast, the main exergy consumption was found to be due to the fermentation in the digestion tanks. The overall technical efficiency of the plant does not compare well with other processes when compost is considered as a waste product. However, the H_2 is produced comes from entirely renewable sources and has the benefit of near-zero carbon emissions in contrast to fossil fuels. Finally, the case study included an indicative economic assessment of the collection to production chain. The use of high quality source sorted waste could yield of high levels of biogas and high quality compost could be produced. Should compost were employed as a useful by-product, then the adoption of the combined process would be economically attractive.

Keywords: hydrogen production, biogenic municipal waste, steam reforming of methane, anaerobic digestion, technology assessment, thermodynamic analysis

1. INTRODUCTION

1.1 Background

The threat of climate change is the dominant challenge to the energy sector globally. The most recent (2013) scientific assessment by the *Intergovernmental Panel on Climate Change* (IPCC) asserts [1] that it is 'extremely likely' that humans are the dominant influence on the observed global warming since the mid-20th Century. Carbon dioxide (CO_2) emissions, the principal 'greenhouse gas' (GHG) having an atmospheric residence time of about 100 years, mainly arises from the use of fossil-fuelled (coal and natural gas) power stations. The 2015 *Paris Agreement* on climate change aims to keep global temperatures "well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels". Indeed, the IPCC in their subsequent 'special report' on the implications of keeping temperatures down to 1.5°C [2] argued that humanity has just 12 years to respond to the climate change challenge (i.e., by about 2030 rather than 2050 presently incorporated in international agreements), if it wishes to keep global warming to 1.5°C above pre-industrial levels.

Hydrogen (H_2) is potentially a low or zero-carbon

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energy carrier; depending on its means of production The notion of the so-called 'hydrogen economy' (see, for example, Hoffman [3]), whereby H_2 is produced on a large scale (typically by the electrolysis of water) and then used as an energy carrier or intermediary, was popular in the aftermath of the oil crises of the 1970s. OECD countries became anxious about the security of fuel supplies, and began to examine what might substitute for oil in the transport sector. These worries largely evaporated in the 1980s and 1990s with the collapse in the spot price of oil to effectively pre-1973 levels in real terms. In any case, H_2 was perceived to have a number of technical and safety (flammability and steel embrittlement) problems when contrasted with the alternatives. In recent years, its attraction as a climate change mitigation option has become apparent.

1.2 The Issues Considered

Commercial H_2 production is almost entirely by reforming of natural gas at the present time. Sustainable production of H_2 may follow either a direct biological route, biological production of methane followed by reforming, or gasification of biomass. Other possible sustainable sources are electrolysis using electricity from wind (e.g., Dutton *et al.* [4] and Hoffman [3]) or solar sources and photocatalytic splitting of water. However, the main priority of this application is the biological routes. The aim of the present study was to provide an indicative appraisal of a H_2 production plant using thermodynamic and other methods of analysis of a novel biochemical process. The facility appraised used synthetically produced methane (CH_4) as a feedstock, generated via *Anaerobic Digestion* (AD) of organic *municipal solid waste* (MSW, followed by its *Steam Methane Reforming* (SMR). The novelty of the study is in the synthesis of the H_2 production and the municipal sourcing of biogenic waste on a community-scale.

2. METHODS AND MATERIALS

2.1 Biochemical Processing

AD is primarily a waste treatment method, widely used on mainland Europe and in America to reduce the volume of waste sent to landfill sites. It is a fermentation process which breaks down biodegradable organic matter into compost. The bacteria responsible for the fermentation give off a synthetic gas known as biogas, which consists mainly of CH_4 and CO_2. In contrast, SMR is a process that has been used for several years to generate hydrogen from methane. The feed is normally natural gas, which is predominantly methane. Since natural gas is a fossil fuel, the hydrogen produced from this process is not a renewable form of energy. However, producing methane from renewable sources of energy (such as biogenic municipal waste) could enable this process to participate in the move towards the generation of a near-zero energy carrier. The combined AD-SMR process that was appraised is illustrated schematically in Fig 1. Here the AD plant was modelled on a full-scale facility operating in Tilburg (The Netherlands).

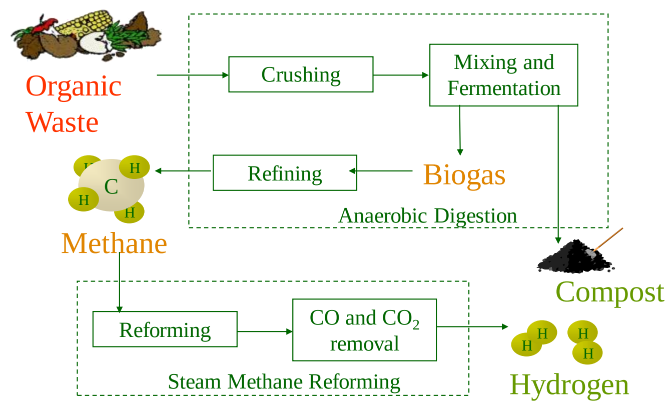

Fig 1 A schematic representation of a combined AD-SMR processing plant utilising biogenic municipal waste as a feedstock

2.2 Biogenic Municipal Waste in a UK Context

In the present study, the 'Unitary Authority' of Bath & North East Somerset (*B&NES*) in the South West of England (UK) as a typical source of MSW. It was selected because the *B&NES* Council had carried out a trial to evaluate waste collection. Their intention was to determine the best method for collecting waste, and the type of response from differing household (hh) types and areas. 'Bin lorries' – special-purpose vehicles for the collection of domestic (and commercial) waste – were weighed in the trials to determine the amount of waste that is collected. These waste collection trucks have a six tonne (t) dry weight, and during the trials increase up to 16 t when loaded; hence they collect up to 10 t of waste. However, this is not the maximum capacity as research from other trials in the country report trucks collecting up to 16 t. If the lorries were to be used to collect waste for a commercial-scale project then they would need to be carried out five days a week; accounting for public holidays that equates to 250 days per year. Therefore one truck would be able to collect 4000 t of compostable waste per year, assuming that they only collect one load per day.

Details of *B&NES* household waste obtained from the collection trial are presented in Fig 2. The bulk of the waste consists of material that can be recycled or composted. The current UK Government strategy for waste management is to reduce the amount of waste produced, reuse anything that can be used again, and recycle as much waste as possible [5]. Landfill use has declined over the past few years, but it still remains an important waste disposal technique in Britain. Waste recycling is rising with the backing of the central government, as well as targets and standards set by *European Union*. Thus, research into composting schemes to recycle the organic element of municipal solid waste is necessary to improve the current recycling rates of the UK.

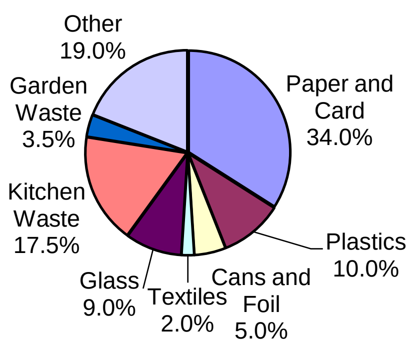

Fig 2 Dustbin waste composition for *Bath & North East Somerset* (B&NES)

2.3 Thermodynamic Analysis

Thermodynamic (energy and exergy) analysis gives rise to differing insights into the relative performance of various process chains. The thermodynamic property known as 'exergy', for example, reflects the ability of undertake 'useful work', but does not represent well heating processes within an energy sector. Methods of analysis employed in the present study are similar to those set out in detail within a related work by Hammond & Mansell [6] on bioethanol production from wheat straw. (They are not reproduced here due to space limitations.)

3. DISCUSSION

3.1 Thermodynamic Implications of H_2 Production

The overall energy and exergy balances for the Tilburg AD plant are illustrated in Fig 3 {(a) and (b) respectively}. These figures have been created using the calculated figure of 10,000 kJ/kg for the calorific value. The left and right half of the energy balance {Fig 3 (a)}, represent the inputs and outputs, including energy losses respectively. Likewise, the left and right half of the exergy balance {Fig 3 (b)} reflects the inputs and outputs, including exergy consumption respectively. The differences between the energy losses and exergy consumptions can be clearly seen from these diagrams. Nearly all of the energy and exergy inputs are associated with the food and garden waste. The majority of the energy outputs are associated with the compost, while most of the exergy outputs are associated with the compost and internal consumptions.

The majority of the energy that is lost in the combined AD-SMR plant (see again Fig 1) is due to waste water and mechanical inefficiencies. The majority of the exergy losses were due to internal processes such as the fermentation process, the combustion process in the boiler and reforming of the methane into H_2. The products from the combined process are 3% by weight of H_2 and 97% by weight of compost. The overall energy efficiency is 74.6% and the overall exergy efficiency is 60.4%. Other H_2 process efficiencies vary from 21% to 86%, the higher efficiencies belonging to non-renewable processes.

If the compost were considered as just 'waste' product, then the overall efficiencies fall to approximately 1% in terms of both the energy and exergy analysis, which are low in comparison to other hydrogen production processes. This is because the high proportion of compost produced dominates the efficiency of the plant and the percentage of hydrogen is small in comparison to other outputs.

3.2 Economic Analysis of H_2 Production

The economic analysis by Petersson & Wellinger [7] reported that the capital investment for the AD plant in Tilburg was £11M. The differences between the Tilburg plant and the model analysed here is small are considered negligible because the investment cost of the pre-sorting unit in the Tilburg plant is considered to be comparable to the investment cost of the H_2 gas refining plant used in the analysis model. The capital investment for a SMR plant that produces 91 kg of H_2 a day was around £474,000 [8]. An average rate on inflation of 3.5% was used to calculate the capital investment, of £391,050, for the SMR plant. The potential revenue from the sale of H_2 gas, given that the proposed process could produce 33,171 kg of hydrogen in 50 litre bottle annually, is £98,015 per year. This is

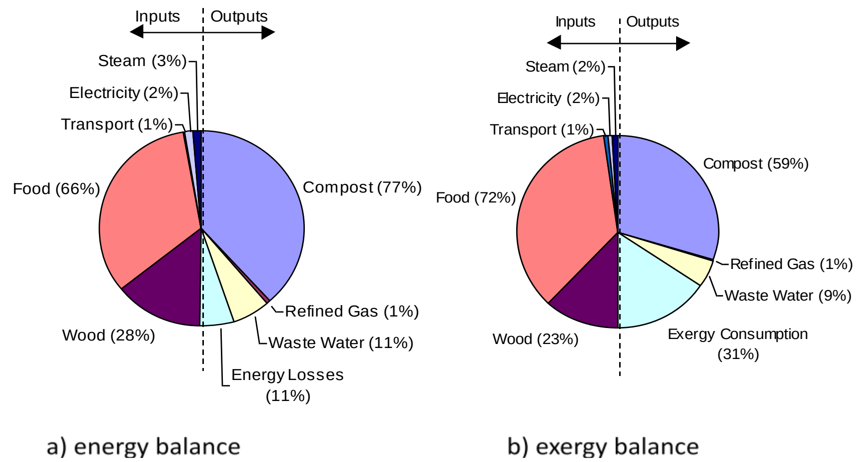

Fig 3 Energy and exergy balances for the AD process (using a calorific value for compost of 10,000 kJ/kg

based on £35 per litre bottle, which is filled at 200 bar. The return from the compost, based on a price of £10.66 per tonne is £225,524 per year. The revenues from the H_2 gas and compost sales would not be sufficient to cover the running and labour costs, therefore a charge would need to be made so that the plant did not run at a loss. The projected annual yield of organic waste per household, based on the *B&NES* trials, was 28 kg/hh per year. This implies that just over 1.4 million households would be needed to collect the 40,000 t of waste per year. In order for the plant to breakeven each year than a charge of £0.28 per hh per year would need to be levied. However, to attain a *DCF payback period* of less than 20 years, then an annual charge of at least £1.04 per hh is needed.

4. CONCLUSIONS

An indicative appraisal has been undertaken of a combined AD-SMR process to produce H_2 from organic waste. The AD plant was based on the plant in Tilburg (The Netherlands), and was modelled from the kerbside organic waste collections through to methane production. The technical feasibility of this H_2 production chain was assessed based on biogenic waste collected in *B&NES*. The overall efficiency of the plant is high only if the plant delivers two co-products: compost, as well as H_2. An important benefit of the H_2 produced from this process is that it is near-zero carbon and renewable. Widespread adoption of such facilities would reduce local waste disposal problems in the UK, and contribute to reducing the GHG emissions (since the reliance on fossil fuels would lessen). The results from the organic MSW collection trials could be used to identify areas that might provide 'good quality' sorted waste, and estimate the geographic area that could most benefit from biogenic municipal waste collection.

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