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What is the most energy efficient route for biogas utilization: Heat, electricity or transport?

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HIGHLIGHTS

- The paper developed an assessment tool for analyzing biogas utilization routes.
- The LCA methodology was used to allow a uniform assessment of the biogas system.
- "% energy efficiency" was used as the functional unit for assessment.
- 49 biogas-to-energy routes were assessed based on their final useful energy form.
- The framework aids policy makers in the decision process for biogas exploitation.

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ABSTRACT

Biogas is a renewable energy source that can be used either directly or through various pathways (e.g. upgrading to bio-methane, use in a fuel cell or conversion to liquid fuels) for heat, electricity generation or mechanical energy for transport. However, although there are various options for biogas utilization, there is limited guidance in the literature on the selection of the optimum route, and comparison between studies is difficult due to the use of different analytical frameworks. The aim of this paper was to fill that knowledge gap and to develop a consistent framework for analysing biogas-to-energy exploitation routes. The paper evaluated 49 biogas-to-energy routes using a consistent life cycle analysis method focusing on energy efficiency as the chosen crtierion. Energy efficiencies varied between 8% and 54% for electricity generation; 16% and 83% for heat; 18% and 90% for electricity and heat; and 4% and 18% for transport. Direct use of biogas has the highest efficiencies, but the use of this fuel is typically limited to sites co-located with the anaerobic digestion facility, limiting available markets and applications. Liquid fuels have the advantage of versatility, but the results show consistently low efficiencies across all routes and applications. The energy efficiency of bio-methane routes competes well with biogas and comes with the advantage that it is more easily transported and used in a wide variety of applications. The results were also compared with fossil fuels and discussed in the context of national policies. This research resulted in the development of a flexible framework for comparing energy efficiencies which can provide the basis for further research on optimizing the sustainability of biogas-to-energy systems across a range of indicators.

1. Introduction

The target set by the EU Renewable Energy Directive (2009/28/EC) [1] requires a 20% energy share from renewable sources by 2020. Thus, exploring alternative, environmentally benign and energy efficient systems has become the focus of governmental policies and industrial as well as academic research. Biogas is a renewable energy source that can be produced from the anaerobic digestion (AD) of biomass, such as sewage sludge, municipal solid waste, agricultural wastes, and energy crops. Biogas consists of around 50–60% methane (CH_4), 40–50% carbon dioxide (CO_2) and some minor constituents, such as hydrogen sulphide (H_2S) and water. The use of biogas for energy production could displace fossil fuels, reduce greenhouse gas emissions and decrease dependence on imported energy [2].

Upgraded biogas, termed bio-methane, is typically composed of ~97% CH_4 and ~3% CO_2, and is converted to the same standard as natural gas through removal of CO_2 (upgrading) and other impurities (cleaning). Another route for upgrading biogas to bio-methane involves

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the chemical transformation of CO_2 to CH_4 by the Sabatier reaction (Eq. (1)); the hydrogen (H_2) in the reaction is usually obtained from water (H_2O) electrolysis (Eq. (2)). This combined pathway could have an important impact on the global carbon cycle [3]. There are various utilization pathways for both raw and upgraded forms of biogas [4]; commercial methods include electricity and heat generation via combined heat and power (CHP) units, electricity generation via fuel cells, and conversion to mechanical energy for transport via internal combustion engines (ICEs). Bio-methane can be injected into the gas grid, and/or converted to compressed renewable natural gas or liquefied renewable natural gas (referred to in this paper as CNG and LNG respectively) to serve as a transport fuel. Biogas can also be reformed to syngas (CO and H_2) for liquid fuel production via Fischer Tropsch (FT) synthesis (see [5] for further details).

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

$$2H_2O \rightarrow 2H_2 + O_2 \quad (2)$$

As with any new energy system, countries are faced with ongoing challenges when designing the optimum pathway to ensure sustainable development and sufficient energy supply [6]. In practice, many European countries have successfully integrated biogas into their energy sectors via different utilization routes. The annual energy production from biogas is around 42 TWh in Germany (the highest production in the EU), 9 TWh in UK, and 2.8 TWh in France; in each of these countries the biogas is mainly used for electricity generation [7]. Sweden produces around 1.7 TWh from biogas and 44% of biogas production is upgraded to bio-methane and used as vehicle fuel [8]. In Italy, biogas is mainly used for power generation while other pathways such as grid injection and CHP require further exploration [9]. However, although there are various options for biogas utilization, there is limited guidance in the literature on the selection of the optimum route.

A number of papers focus specifically on biogas utilization as a vehicle fuel [9,10] while others assess certain aspects of potential biogas utilization methods. Pöschl et al. [11] considered the energy efficiency of CHP, upgrading, gas turbine and fuel cell pathways within the biogas system, but the focus was mainly on the impact of feedstock and scale on the overall energy balance. Chen et al. [12] looked at the energy conversion efficiency of a single biogas reforming technique under various O_2 concentrations but did not investigate syngas utilization options. Friesenhan et al. [13] looked at the energy efficiency of three utilization routes specifically for landfill biogas. Djatkov et al. [14] investigated the energy efficiency of agricultural biogas plants using manure as feedstock material and analysed the use of biogas in a single route, in a CHP plant. Goulding and Power [15] looked at the direct use of biogas in a CHP unit, and its upgrading to bio-methane for use as transport fuel in Ireland, from an economic and energy point of view. Börjesson and Berglund [16] conducted an environmental evaluation of biogas to CHP, while Morero et al. [17] tackled environmental and economic assessment of biogas upgrading. In both cases energetic performance was neglected. Wu et al. [18] presented a comprehensive assessment from an energetic, economic and environmental point of view targeting three pathways (CHP, upgrading and fuel cell) for electricity production only.

Based on the information in the literature, three main issues can be identified: (i) there is no complete biogas framework of the numerous possible interlinked routes serving three final useful forms of energy (electricity, heat, and mechanical energy for transport), (ii) the criteria (economic, technical, energy efficiency, social or environmental, etc.) used for route evaluation vary between studies and direct comparison between different studies is therefore not possible, and (iii) the system boundary conditions are often not clearly defined and involve different site locations as well as different feedstocks. Thus in order to choose the most suitable alternative and allow direct comparison amongst possible routes, there is a need to develop a consistent framework of predefined boundary conditions focused on specific criteria.

To develop the framework, decision making tools are needed [19]. One such tool is technology road mapping for strategic planning, which can help countries decide on investments; however this tool is very resource intensive and location specific as it requires extensive research and collaboration amongst experts [6]. Life cycle assessment (LCA) is an alternative method which is considered one of the most suitable tools that allows a uniform assessment of a biofuel system [20]. LCA should include a defined functional unit (criterion of study), consistent system boundaries and a defined methodology [20]. Decision making tools should be informed by solid scientific data and, although technical, political, social and economic factors are all important parts of the decision making toolbox, Trianni et al. [21] has reported that energy efficiency is considered the primary factor (criterion) of competitiveness amongst enterprises.

In this paper, different biogas-to-energy exploitation routes were evaluated using a comprehensive LCA, a tool for system analysis, focusing on energy efficiency as the chosen criterion. The resulting framework of energy efficiencies allows the direct comparison of numerous routes while identifying opportunities for process development. The work done developed an assessment tool that appraises biogas-to-energy routes in an objective manner. The results can be incorporated into wider studies that include elements that are specific to local regions or plants, thus providing the basis for further research on optimizing the sustainability of biogas-to-energy systems.

2. Methodology

2.1. Overview

Tracing the flow of energy through the industrial system is necessary to critically evaluate the sustainability of energy systems and components [22].The energy analysis of the alternative routes for biogas utilization was conducted using LCA techniques. LCA is defined as a technique to address the environmental aspects and potential impacts associated with a product, process or service [23]. The standard LCA framework was followed for this analysis: goal and scope definition; inventory analysis and impact assessment; and interpretation.

2.2. Goal and scope definition

2.2.1. Boundary conditions

The goal of this LCA was to investigate the energy balance of alternative routes for biogas utilization, and to identify the most energy efficient utilization pathway. The scope of the analysis started with clean biogas at 60% CH_4 and 40% CO_2 (without impurities such as sulphur) and ended with its transformation to a useful form of energy as either heat, mechanical energy for transportation, or electricity (Fig. 1). The boundary included routes involving the direct use of raw biogas, as well as the production of intermediate fuels from biogas (such as syngas from reforming and bio-methane from upgrading) and ancillary processes such as electrolysis. For the base case analysis, only direct energy was taken into account. Direct energy is that used directly in the system (for example, electricity used for upgrading), while indirect energy is that used to produce a material which is then used within the system boundaries (for example, the energy to produce the fuels which are then used to generate the electricity used within the boundaries).

Fuel carriers such as pipelines and road haulage were omitted, as the associated energy demands are highly site specific and can vary from zero in the case of distribution through the local gas network [24] to approximately 1.5 MJ/km for transport on an average laden heavy goods vehicle [25] (not including the energy for compression and chilling). Feedstock production and the anaerobic digestion process were also outside the analysis boundary, as was the end user's specific equipment for electricity or heat utilization, for example, the efficiency of an electrical appliance (although a sensitivity analysis expanded the boundaries to compare electric vehicles to ICE vehicles). The selected base case boundary conditions ensured that the results of the energy