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Feasibility study on combining anaerobic digestion and biomass gasification to increase the production of biomethane

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ABSTRACT

There is a rapid growing interest in using biomethane as fuel for transport applications. A new concept is proposed to combine anaerobic digestion and biomass gasification to produce biomethane. H_2 is separated from the syngas generated by biomass gasification in a membrane system, and then is used to upgrade raw biogas from anaerobic digestion. Simulations have been conducted based on the real operation data of one full scale biogas plant and one full scale biomass gasification plant in order to investigate the feasibility of the new concept. Results show that although less power and heat are generated compared to the gasification plant, which results in a lower overall efficiency, much more biomethane can be produced than the biogas plant; and the new concept can achieve a higher exergy efficiency. Due to the increasing price of biomethane, the novel concept demonstrates a big potential of income increase. For example, at a biomethane price of 12.74SEK/kg, the annual income can be increased by 5.3% compared to the total income of the biogas and gasification plant.

1. Introduction

Biogas produced from anaerobic digestion processes and landfill is playing a key role in the emerging market for renewable energy. It is estimated that a major part of the EU-27 renewable energy target by 2020 will be met by bioenergy, at least 25% of which will be biogas [1,2]. In order to increase the calorific value and reduce unwanted components, e.g. CO_2 and H_2S, which are harmful to utilization systems, it is important to clean raw biogas and upgrade it to a higher fuel standard. Since there is a rapid growing interest in the use of biogas as a fuel for transport applications, biogas upgrading is attracting great interest in the bioenergy industry. For example, in Europe, the total installed capacity for biogas upgrading grew from less than 10,000 Nm^3/h (raw gas) in 2001 to over 160,000 Nm^3/h (raw gas) in 2011 [3]. In Sweden, the use of biogas upgraded to vehicle fuel increased from less than 20% of the total biogas production in 2006 to about 50% in 2011 [4]. However, the boost of the capacity of biogas upgrading is still behind the fast increasing demand of biomethane. According to Vanciu and Miresashvili [5], the number of biogas cars in Sweden has been more than doubled during 2008 and 2012, reaching 40,000. Nevertheless, the biogas production in 2013 is only about 169 M Nm^3 in Sweden [4]. It implies that even though all of the raw biogas can be upgraded, it can only satisfy 1/3 of the fuel demand of the 40,000 biogas cars. In the meantime, the costs of common methods of biogas upgrading including water scrubbing, pressure swing adsorption, chemical absorption, etc. are relatively high due to the use of either energy, chemicals or both [6–8]. Therefore, there is a big challenge about increasing the production of biomethane in an energy and cost efficient way.

Biomass gasification, as a technology for efficient utilization of biomass, has drawn more and more attentions due to the energy security reasons and environmental concerns [1]. The produced syngas can be further used to generate power, heat [9] and fuels, such as hydrogen [10] and ethanol [11]. There are also attempts to produce CH_4 from biomass gasification. However, due to the low content of CH_4 in the syngas, it normally requires a methanation process, which can convert CO and H_2 [12] to CH_4. To conduct methanation, the water–gas-shift (WGS) process is often needed, which can control the C/H ratio of syngas. Nevertheless, the additional WGS and methanation processes result in a lower overall efficiency of gasification, a more complicated system configuration and higher investment costs and operation costs.

In order to increase the production of biomethane, converting CO_2 to CH_4 by adding H_2 can be a promising way for biogas upgrading, which can efficiently use the carbon in the biogas. $CO_2 + 4H_2 - CH_4 + 2H_2O$ has been known as the Sabatier reaction since the early 1900s. Chemically, it can be achieved by using ruthenium and nickel based catalyst [13]. This technology has been

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Nomenclature

Abbreviations

CHP	combined heat and power
LHV	lower heating value
NPV	net present value
SNG	synthetic natural gas
WGS	water-gas-shift

Symbols

A	area
A_m	membrane area
Exergy_i	exergy of component i
$\text{Exergy}_{\text{heat}}$	exergy of produced heat
$\text{Exergy}_{\text{thermal-input}}$	exergy coming from the fuel
I_o	initial investment
k	interest
n_i	the mole number of component i passing through the membrane
p_i	partial pressure of component i
$\Delta P_{lm,i}$	defined parameter
Q	heat flux
Q_i	permeation constant for component i
R_n	the revenue of period n
ΔT_{lm}	logarithmic mean temperature difference
U	heat transfer coefficient
y_i	the mole concentration of component i

Subscript

f	feed
i	component i
p	permeate
pc	closed end of permeate side
r	retenate

applied on an industrial scale in ammonia plants for the removal of carbon oxides from feed gases [14], and in Synthetic natural gas (SNG) plants for methane production from syngas [15]. As the Sabatier reaction is exothermic, it does not consume much energy, resulting in a high energy efficiency and low cost, consequently. The Sabatier reaction can also be realized biologically. For example, it can utilize hydrogenotrophic archaea, microorganisms which can bind CO_2 with H_2 and convert them to methane [16,17]. In order to achieve a fully renewable way for biomethane production using the biological upgrading method, hydrogen should also come from renewable sources. This paper proposes a novel concept that combines the anaerobic digestion and biomass gasification. As hydrogen is one of the major components in the syngas, biomass gasification has the ability to provide the hydrogen needed by the biogas upgrading. Previously, there have been a couple of studies combining biomass fermentation and gasification. For example, Wang et al. investigated the syngas production via co-reforming of biogas and H_2-rich syngas produced by biomass air–steam gasification in a bubbling bed gasifier [18]. In order to avoid removing CO_2 from syngas for the desired stoichiometric factor (H_2, CO, CO_2), CH_4 is used to reform the excess CO_2 to produce H_2 and CO. However, the content of CH_4 inherent in the syngas is usually low (4–8 mol%), therefore, biogas produced from anabatic digestion was added. Zöhrer and Vogel [19] tested using the fermentation residues as the feedstock of gasification; and Methling et al. [20] proposed a new configuration combining fermentation and gasification of sewage sludge and wood, and studied the feasibility of the subsequent utilization of the biogenic gases in a hybrid power plant, consisting of a solid oxide fuel cell and a gas turbine. Different from these works, this paper focuses on the production of CH_4 and the improvement of the efficiency of biogas upgrading and the overall efficiency of biomass utilization. To the best of authors' knowledge, this the first attempt to combine the biomass gasification and the anaerobic digestion in order to increase the production of CH_4. The objective is to study the feasibility of the novel concept and provide insights regarding the further development of the combined process.

2. Plant overview and the novel concept

The process assessment was conducted based on the real operating data from one full scale biogas plant and one full scale biomass gasification plant.

2.1. biogas plant

The biogas plant, located in Västerås, Sweden, was taken into operation in 2005. It was designed to produce 15 GW h biogas, in a mesophilic anaerobic process, from source-separated organic waste from households and institutional kitchens, liquid waste and ley crop silage from a contracted acreage of 300 hectares annually [21]. Based on the operating data in 2009, Table 1 summaries some facts of the production:

Table 1
Key operating parameters of the biogas plant [21].

Item	Value
Total feedstock mass without water	4415 ton/year
Biogas production	2805 ton/year (~2.43million Nm^3/year)
Operation time	8760 hr
Raw gas composition	mol%
CH_4	63
CO_2	35
H_2O	2

2.2. Biomass gasification plant

The Skive biomass gasification plant is designed by Carbona [22]. The plant has a bubbling bed gasifier and uses wood pellets as feedstock. It operates at a temperature between 850 and 930 °C and a pressure between 0.5 and 2 bar(g). The thermal capacity of the Skive plant is about 19.5 MW_{th} (fuel input). The gas cleaning at the plant consists of a catalytic cracker, which destroys tar compounds, a gas cooler, a bag filter, which removes dust, and a water scrubber. The produced syngas is utilized in gas engines to generate power and provide heat for the district heating system. The key operating parameters, including the syngas composition, are summarized in Table 2 [22–24].

2.3. The novel concept

Fig. 1 shows the system configuration of the proposed novel concept. The cleaned syngas (Stream 2) is compressed before it goes into the membrane system, where hydrogen is separated. In order to achieve high purity H_2, a two-stage membrane process is applied. The separated H_2 (Stream 9) is mixed with raw biogas