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Review

Biogas as a renewable energy fuel – A review of biogas upgrading, utilisation and storage

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ABSTRACT

Biogas upgrading is a widely studied and discussed topic and its utilisation as a natural gas substitute has gained a significant attention in recent years. The production of biomethane provides a versatile application in both heat and power generation and as a vehicular fuel. This paper systematically reviews the state of the art of biogas upgrading technologies with upgrading efficiency, methane (CH_4) loss, environmental effect, development and commercialisation, and challenges in terms of energy consumption and economic assessment. The market situation for biogas upgrading has changed rapidly in recent years, making the membrane separation gets significant market share with traditional biogas upgrading technologies. In addition, the potential utilisation of biogas, efficient conversion into bio-compressed natural gas (bio-CNG), and storage systems are investigated in depth. Two storing systems for bio-CNG at filling stations, namely buffer and cascade storage systems are used. The best storage system should be selected on the basis of the advantages of both systems. Also, the fuel economy and mass emissions for bio-CNG and CNG filled vehicles are studied. There is the same fuel economy and less carbon dioxide (CO_2) emission for bio-CNG. Based on the results of comparisons between the technical features of upgrading technologies, various specific requirements for biogas utilisation and the relevant investment, and operating and maintenance costs, future recommendations are made for biogas upgrading.

1. Introduction

Biogas is produced by anaerobic degradation of organic compounds and could be the substitute for natural gas and fossil fuels. It contains mostly three components, which are methane (CH_4), carbon dioxide (CO_2) and nitrogen (N_2). However, other trace species exist as well, which are hydrogen sulphide (H_2S), hydrogen (H_2), nitrogen (N_2), ammonia (NH_3), oxygen (O_2) and carbon monoxide (CO). Furthermore, typical biogas is saturated with water, dust particles, siloxanes, aromatic and halogenated compounds [1,2], but the amounts of these trace compounds are very low compared to CH_4 and CO_2. Various biogas sources with their impurities levels are shown in Table 1.

Biogas can play a major role in the developing market for renewable energy and it is estimated that biogas usage in the world will be doubled in the coming years ranging from 14.5 gigawatts (GW) in 2012 to 29.5 GW in 2022 [7,8]. The demand for renewable fuels is increasing with growing concern about environmental problems due to the high greenhouse gases (GHGs) emission from fossil fuel combustion [9–12]. Purified biogas can be used in various applications such as the production of electricity, heat and steam generation in household and

Abbreviations: AS, amine scrubbing; AMDEA, activated methyl diethanolamine; Bio-CNG, bio-compressed natural gas; CA, cellulose acetate; CSP, chemical scrubbing process; CNG, compressed natural gas; CHP, combined heat and power; CMS, carbon molecular sieve; CNT, carbon nanotubes; CCM, carbon cryogel microspheres; CS, cryogenic separation; CXM, carbon xerogel microspheres; DEA, diethanol amine; ESA, electrical swing adsorption; EU, European Union; GW, gigawatts; GHG, greenhouse gas; HPWS, high pressure water scrubbing; ISS, inorganic solvent scrubbing; IEA, international energy agency; LCA, life cycle assessment; LBM, liquefied biomethane; LNG, liquid natural gas; MMM, mixed matrix membrane; MOF, metal-organic framework; MEA, monoethanol amine; MDEA, methyl diethanol amine; Mtoe, million tons of oil equivalents; MS, membrane separation; NGV, natural gas vehicle; NYT, neapolitan yellow tuff; NMP, N-methyl pyrrolidone; OPS, organic physical scrubbing; PSA, pressure swing adsorption; PSf, polysulfone; PI, polyimide; PC, polycarbonate; PDMS, polydimethyl siloxane; PEG, polyethylene glycol; PZ, piperazine; SGC, Swedish gas technology centre; TSA, temperature swing adsorption; VOC, volatile organic compounds; ZIFs, zeolitic imidazolate frameworks

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Table 1
Guidelines for impurities removal for specific biogas applications.

Biogas	CH_4 (%)	CO_2 (%)	N_2 (%)	O_2 (%)	H_2S (ppm)	Benzene (mg m^{-3})	Toluene (mg m^{-3})	Ref.
Landfills	45–62	24–40	1–17	1–2.6	15–427	0.6–35.6	1.7–287	[2–4]
Sewage digesters	58–65	33–40	1–8	< 1	0–24	0.1–0.3	2.8–11.8	[2,5,6]
Organic waste digesters	60–70	30–40	1	1–5	10–180	0.1–1.1	3–7	[2]

industry, injection into the natural gas grid as well as a vehicular fuel. Biogas production in Europe was estimated at 6 million tons of oil equivalents (Mtoe) in 2007 and it is expected to increase to 23 Mtoe by 2020 [13] and [14,15]. As a result, 60% reduction in GHGs emission is expected after 2017 [16]. In addition, the European Union (EU) countries have set a goal of supplying 20% of European energy demand using renewable energy systems (RES) by 2020 and at least 25% of bioenergy will be produced by biogas [17,18]. Besides, it is estimated that the world share of bio-compressed natural gas (bio-CNG) in all vehicular fuels will rise up from 2% today to 27% in 2050 [19,20]. Global climate changes caused by CO_2 emissions are currently debated around the world. Therefore, greener sources of energy are being required as alternatives to replace fossil fuels [21–24]. Different technologies for biogas upgrading have been developed to date and some of them are commercially available. The technologies that are used commercially for biogas upgrading today are pressure swing adsorption, high pressure water scrubbing, organic solvent scrubbing, amine scrubbing, membrane separation and cryogenic separation which are briefly described in the next section. The selection of suitable technology by considering the efficiency and economy of a specific application is important [25,26].

IEA Bioenergy, an international collaboration on bioenergy under the International Energy Agency (IEA), has investigated various renewable energy tasks, concentrating on updating the raw biogas for various applications but did not intend to give detailed descriptions of the technical or economic performance of the technologies [27,28]. The Swedish Gas Technology Centre (SGC) is another group focused on biogas upgrading research and it has published several reports on commercially available technologies [29,30]. Biogas purification and upgrading have also been a highlighted topic in scientific articles in recent years [8,23,31–39]. Xiu and Shahbazi [36] summarised the state of the art technology for producing and upgrading bio-oil, with the focus on the hydrothermal liquefaction process. Abatzoglou and Boivin [31] reviewed biogas purification with the focus on the removal of contaminants, such as H_2S, NH_3, and siloxanes, but the removal of CO_2 was only briefly mentioned. Weiland [32] presented an overview of the complete biogas production and consumption chain but did not focus on currently available upgrading technologies. Bekkering et al. [33] studied the current status and future options of biogas upgrading technologies but did not present the technical performance and economic report on various upgrading technologies. Ryckebosch et al. [35] reviewed different biogas upgrading technologies with the focus on their operating conditions, drawbacks, and efficiency. Pertl et al. [34] and Starr et al. [37] applied life cycle assessment (LCA) to biogas upgrading. Bauer et al. [38] found that the market shares for biogas upgrading technologies have been changed rapidly in recent years, amine scrubbing is continuously achieving significant market shares, and a competition between pressure swing adsorption (PSA) and high pressure water scrubbing (HPWS). Kárászová et al. [8] reviewed membrane separation processes for biogas and found that membrane gas permeation is able to compete with classical biogas upgrading technologies. However researchers still need to solve the challenges in using membrane for the removal of volatile organic compounds (VOC) and siloxanes from raw biogas. Sun et al. [23] encouraged more researches on membrane separation process for economical biogas upgrading and its utilisation as a vehicular fuel as it is more beneficial for the environment. Chen et al. [39] revealed that hybrid processes for biogas upgrading are more efficient, where membrane separation is combined with absorption, adsorption, and cryogenic technique. This combined separation processes can improve the performance and reduce the operational cost of the process. Although the production of biogas is a well-established technology, its commercial utilisation as a vehicular fuel is still limited because high purification is needed.

Meanwhile, the existing reviews and studies have explored the concepts and comprehensively investigated the techno-economic performance of biogas upgrading technologies, their developments, energy requirements, market shares, environmental analysis, utilisation of upgraded biogas, and conversion and storage of bio-CNG. Purified bio-CNG is a substitute for CNG for automobiles [16,40]. Biogas utilisation as a vehicular fuel is beneficial since the vehicles using bio-CNG have CO_2 emission 80% less than those using fossil fuels [41,42]. Sweden and Germany are among the countries that already used bio-CNG as vehicular fuel in the form of pure methane or mixed with natural gas [8]. Also, the total global warming related to the bio-CNG utilisation is approximately 20% less than that of CNG [16]. Bio-CNG storage is also critical and important step as it affects vehicle filling time, mass of gas, temperature, entropy generation, and energy consumption [43]. Therefore, one of the main contributions of this work is to provide insights and guidelines regarding the biogas upgrading technology selection based on the specific utilisation, efficiency, investment cost, and operational and maintenance cost. In addition, this work also summarizes the biogas utilisation and its conversion into bio-CNG and highlights the potential benefits of bio-CNG as a vehicular fuel. Bio-CNG has been explored as an alternative to fossil fuels. Lastly, various methods of storage for bio-CNG are comprehensively discussed and compared. Finally, based on the investigation and recommendations main conclusions are drawn in this work.

2. Biogas upgrading and purification technologies

The technologies currently developed and available on the industrial scale for the upgrading of biogas include adsorption, absorption (physical and chemical), membrane separation, and cryogenic. These technologies are primarily used for CO_2 separation while the pre-upgrade stage is required to reduce the high concentrations of contaminants such as H_2O, H_2S, and siloxanes. Further classification of these upgrading technologies is shown in Fig. 1. Also, major strengths and weaknesses of these existing upgrading technologies are summarised in Table 2.

2.1. Pressure swing adsorption (PSA)

Adsorption process involves the transfer of solute in the gas stream to the surface of an absorbent material due to physical or van der Waals forces. In pressure swing adsorption (PSA), some undesirable gases like CO_2 are separated from biogas under elevated pressure using adsorbent materials. Later, the pressure is reduced to desorb the adsorbed gases [44,45]. Carbotech, Acrona, Cirmac, Gasrec, Xebec Inc., and Guild Associates are well-known companies which develop and commercialise this technology at low and high capacity (flow rate of 10–10,000 m^3/h of biogas). In PSA, H_2S gas removing is a primary step because it is considered as toxic to the process and adsorption of this gas is normally irreversible [46]. Fig. 2 shows a simplified process flow diagram for a PSA process.