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Article

Alternative of Biogas Injection into the Danish Gas Grid System—A Study from Demand Perspective

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Abstract: The Danish government has set an ambitious target to achieve 100% fossil independence across all energy sectors, which demands optimum utilization of renewable energy sources, such as wind and biogas, by 2050. Biogas production has increased, and the upgrading of biogas offers a broad range of applications, such as transportation, and gas grid injection for downstream utilization. The biogas has to meet natural gas quality prior to injection into the gas grid system. The investment costs of the gas grid, upgrading cost, and gas compression costs are the major challenges for integrating the biogas into the existing gas infrastructure. In this investigation, the Wobbe index (*WI*) for raw biogas and upgraded biogas was measured to evaluate the scenario for biogas injection into the gas grid system. It was found that raw biogas has to improve its *WI* from 28.3 MJ/m^3(n) to a minimum of 50.76 MJ/m^3(n) via upgrading, and compressed to 40 bar system, to supply the gas grid system for trading. Then, yearly gas consumption by larger gas consumers was studied to evaluate the alternative approach of biogas utilization to save upgrading and compression costs for gas grid injection.

Keywords: biogas; Wobbe index; gas grid; biogas upgrading; biogas introduction

1. Introduction

Biogas is produced by anaerobic biodegradation of waste, e.g. municipal solid waste, landfills, sludge from wastewater treatment plants, industrial waste, agricultural waste, manure, and energy crops. It is mostly composed of a large proportion of CH_4 and carbon dioxide (CO_2), followed by other contaminants like hydrogen sulfide (H_2S), oxygen (O_2), ammonia (NH_3), and siloxanes, depending on the feedstock [1,2]. It is used for various energy utilizations, in particular, heat production by direct combustion, electricity production by fuel cells or microturbines, combined heat and power (CHP) generation, or transportation fuel [3]. Nevertheless, low calorific value (CV) due to the existence of carbon dioxide and other impurities is one of the foremost bottlenecks for injection in gas grid system.

Denmark is making considerable efforts to replace conventional fossil energy sources by renewable energy, in particular, wind, solar, and biogas [4,5]. The Danish biogas industry started to flourish in the 1970s. Later, legislation was formulated to establish the biogas technology and, thus, increase the renewable biogas energy production based on local resources, such as agriculture waste. Recent statistics from Danish Energy Agency (Energistyrelsen) show that the current biogas production in Denmark is 9146 TJ, which is almost 1116% higher compared to the biogas production in 1990 [6]. Primarily, biogas was utilized for combined heat and power (CHP) and gas grid injection after upgrading [7]. The Danish gas grid was built in the 1980s with a 40 bar pressure system and a 4 bar pressure system. Moreover, the Danish gas grid system is an integral part of the European gas grid infrastructure, where gas is being transported from both the North Sea and Germany.

Several biogas upgrading technologies are available to enhance methane, such as water scrubbing and/or physical absorption, pressure swing adsorption, chemical absorption, membrane separation, and cryogenic and biological technologies [1,2]. Water scrubber is a worldwide-applied common technology for biogas upgrading, nevertheless, amine-based technology is mostly applied in Denmark [1]. A recent survey from Danish Gas Technology Center has reported 25 biogas upgrading facilities available in Denmark, including 9 water scrubbers, 8 that are amine-based, and 8 that are membrane-based (unpublished data). Meanwhile, ex situ and in situ H_2 injection for CH_4 enrichment has also been applied in selected biogas plants in Denmark [1,2,8]. Furthermore, power-to-gas (PtG) and other carbon dioxide utilization technologies utilize energy to convert CO_2 into chemicals, and fuels, like H_2, CH_4, acetate, and synthetic natural gas (SNG), are under investigation [9–11]. In Denmark, H_2 injection into the natural gas grid has been proposed, where surplus electricity from wind may be utilized for H_2 production. Mixing H_2 in natural gas has a notable impact on the Wobbe index (*WI*), which is a critical gas quality indicator. Recent investigations claimed that 2% H_2 in the Danish gas grid system is acceptable [12].

The gas transmission systems include pipes, compressor stations, and storage facilities to distribute the produced gas. It allows time-independent storage flexibility for gas with a wider range of capacity [13,14]. Gas grid operation plays an important role for biogas technology expansion and distribution, but even so, only little research in the field of gas grid infrastructure, and biogas collection and distribution, has been performed [14–19]. Currently, various aspects of gas grid management have received widespread attention and have been researched extensively, in particular, biogas injection, developing models, corrosion effect, and development of semi-grid [20–23]. Hengeveld et al. investigated the technical and economical assessment of biogas transportation from anaerobic digesters to the centralized upgrading facility with pressure at 0.101325 MPa. The model study recommended the substantial increase of biogas transportation cost [24]. Nonetheless, investments in grid development, and upgrading costs to meet *WI* and gas compression costs, are major obstacles in connection with remotely built biogas plants in the grid system. Thus, onsite biogas utilization (either storage or utilization and an alternative strategy) is appropriate for locally produced biogas in Denmark. In this research, the *WI* of biogas, upgraded biogas from commercially operating plants, and gas from the existing gas grid, have been measured and compared. Then, yearly gas consumption trends for selected users were studied to evaluate an alternative approach of gas utilization instead of injection into the gas grid network to overcome compression costs.

2. Method

2.1. Gas Measurement

Raw biogas from manure feed biogas plants, upgraded biogas from water scrubber biogas upgrading plants and natural gas from the Danish gas grid were collected in Supel^{TM} inert foil gas sampling bags with screw cap valve supplied by SUPELCO. At least duplicate measurement was done using gas chromatography (GC) at DGC's laboratory [25]. Briefly, analyses were performed on a Varian CP3800 gas chromatograph equipped with two TCDs and one FID. The columns used were Hayesep Q and Hayesep T and Molsieve 13X. The volume of the sample loop containing 1 mL was injected into the GC by first flushing the sample loop for 0.8 min at 100–150 mL/min and waiting 0.2 min for the pressure to equalize, prior to injection into the gas chromatograph.

2.2. Wobbe Index (WI)

The *WI* of raw biogas and upgraded biogas was calculated by using the following equation:

$$WI = \frac{H_u}{\sqrt{\frac{\rho}{\rho_{air}}}} \; (\text{unit MJ/m}^3(\text{n})), \tag{1}$$

where *WI* is an indicator of interchangeability, which is measured by taking the ratio of specific energy of gas concerning its relative flow rate as shown in the equation. Importantly, when two-fuel gases have the same *WI*, they will have similar energy content delivered at similar pressure. H_u is higher heating value, which is a measure of the energy per volume; and ρ and ρ_{air}, is density of gas and air, respectively. Reference temperature for heating was kept at 25 °C, where 0 °C volume temperature was maintained.

2.3. Gas Consumption Trend and Cost Analysis

Yearly gas consumption data from ten different district heating systems (DHS), four different food industries, and six different general industries were collected from gas distribution companies. The gas consumption data were collected from Danish gas distribution companies. Hourly gas consumption was further analyzed to evaluate the sum of yearly consumption, and yearly consumption trend in descending order. Moreover, raw biogas upgrading costs and gas compression costs for food industries were analyzed as described in International Renewable Energy Agency (IREA 2017) [26]. The compression and upgrading costs are calculated based on €0.05/m^3 and €0.078/m^3 for water scrubber recommended by International Renewable Energy Agency [26].

3. Results and Discussion

3.1. Gas Quality

Raw biogas from manure feed biogas plants and upgraded biogas quality were measured and then compared. The raw biogas contained 66.1% CH_4 and 33.3% CO_2 with a significant amount of H_2S. In parallel, the upgraded gas has 97.55% CH_4, with trace amounts of N_2 and O_2, which was increased compared to raw biogas, due to application of water scrubber for upgrading as shown in Table 1. The highest CH_4 content was achieved after upgrading, where CO_2 and O_2 was also presence due to application of water scrubber technology, which might have an impact on *WI*.

Table 1. Gas quality for different gas compositions.

Sn.	Gas	Concentration of CH_4 (%)	Other Composition Constituents (%)
1	Raw biogas	66.1 ± 0.29	CO_2 (33.3 ± 0.15), N_2 (0.5 ± 0.14), O_2 (0.1), and H_2S # (103.5 ± 9.2)
2	Upgraded biogas (SNG)	97.55 ± 0.07	CO_2 (1.35 ± 0.07), N_2 (0.6 ± 0.14), O_2 (0.6 ± 0.14)
3	Natural gas from grid †	97.28	CO_2 (1.73), N_2 (0.65), O_2 (0.1), H_2S # (6.6) and other hydrocarbons such as C_2H_6 (8.03) C_3H_8 (3.87), C_4H_{10} (0.46) C_4H_{10} (0.84) C_5H_{12} (0.18)

All data were derived from triplicate sample measurement, # mg/m^3, † reference provided from Energinet [27].

3.2. Wobbe Index (WI) of Different Gases

The Wobbe index indicates the heating value of a gas composition and reflects the quality of natural gas and interchangeability of different gases [28]. In this study, *WI* of raw biogas was 28.03 MJ/m^3(n), and after upgrading, it reached 51.31 MJ/m^3(n) which meets the minimum level of Danish national legal requirements for *WI*, 50.76 MJ/m^3(n), as shown in Figure 1. Similarly, Pannucharoenwong et al. compared *WI* of biogas produced from pig manure, hen manure, and a mixture of both manures, and reported 38.92, 37.36, 37.88 MJ/Nm^3(n), respectively, notwithstanding that they have identical heating value [29]. The author further suggested *WI* of biogas is dependent on the feedstock for biogas production. Abeysekera M. et al. also developed a model to identify effects of decentralized H_2 fuel injections on low-pressure gas networks, and found that increasing H_2 percentage reduces *WI* [30]. Hence, the presence of other hydrocarbons has significant impact on *WI*. In this study, CO_2 from raw biogas has to be removed by upgrading, and then compression up to 40 bar is required for it to be injected into the transmission grid connected with the European grid, as shown in Figure 1, which incurs extra costs for the compression. In this regard, an alternative approach might be to consider trading biogas directly to industrial customers. Interestingly, direct utilization of gas would thus save costs of upgrading and compression, which perhaps could be implemented by identifying possible consumers.

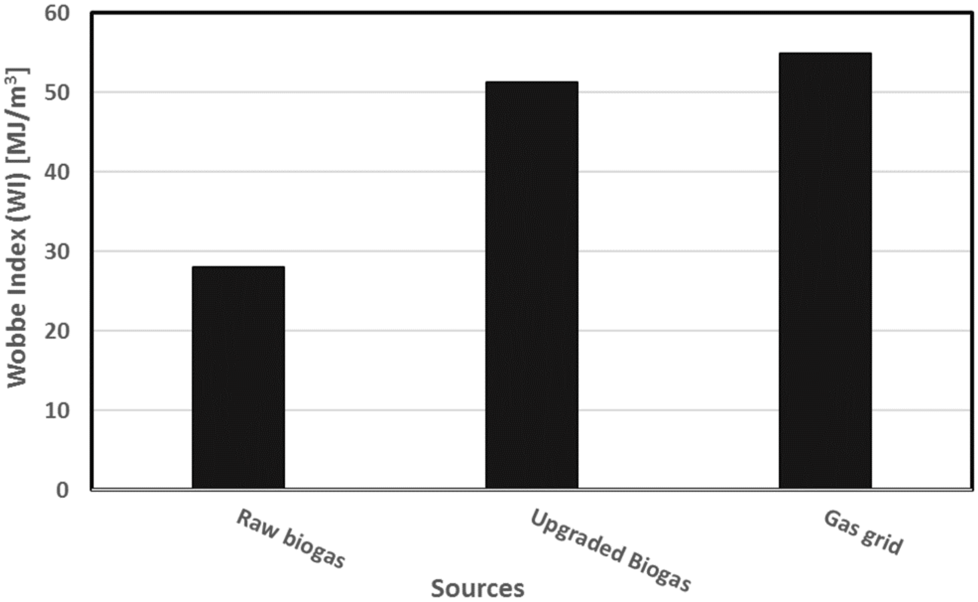

Figure 1. Wobbe index of different gases.

3.3. Gas Consumption Trend from Selected Users

3.3.1. District Heating System (DHS)

In Denmark, natural gas is primarily utilized in the DHS and different industries. Therefore, DHS, general industries, and food industries were selected for a demand study. Biogas is broadly utilized in CHP for DHS, which is projected to slightly increase in the future. Excess heat from CHP is distributed through networks. The biogas plants may be connected separately via low-pressure pipeline for direct application in DHS. When gas consumption data were evaluated, DHS 1 had the highest consumption, followed by 2 and 3, respectively, as shown in Figure 2A. The gas consumption was further evaluated by treating the data in descending order as a function of time, as shown in Figure 2B, which reflects the yearly supply rate of gas. The gas consumption is not constant throughout the year, as shown in Figure 2B, where gas consumption during the first 1500 h has the highest consumption rate compared to the rest of the time. Moreover, there is an increasing trend starting from October, which ends in March, reflecting yearly irregular consumption. The gas consumption during winter was relatively higher compared to summer, which presumably is associated with unutilized heat energy for building heating and energy used from other possible sources, for instance, solar panels. Thus, direct supply of biogas from biogas plants to DHS may not be a viable strategy considering uneven yearly gas consumption trends. Until 2012, biogas was directly utilized often for CHP and DHS, which naturally would avoid costs related to biogas upgrading and compression. However, limited gas consumption in DHS, specifically in summer, is the foremost bottleneck for biogas producers to trade biogas directly to DHS. Rehl T. 2013 also stated that transportation of biogas for DH is not economical [31]. Furthermore, corrosion in the steel grid due to the existence of four parameters, particularly CO_2, H_2, H_2S, and O_2, are major challenges for the introduction of biomethane in the grid system [14].

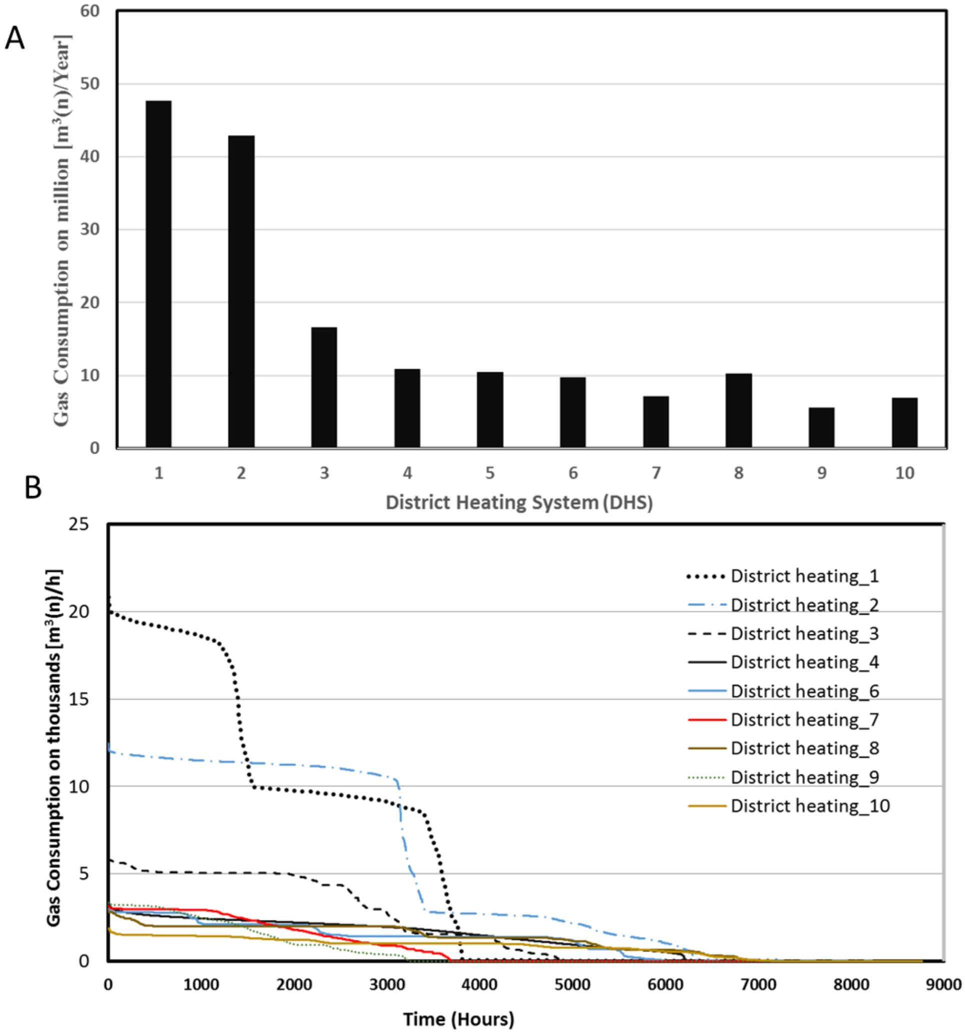

Figure 2. Gas consumption trend by district heating system (DHS). (**A**) Yearly consumption; (**B**) Consumption rate for one year, when data are treated in descending order.

3.3.2. Industry

Natural gas is used in industrial processes for the manufacture of plastic, glass and concrete, metal products, paper products, and the manufacture of machinery. Industries often consume significant amounts of gas for boiler, steam, or hot water generation, industrial processes like heating, feedstock, space heating in buildings, and cleaning. Gas consumption data for six different industries were compared as shown in Figure 3A,B, where the second industry has the highest gas consumption for a short period, even though it has regular gas consumption for most of the period and is comparable with other industries. Thus, industry 2 is relevant with regard to being considered as a biogas consumer, due to high constant gas consumption. The monthly gas consumption rate is not regular throughout the year when gas consumption data are treated in descending order. Monthly total gas consumption data are not correlated, however, there is a huge deviation as shown in Figure 3B. Nevertheless, gas consumption was lower during summer, which is potentially associated with holiday periods and fewer operational hours. It is conceivably an alternative approach to supply biogas directly from plants to industries, rather than introducing it into the gas grid system. Direct supply of biogas, avoiding costs of maintaining *WI* and compression costs, could be possible. Nonetheless, further assessment has to be done to evaluate the effect of biogas utilization with existing gas utilizing facilities, such as burners, boilers, and pipelines.

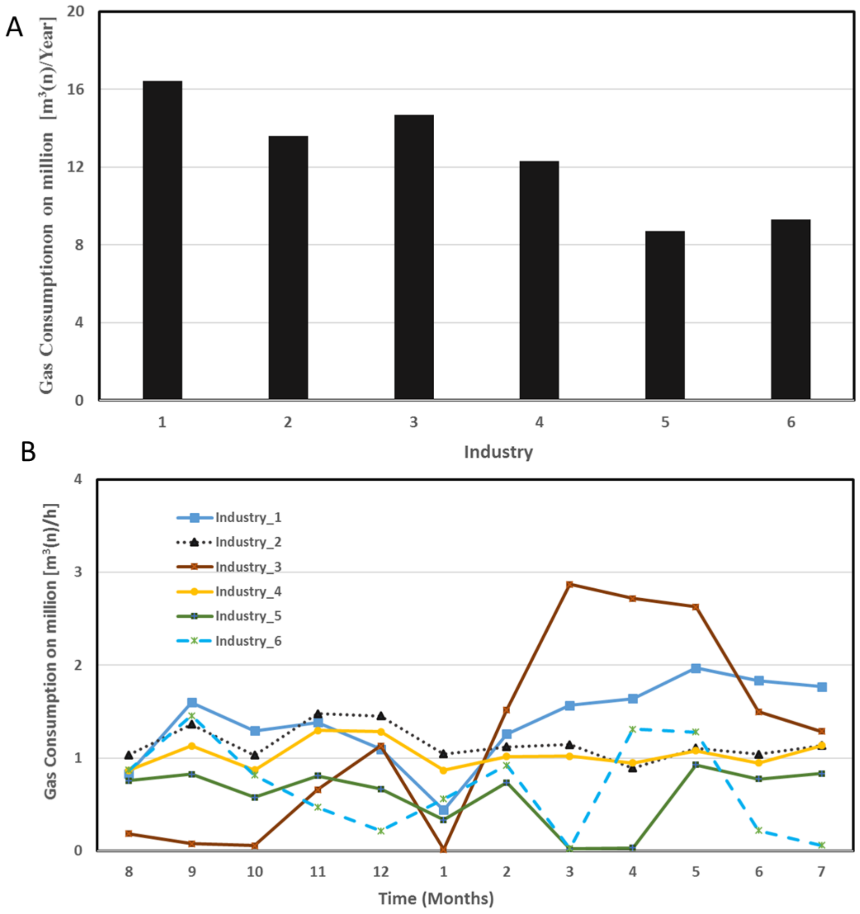

Figure 3. Gas consumption trend by different industries. (**A**) Yearly consumption; (**B**) Monthly consumption.

3.3.3. Food Industries

Food industries, and most importantly, dairy, food product processing, beverages, and tobacco, alone, utilize most of the natural gas utilized in the industry sector. Natural gas is used for pasteurizing, blanching, extraction, sterilization, cleaning water for production, washing of raw materials, and heat retention of tanks and pipes. The gas consumption rate for food industries, in particular dairy, is below 4000 m^3(n)/h throughout the year as shown in Figure 4B. Interestingly, consumption trends are almost similar and constant, as shown in Figure 5A–D. The consumption trend during summer was lower compared to winter in industry 3, which perhaps is associated with a holiday period with fewer operating hours, as shown in Figures 4 and 5C. Thus, alternatively, biogas can be directly utilized in the food industries, saving upgrading and compression costs for gas grid injection, if required. Particularly, mapping of gas utilizing industries and networks for efficient supply of biogas could save costs. Nevertheless, direct application of biogas in industry might require changing the appliances, in particular, burners, boilers, engines, and gas turbines, to cope with the wider range of heating values and other impurities in the biogas. Some of the harmful impurities for industrial appliances, such as H_2S and ammonia (NH_3), may be removed by applying the economical bioreactor without using expensive upgrading technology [32]. Borjesson, M. et al. investigated the cost-effective biogas utilization in a regional geographical area of Sweden, incorporating local biogas systems and several energy demand systems [33]. The author recommended biogas distribution strategy based on truck transportation or connection to regional biogas semi-grids, which would have economic and environmental benefits compared to natural gas grid expansion. Hence, connecting biogas plants with larger gas consumers, especially the food processing industry in Denmark, is an effective approach of biogas utilization.

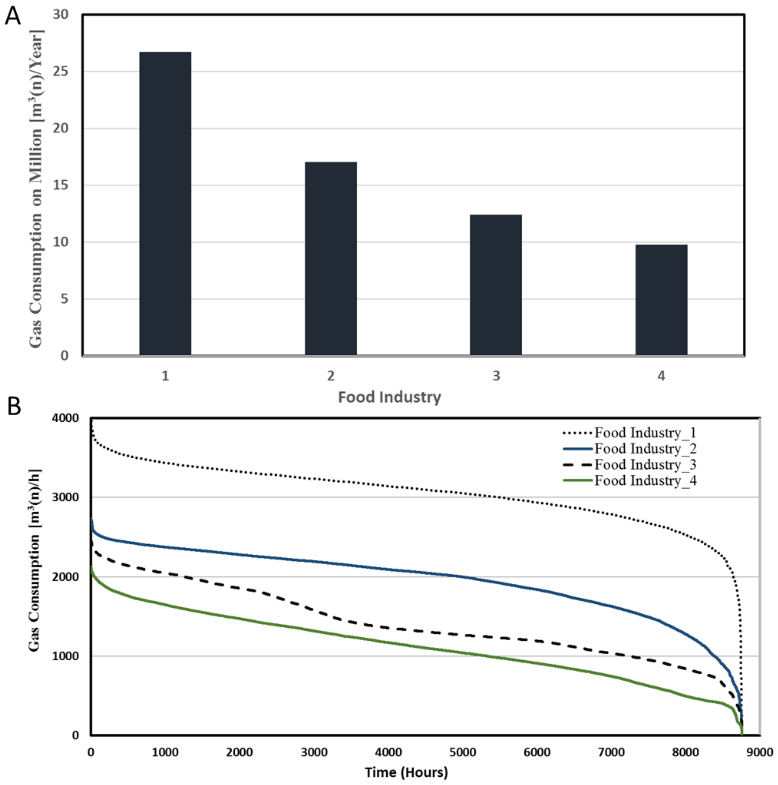

Figure 4. Gas consumption trend in different food processing industries. (**A**) Yearly consumption; (**B**) Consumption rate for one year when data are treated in descending order.

3.4. Compression and Upgrading Cost Analysis

Biogas upgrading costs significantly vary with quality requirements for biomethane, quality of raw biogas, technology used, and legal environmental regulations [26]. However, capital expenditure (CAPEX) and operating expense (OPEX) decrease significantly with larger installation capacities. A recent study has reported upgrading cost of €0.078/m^3 for methane at a 2000 m^3/h biogas upgrading installation [26]. Furthermore, gas transportation costs mainly depend on investment costs for gas grid facility and gas injection costs at specific pressures. There will be minimum gas injection costs into distribution grids working at low pressure, while the maximum cost will be for higher pressure, in particular, 40 bar to 55 bar. The Danish transmission line is a 40 bar system connected with the German transmission grid. The study has reported compression cost €0.051/m^3 based on circumstances in Germany [26]. In this study, costs for compression and upgrading have been calculated as dedicated to food processing industries, as shown in Table 2. Interestingly, €3.48 million could be saved, if biogas was directly supplied to the first food processing industries considering stable consumption of gas, as discussed in Section 3.3.3. Furthermore, upgrading and compression costs for equivalent gas consumption by four different industries are €5.13 and €3.3 million, respectively. In one of the studies, the upgrading costs with chemical scrubber, water scrubber, and membrane were €0.16/m^3, €0.13/m^3, and €0.25/m^3, respectively [34]. The biogas upgrading operating cost per unit of treatment decreases with the size of facility, for example, operating costs for 500 Nm^3 biogas/h plant, are €440/Nm^3 and €340/Nm^3, for a plant treating 2000 Nm^3 biogas/h [3,26,35]. Furthermore, a recent study has shown between €0.63 to €0.86/Nm^3 raw biogas upgrading, and the gas grid injection cost was estimated at €0.38 /Nm^3 [36]. Therefore, the alternative approaches, in particular, onsite gas utilization by industries or chemical production from biogas, may be appropriate alternatives. Moreover, propane mixing in gas to maintain the heating value or *WI*, as implemented in Germany, could be avoided, resulting in a considerable cost reduction.

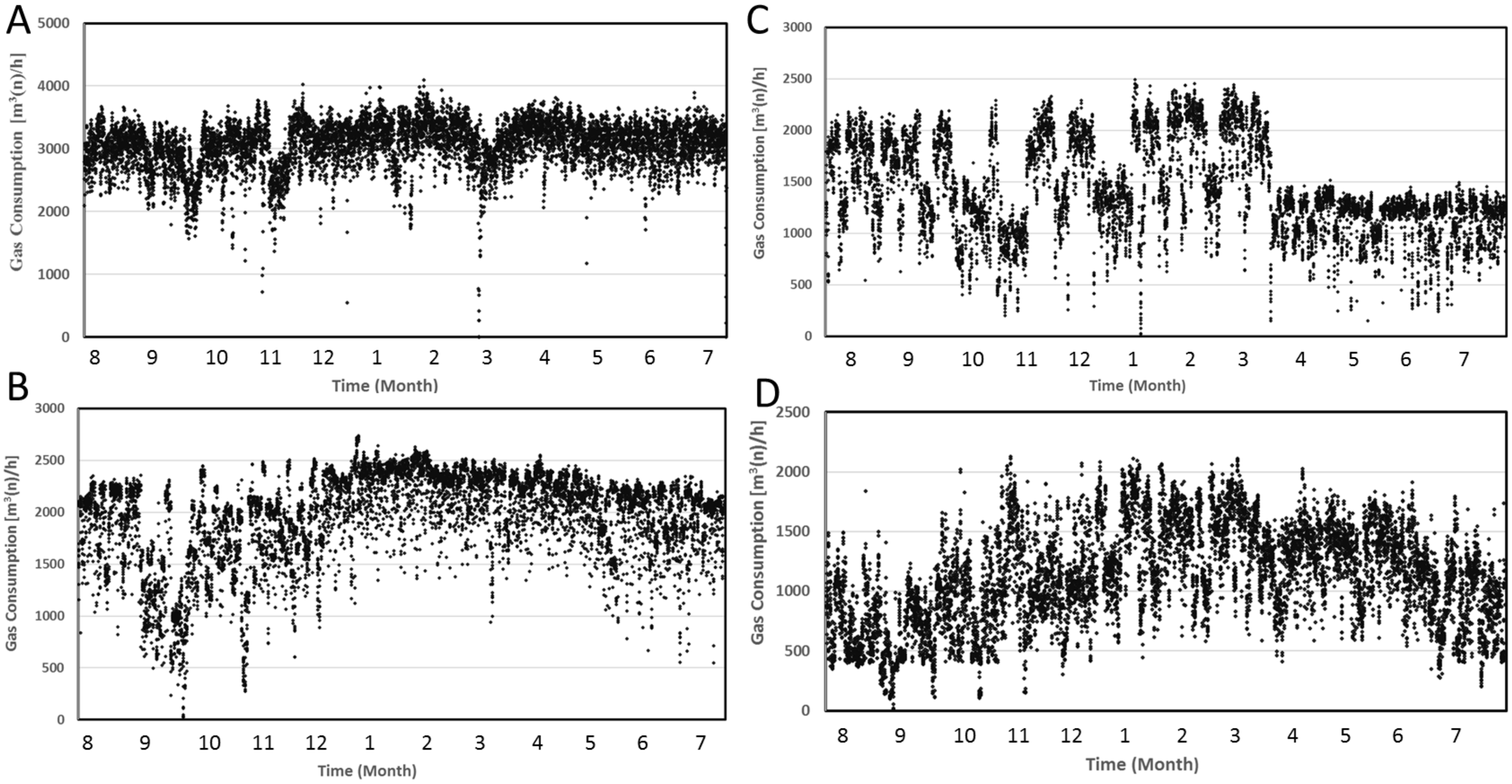

Figure 5. Hourly gas consumption data for the period of one year where (**A**–**D**) denote the four different food industries, and X-axis denotes the 12 months starting from August to July.

Table 2. Gas consumption by food processing industries and economic calculation of compression and upgrading equivalent amount of gas.

Food Industry	Yearly Gas Consumption in Million (m^3/Year)	Compression Cost in Million (€) #	Upgrading Cost in Million (€) &	Total Cost (€) in Million
1	26.7	1.4	2.08	3.48
2	17.1	0.8	1.33	2.13
3	12.4	0.6	0.96	1.56
4	9.8	0.5	0.76	1.26

costs are calculated based on €0.05/m^3; & costs are calculated based on €0.078/m^3 for large scale water scrubber [26].

4. Conclusions

Biogas upgrading to gas grid quality for grid injection or transportation fuel is particularly relevant in the Danish framework of achieving a fossil-independent energy sector. For instance, economic and effective utilization of biogas is also significant to develop biogas technologies. In this study, gas qualities of raw biogas, upgraded biogas, natural gas from North Sea and Russian origin imported from European gas grid, were compared, and then *WI* was calculated, where *WI* of raw biogas has to improve from 28.03 MJ/m^3(n) to 51.31 MJ/m^3(n), adding extra costs of CO_2 removal from gas. Alternatively, large customer mapping would presumably be an appropriate way to supply biogas, avoiding additional compression costs. The biogas supply to industry, in particular, food processing industries, might be an effective alternative considering gas consumption trends. The upgrading and compression costs of €5.13 and €3.3 million could be saved, if the biogas were directly supplied to the selected food processing industries in Denmark. Furthermore, addition of propane in order to maintain the heating value or *WI*, could be avoided, which may also save cost and energy.

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