Available online at www.dergipark.org.tr/en

INTERNATIONAL ADVANCED RESEARCHES and ENGINEERING JOURNAL

Journal homepage: www.dergipark.org.tr/en/pub/iarej

e-ISSN: 2618-575X

International Open Access

Volume 09
Issue 01

April, 2025

Research Article

Thermodynamic and technoeconomic feasibility assessment on liquefaction of CO_2 by-product of Afyon biogas power plant

Muhammed Arslan [*, a]

[a] *Afyon Kocatepe University, Çay Vocational High School, Afyon, 03700, Turkey*

ARTICLE INFO

Article history:
Received 02 October 2024
Accepted 16 February 2025
Published 23 April 2025

Keywords:
Biogas
CO_2 liquefaction
Thermodynamic analysis
Technoeconomic analysis.

ABSTRACT

The composition of the biogas produced in Afyon biogas power plant is approximately as follows: 55% CH_4 (methane) - 40% CO_2 (carbon dioxide)- 4.5% H_2O (water) and trace amounts of other components. The methane produced is used in gas engines to generate electricity. Carbon dioxide, however, increases greenhouse gas emissions when released into the atmosphere. The model designed in this study includes the liquefaction and storage of CO_2 and the technoeconomic analysis of this process. The analysis was performed in the Aspen Plus software, which is widely used in the analysis of complex processes involving numerious chemical reactions. According to the results of the thermodynamic analysis, the energy efficiency, exergy efficiency, net electrical power and liquid CO_2 production rate of the plant were determined as 14.92%, 13.08%, 4,000 kW and 99 kg/h, respectively. According to the results of the technoeconomic analysis, unit electricity cost, liquid CO_2 flow cost and TCC (total capital cost) are 77.5 $/MWh, 993.68 $/h and 47,548,200 $ respectively. The designed model has the potential to prevent the release of CO_2 into the atmosphere at reasonable prices.

1. Introduction

With the depletion of fossil fuels and the acceleration of climate change, the need for and opportunities in renewable energy are increasing. Biomass-based energy is becoming an important way to generate sustainable power, reduce greenhouse gas emissions, improve energy security, contribute to development, increase the use of green energy and alleviate dependence on limited resources [1-3]. Anaerobic digestion technology, a widely used method for utilizing biomass energy, is recognized as highly effective and promising. The anaerobic digestion process, which involves a series of biochemical reactions, results in biogas production [1, 4, 5].

Biogas from anaerobic digestion of organic waste is a renewable energy source with great potential to reduce global dependence on fossil fuels. As an environmentally friendly and sustainable energy source, biogas can be used for heat and electricity generation. Moreover, the digestion product can be used to produce fertilizers [6, 7].

On the other hand, societies today face severe weather events, rising sea levels and natural disasters. An important cause of these problems is carbon emissions that cause greenhouse gases and these emissions need to be reduced [8]. One of the important components of biogas in the biogas production process is carbon dioxide, which constitutes about 40% of the gas. Releasing carbon dioxide into the atmosphere, whether directly from gas engines or after separation from methane, significantly contributes to greenhouse gas emissions. However, liquefaction and storage of carbon dioxide after separation from methane can solve this problem. Such biogas separation is also necessary for the utilization of carbon dioxide, a valuable molecule in the food and beverage industries, chemical synthesis and greenhouses and other industrial activities [6].

Many studies on electricity generation from biogas and carbon dioxide liquefaction have been conducted in the literature and some of them are summarized below.

Rostamzadeh et al. (2018) proposed a hybrid model powered by biogas and geothermal energy source and analyzed the model thermodynamically. According to the results of the analysis, the model has 62.28% thermal efficiency and 74.9% exergy efficiency and generates 443.4 kW of electricity [9].

Sun et al. (2024) proposed a multigeneration system for heating, cooling, clean water and power generation and

* Corresponding author. Tel.: +0 272 218 35 35
E-mail addresses: muarslan@aku.edu.tr *(M.Arslan)*
ORCID: 0000-0001-8387-7008 *(M.Arslan)*
DOI: 10.35860/iarej.1560048

analyzed the system from thermodynamic and thermoeconomic perspectives. According to the thermodynamic analysis results, the multigeneration system has 58.06% energy efficiency, 36% exergy efficiency and 9,775.5 kW electrical power generation capacity. According to the results of the thermoeconomic analysis, the multigeneration system has 59,536 k$ total equipment cost and 29 $/MWh levelized cost of products [10].

Zhao et al. (2024) developed a hybrid model that efficiently utilizes exhaust gas (after turbine) from biogas combustion and flue gas from silicon production and analyzed the model from thermodynamic and economic perspectives. According to the results of the thermodynamic analysis, the model has an energy efficiency of 43.61%, an exergy efficiency of 51.07% and an annual power generation capacity of 293 GWh. According to the economic analysis results, the initial investment requirement, dynamic payback period and net present value are 50,132.47 k$, 4.09 and 136,864.14 k$, respectively [11].

Cao et al. (2022) modeled a cogeneration system generating electrical and cooling power and analyzed the system from a thermodynamic point of view by optimizing. The analysis revealed that the system has an electricity generation capacity of 1,140 kW, an energy efficiency of 57.11%, and an exergy efficiency of 36.68% [12].

Gholizadeh et al. (2019) modeled a biogas-fired gas turbine assisted by an ORC (Organic Rankine Cycle) and a modified-ORC, and analyzed the model from thermodynamic and thermoeconomic aspects. According to the results of the analysis, the energy efficiency, exergy efficiency, power generated and average product cost of the gas turbine assisted by modified-ORC are calculated as 41.83%, 38.91%, 1,368 kW and $17.2/GJ, respectively [13].

Ghorbani et al. (2021) developed an integrated system for liquid bio-CO_2 production by cryogenic separation, CO_2 capture and liquefaction and evaluated the system from thermodynamic and thermoeconomic perspectives. According to the evaluation results, 0.2102 kg/h liquid bio-CO_2 production, 73.11% thermal efficiency and 72.58% exergy efficiency were obtained [14].

Jung et al. (2021) conducted a technoeconomic analysis of four different CCL (carbon dioxide compression and liquefaction) processes with high purity and recovery using a distillation column. As a result of the analysis, the cost of CO_2 liquefaction with 99.9% purity and 93% recovery at 80 bar pressure was 22 $/$CO_2$ [15].

Yousef et al. (2017) proposed a model to separate carbon dioxide from methane at low temperatures for biogas upgrading with HYSYS software. The model liquefies CO2 at 110 bar pressure and 99.9% purity, increasing the methane purity from 60% to 97.1% by mol. [16].

Øi et al. (2016) developed different models for liquefaction of 1 million tons of CO_2 per year with HYSYS software. The models are focused on two points as external refrigeration and integrated refrigeration. According to the analysis results, the model with the optimum cost is the one based on external refrigeration and has an 23 M€ investment and an operating cost of 4 M€/ton [17].

Liu et al. (2024) designed four different models on CO_2 liquefaction and storage and analyzed the models from thermodynamic and economic perspectives. According to the thermodynamic analysis results, the best model has 71.54% round-trip efficiency and 40.61 kWh/m^3 energy density, and 37.86 kg/s CO_2 is liquefied. According to the thermoeconomic analysis results, levelized cost of electricity and net present value are 110.9 $/MWh and 3.03 M$, respectively [18].

Khosravi et al. (2023) modeled a cogeneration system that produces electrical power, CO_2 liquefaction, solid waste gasification and steam production and analyzed the system from thermodynamic and thermoeconomic perspectives. According to the thermodynamic analysis results, the system has 11.9% electrical energy efficiency, 19.48 MW electrical power capacity and 1.9 CO_2 liquefaction-COP (coefficient of performance). According to the thermoeconomic analysis results, the electricity cost was determined as 60.1 $/MWh [19].

In this study, biogas produced in Afyon biogas power plant is purified from carbon dioxide and other undesired components before being sent to gas engines. While electricity is generated from pure methane in the engines, carbon dioxide is sent to the cooling unit for liquefaction. In this way, 95% of the biogas is utilized, and carbon dioxide emissions to the atmosphere are prevented. In addition, electricity and liquid carbon dioxide can be used to meet many needs. The model proposed in this study represents the process from biomass digestion to electricity and liquid carbon dioxide production. It is designed using Aspen Plus software and analyzed from thermodynamic and technoeconomic point of view. The originality of this study lies in the technoeconomic analysis of the process from the release to the liquefaction of by-product carbon dioxide, conducted using Aspen Plus software. Aspen Plus is a complex software that realistically simulates physical and chemical processes while incorporating up-to-date economic data. A realistic analysis of such a process using Aspen Plus has not been encountered in the literature. Figure 1 illustrates the Afyon biogas power plant.

Figure 1. Afyon Biogas Power Plant [20].

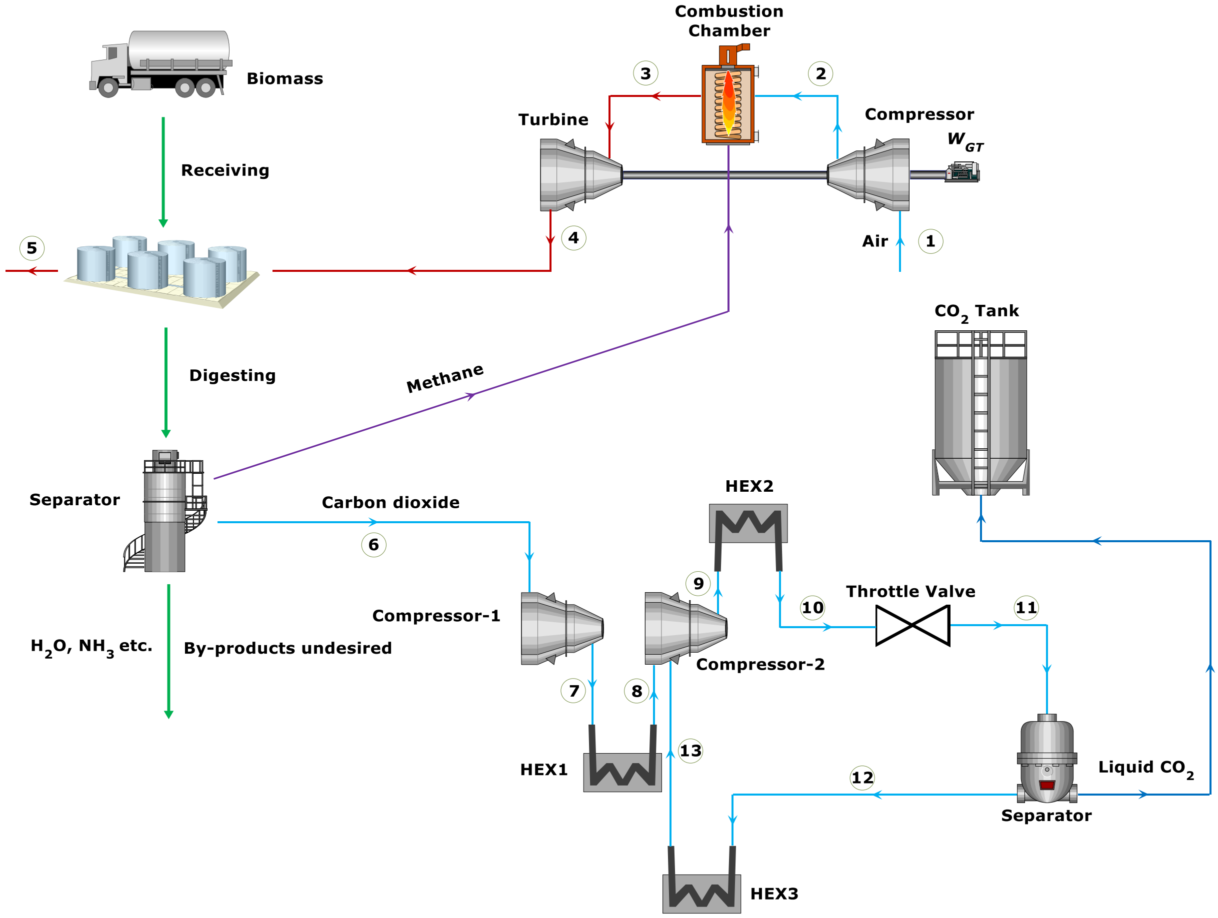

Figure 2. The operation flow of designed model.

In Fig. 2, the operation flow of the designed model is shown. Biogas is produced in the reactor and methane, carbon dioxide and other components are separated from each other. Methane is then sent to the combustion chamber. The exhaust gas, exiting the turbine, is sent to the reactor to increase reactor's temperature and is then released into the atmosphere. Meanwhile, carbon dioxide is liquefied using the Linde-Hampson process.

2. Analysis and Aspen Plus

This section presents the methodology of the study, including the main equations and the software used for the analysis.

2.1 Analysis

The analysis consists of two steps: thermodynamic and technoeconomic analysis. The first step is thermodynamic analysis and the designed model is analyzed in terms of energy and exergy at both equipment and plant levels. In this way, the thermodynamic performance and flow data of the plant and equipment can be measured. The exergy data obtained from the thermodynamic analysis, along with the economic data, form the basis of the technoeconomic analysis. The logic of the technoeconomic analysis is to assign costs to each flow in the process using various up-to-date data such as equipment purchase costs, interest rate, capital recovery factor, operation and maintenance factor. In this way, product costs and total capital cost can be calculated. The main equations used in the analysis are as follows:

The net power of the power plant is the difference between the power produced in the turbine and the power consumed by the compressor.

$$\dot{W}_{net\ electricity} = \dot{W}_{Turbine} - \dot{W}_{Compressor} \quad (1)$$

The energy efficiency is the ratio of the net power produced by the plant to the fuel power entering the plant.

$$\eta_{energy} = \frac{\dot{W}_{net\ electricity}}{\dot{m}_{methane}.HV_{methane}} \quad (2)$$

The exergy efficiency is the ratio of the net power produced by the plant to the fuel exergy entering the plant.

$$\eta_{exergy} = \frac{\dot{W}_{net\ electricity}}{\dot{m}_{methane}.ex^{ch}_{methane}} \quad (3)$$

The exergy cost rate is calculated by multiplying the unit flow cost rate by the flow exergy. *k* represents flow number.

$$\dot{C}_k = c_k.\dot{E}_k \quad (4)$$

The cost balance for an equipment with power and heat inputs and outputs is expressed as follows. $\dot{Z}_k$ and subscripts *q, w, i and o* represent total cost rate, heat, power, input and output, respectively.

$$\sum_i \dot{C}_{i,k} + \dot{C}_q + \dot{Z}_k = \sum_o \dot{C}_{o,k} + \dot{C}_W \quad (5)$$

2.2 Aspen Plus

Aspen Plus is a software that is very well known for chemical processes and presents the most realistic results in a simple way. Designers can design complex models with Aspen Plus and simulate by solving them with mathematical methods. They can also make designed models better. It can instantly display thermodynamic data (pressure, temperature, mass flow rate, vapor fraction, heat/work etc.) for each flow and show areas open to development. It evaluates chemical and physical events in processes with thermodynamic laws and equations. If there is a thermodynamically impossible situation in the designed model, the error is explained to the designer by Aspen Plus. In addition, all equations required for economic and technoeconomic analysis are available in the Aspen Plus database. Aspen Plus automatically selects the equipment that is most suitable for thermodynamic conditions in a designed model by sizing and includes that equipment in the economic analysis. Therefore, there is no need for manual sizing and costing. For example, when the air flow rate entering a compressor in the current design is changed, Aspen Plus assigns a new compressor suitable for the current conditions instead of the current compressor and the economic data changes. When the economic analysis tab is activated, data such as total capital cost, equipment purchase cost, installed cost, unit flow cost are displayed [21].

Since this study involves biogas production from biomass, combustion of methane and liquefaction of carbon dioxide, thermodynamic analysis and technoeconomic analysis, Aspen Plus is an indispensable software for the study.

3. Numerical Results

Figure 3 shows the model designed in Aspen Plus. The process starts with anaerobic digestion of biomass in the reactor and as a result of gasification, 3523 kg/h of biogas is released at 308 K temperature and 101 kPa pressure. Methane, carbon dioxide and other unwanted components are separated in the biocleaner unit. Methane is sent to the combustion chamber and reacts with compressed air supplied by compressor. The exhaust gas generated from combustion drives the turbine. The 10,800 kW power required by the compressor is met by the 14,800 kW power produced by the turbine. Thus, the net electrical power is 4,000 kW. The exhaust gas exiting the turbine heats the reactor before being released into the atmosphere to increase the reactor temperature. On the other hand, the separated carbon dioxide is liquefied and stored instead of being released into the atmosphere. With the Linde Hampson process, carbon dioxide is compressed and cooled in two stages in the compressor. Finally, liquid carbon dioxide is separated from gaseous carbon dioxide by throttling in the throttle valve. The gaseous form of carbon dioxide is recirculated to the second compressor. In this way, 99 kg/h of liquid carbon dioxide at 253 K and 1970 kPa is obtained.

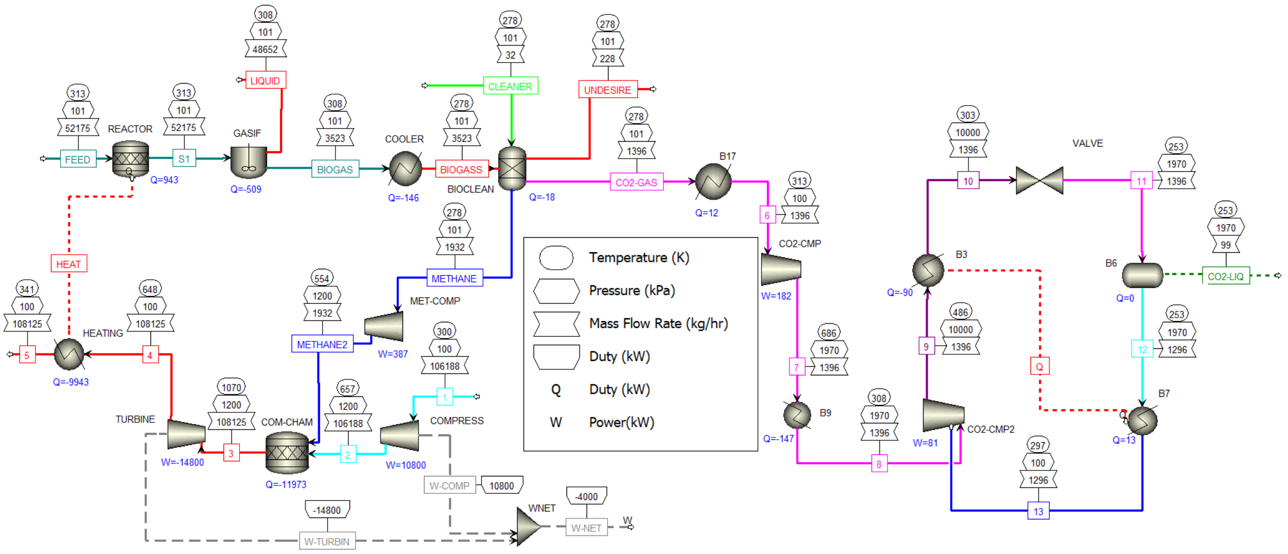

Figure 3. The designed model in Aspen Plus.

Table 1. The thermodynamic analysis results of the designed model.

	Value
Produced methane	1932 kg/h
η_{energy}	14.92%
η_{exergy}	13.08%
Net electrical power	4,000 kW
Produced liquid CO_2	99 kg/h

The technoeconomic analysis results of the model are given in Table 2.

Table 2. The technoeconomic analysis results of the designed model.

	Value
The unit cost of electricity	77.5 \$/MWh
The cost of liquid CO_2	10.1 \$/kg
The flow cost of liquid CO_2	993.68 \$/h
Total installed cost	37,156,100 \$
TCC	47,548,200 \$

The thermodynamic analysis results of the model are given in Table 1.

4. Conclusions

In this study, a model representing the process of electricity production and liquefaction of by-product carbon dioxide in Afyon biogas power plant was developed. Carbon dioxide released to the atmosphere in the existing plant is liquefied and stored with the designed model. This has a positive impact on reducing greenhouse gas emissions. The liquid carbon dioxide obtained can be used for various purposes such as food and beverage production, chemical production, welding and metal fabrication, fire extinguishers, medical applications, and environmental applications. In this way, approximately 95% of the biogas produced from biomass in the plant is utilized effectively. The key numerical results of the study are as follows:

- The plant produces 4,000 kW net electrical power and 99 kg/h liquid CO_2.

- The energy and exergy efficiency of the plant are 14.92% and 13.08%, respectively.

- The unit cost of the produced electricity and the flow cost of carbon dioxide are 77.5 \$/MWh and 993.68 \$/h, respectively.

- TCC is 47,548,200 \$.

The proposals of the study are as follows:

- Thermodynamic optimization of the plant will increase energy and exergy efficiency and therefore reduce electricity cost.

- The equipment involved in the liquefaction process of carbon dioxide operates with the electricity produced by the plant. Therefore, reducing the cost of electricity produced in the plant will reduce the flow cost of liquid carbon dioxide.

- The type and amount of raw material used in biogas production and the reactor temperature determine the composition of the biogas. These key parameters should be investigated to improve methane production efficiency.

- Other components released during the production of biogas can be utilized beneficially, and technoeconomic analysis should be conducted on this matter.

- To improve the process from a technoeconomic perspective, studies can be carried out on the liquefaction of CO_2 using different thermodynamic cycles.

- The effects of the analysis on emission values can be investigated.

- A more comprehensive technoeconomic analysis can be conducted to see the effects of different operating conditions and costs.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Nomenclature

CCL	Carbon dioxide compression and liquefaction
CH_4	Methane
CO_2	Carbon dioxide
COP	Coefficient of performance
H_2O	Water
ORC	Organic Rankine Cycle
TCC	Total capital cost ($)
HV	Heating Value (kJ/kg)
$\dot{E}$	Exergy (kW)
c	Unit flow cost rate ($/kWh)
$\dot{C}$	Exergy cost rate ($/h)
ex^{ch}	Chemical exergy (kJ/kg)
η	Efficiency
$\dot{m}$	Mass flow rate (kg/s)
$\dot{W}$	Power (kW)
$\dot{Z}_k$	Total cost rate ($/h)

References

1. Prasad, R. K., A. Sharma, P. B. Mazumder, and A. Dhussa, *A comprehensive pre-treatment strategy evaluation of ligno-hemicellulosic biomass to enhance biogas potential in the anaerobic digestion process*. RCS Sustainability, 2024. **2**: p. 2444-2467.
2. Tjutju, N. A. S., J. Ammenberg, and A. Lindfors, *Biogas potential studies: A review of their scope, approach, and relevance*. Renewable and Sustainable Energy Reviews, 2024. **201**: p. 114631.
3. Aigbe, U. O., K. E. Ukhurebor, A. O. Osibote, M. A. Hassaan, and A. E. Nemr, *Optimization and prediction of biogas yield from pretreated Ulva Intestinalis Linnaeus applying statistical-based regression approach and machine learning algorithms*. Renewable Energy, 2024. **235**: p. 121347.
4. Joshi, J., P. Bhatt, P. Kandel, M. Khadka, S. Kathariya, S. Thapa, S. Jha, S. Phaiju, S. Bajracharya, and A. P. Yadav, *Integrating microbial electrochemical cell in anaerobic digestion of vegetable wastes to enhance biogas production*. Bioresource Technology Reports, 2024. **27**: p. 101940.
5. Shen, R., P. Sun, J. Liu, J. Luo, Z. Yao, R. Zhang, J. Yu, and L. Zhao, *Robust prediction for characteristics of digestion products in an industrial-scale biogas project via typical non-time series and time-series machine learning algorithms*. Chemical Engineering Journal, 2024. **498**: p. 155582.
6. Rodero, M. D. R., R. Muñoz, A. G. Sánchez, H. A. Ruiz, and G. Quijano, *Membrane materials for biogas purification and upgrading: Fundamentals, recent advances and challenges*. Journal of Environmental Chemical Engineering, 2024. Available online 14 September 2024, p. 114106.
7. Alharbi, R. M., *Anaerobic co-digestion of cow manure and microalgae to increase biogas production: A sustainable bioenergy source*. Journal of King Saud University-Science, 2024. **36**(9): p. 103380.
8. Ma, C., H. Yu, G. Monticone, S. Ma, J. V. Herle, and L. Wang, *Techno-economic evaluation of biogas-fed SOFC systems with novel biogas purification and carbon capture technologies*. Renewable Energy, 2024. **235**: p. 121302.
9. Rostamzadeh, H., S. G. Gargari, A. S. Namin, and H. Ghaebi, *A novel multigeneration system driven by a hybrid biogas-geothermal heat source, Part I: Thermodynamic modeling*. Energy Conversion and Management, 2018. **177**: p. 535–562.
10. Sun, K., W. Zhang, R. Li, D. Liu, X. Gao, H. Song, X. Chen, and L. Zhou, *Thermodynamic feasibility evaluation of an innovative multigeneration system using biogas dry reforming integrated with a CCHP-desalination process*. Desalination, 2024. **580**: p. 117526.
11. Zhao, X., H. Chen, J. Li, P. Pan, F. Gui, and G. Xu, *Thermodynamic and economic analysis of a novel design for combined waste heat recovery of biogas power generation and silicon production*. Energy, 2024. **290**: p. 130272.
12. Cao, Y., H. A. Dhahad, H. M. Hussen, and T. Parikhani, *Proposal and evaluation of two innovative combined gas turbine and ejector refrigeration cycles fueled by biogas: Thermodynamic and optimization analysis*. Renewable Energy, 2022. **181**: p. 749-764.
13. Gholizadeh, T., M. Vajdi, and F. Mohammadkhani, *Thermodynamic and thermoeconomic analysis of basic and modified power generation systems fueled by biogas*. Energy Conversion and Management, 2019. **181**: p. 463–475.
14. Ghorbani, B., A. Ebrahimi, and M. Ziabasharhagh, *Thermodynamic and economic evaluation of biomethane and carbon dioxide liquefaction process in a hybridized system of biogas upgrading process and mixed fluid cascade liquefaction cycle*. Process Safety and Environmental Protection, 2021. **151**: p. 222–243.
15. Jung, P. G., S. Kim, Y. I. Lim, H. Kim, and H. M. Moon, *Techno-economic comparisons of CO_2 compression and liquefaction processes with distillation columns for high purity and recovery*. International Journal of Greenhouse Gas Control, 2024. **134**: p. 104113.
16. Yousef, A. M., Y. A. Eldrainy, W. M. El-Maghlany, and A. Attia, *Biogas upgrading process via low-temperature CO_2 liquefaction and separation*. Journal of Natural Gas Science and Engineering, 2017. **45**: p. 812-824.
17. Øi, L. E., N. Eldrup, U. Adhikari, M. H. Bentsen, J. L. Badalge, and S. Yang, *Simulation and cost comparison of CO_2 liquefaction*. Energy Procedia, 2016. **86**: p. 500–510.
18. Liu, Z. X. Yan, S. Wang, X. Wei, Y. Zhang, J. Ding, and C. Su, *Performance of compressed CO_2 energy storage systems with different liquefaction and storage scenarios*. Fuel, 2024. **359**: p. 130527.
19. Khosravi, S., R. K. Saray, E. Neshat, and A.

Arabkoohsar, *Towards an environmentally friendly power and hydrogen co-generation system: Integration of solar-based sorption enhanced gasification with in-situ* CO_2 *capture and liquefaction process*. Chemosphere, 2023. **343**: p. 140226.

20. Afyon Energy, [access date 09.15.2024], https://afyonenerji.com.tr/
21. Aspen Plus, *Engineering Analysis Database*. 2024.