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Process Analysis and Comparison of Biogas Techniques

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تحليل العمليات ومقارنة تقنيات الغاز الحيوي

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Abstract:
Upgrading biogas to high energy biomethane is commonly utilized to produce substitute natural gas (SNG) where the most crucial operation is a separation of CO2from biogas, which is carried out by several technologies such as, amine scrubbing, cryogenic separation. The aim of this study, was to perform a design and optimization comparative process for upgrading section of biogas production and processing plant of the two technologies (absorption and cryogenic separation).The two technologies were examined and analyzed to assess their pros and cons in order to choose the most appropriate method to be implemented, where three aspects were chosen for the assessment: (1) process technology and product quality, (2) methane recovery and losses, (3) energy consumption and economy. The research was carried out using a package of commercial software's including, Aspen HYSYS v11, Exchanger design and rating (EDR), Aspen Process Economic Analyzer (APEA) and MS excel.

The obtained results of amine process show that the total energy and power consumption in the optimized case are reduced by 73% and 11% respectively in comparison with the base case, furthermore the methane losses in the entire system were reduced by 27% and consequently the methane recovery was increased to 99,93%.

Due to the implementation of heat integration process by cryogenic process, the total energy consumption in the optimized case was reduced by 44% in comparison with the base case, in the other hand, implementation of the methane recovery stage reduces the methane losses in the entire system by 76% and consequently the methane recovery in the upgraded biogas stream is increased from 85.15% to 95.91%, however, it causes slight increasing in the total power from 230.7 kW to 241.7 kW, moreover, the CO2 mole fraction in the upgraded biogas remains within the limits (<3%).

Comparison between both cases shows, the energy required in the amine process is much higher than that in the cryogenic process, while the power consumption is higher in the cryogenic process than amine process, and the methane recovery in the amine process is higher than in the cryogenic process. Economic analysis shows that the amine process has a lower installation cost than the cryogenic process but higher operation cost, however, the net present cost shows a preference for the amine process over the cryogenic .

Keywords: The Process of Converting Biogas, Biomethane, To Produce Natural Gas, Separating Carbon Dioxide, Integrating Heat.

الملخص

تُستخدم عملية تحويل الغاز الحيوي إلى غاز الميثان الحيوي عالي الطاقة على نطاق واسع لإنتاج الغاز الطبيعي البديل (SNG)، حيث تُعدّ عملية فصل ثاني أكسيد الكربون عن الغاز الحيوي أهم العمليات، ويتم ذلك باستخدام تقنيات متعددة مثل التنقية بالأمينات والفصل بالتبريد. هدفت هذه الدراسة إلى إجراء مقارنة بين تصميم وتحسين قسم تحويل الغاز الحيوي في محطة إنتاج ومعالجة الغاز الحيوي باستخدام تقنيتين (الامتصاص والفصل بالتبريد). تم فحص التقنيتين وتحليلهما لتقييم مزايا وعيوب كل منهما لاختيار الطريقة الأنسب للتطبيق، حيث تم اختيار ثلاثة جوانب للتقييم: (1) تكنولوجيا العملية وجودة المنتج، (2) استخلاص الميثان وفقدانه، (3) استهلاك الطاقة والاقتصاد. أُجري البحث باستخدام حزمة من البرامج التجارية، بما في ذلكAspen HYSYS v11 ، وبرنامج تصميم وتقييم المبادلات الحرارية(EDR) ، وبرنامج Aspen Process Economic Analyzer (APEA)، وبرنامج MS Excel.

...أظهرت نتائج عملية الأمين انخفاضًا في إجمالي استهلاك الطاقة والقدرة في الحالة المُحسَّنة بنسبة 73% و11% على التوالي مقارنةً بالحالة الأساسية. كما انخفضت خسائر الميثان في النظام بنسبة 27%، مما أدى إلى زيادة استخلاص الميثان إلى 99.93%.

وبفضل تطبيق عملية دمج الحرارة باستخدام التبريد العميق، انخفض إجمالي استهلاك الطاقة في الحالة المُحسَّنة بنسبة 44% مقارنةً بالحالة الأساسية. من جهة أخرى، أدى تطبيق مرحلة استخلاص الميثان إلى تقليل خسائر الميثان في النظام بنسبة 76%، مما أدى إلى زيادة استخلاص الميثان في تيار الغاز الحيوي المُحسَّن من 85.15% إلى 95.91%. مع ذلك، تسبب ذلك في زيادة طفيفة في إجمالي القدرة من 230.7 كيلوواط إلى 241.7 كيلوواط. علاوة على ذلك، بقي الكسر المولي لثاني أكسيد الكربون في الغاز الحيوي المُحسَّن ضمن الحدود المسموح بها.(<3%)

تُظهر المقارنة بين الحالتين أن الطاقة المطلوبة في عملية الأمين أعلى بكثير من تلك المطلوبة في عملية التبريد العميق، بينما يكون استهلاك الطاقة أعلى في عملية التبريد العميق مقارنةً بعملية الأمين، كما أن استخلاص الميثان في عملية الأمين أعلى منه في عملية التبريد العميق. يُشير التحليل الاقتصادي إلى أن عملية الأمين تتميز بتكلفة تركيب أقل من عملية التبريد العميق، ولكن بتكلفة تشغيل أعلى، ومع ذلك، فإن صافي التكلفة الحالية يُرجّح كفة عملية الأمين على عملية التبريد العميق.

الكلمات المفتاحية: عملية تحويل الغاز الحيوي، غاز الميثان الحيوي، لإنتاج الغاز الطبيعي، فصل ثاني أكسيد الكربون، دمج الحرارة.

Introduction

Biomass is biological material derived from living, or recently deceased organisms, which have stored sunlight in the form of chemical energy. This trapped energy can be reclaimed thermally, chemically or biochemically for further utilization. One of the most important energetic uses is the generation of biogas via anaerobic digestion, which contributes greatly to the future realization of a sustainable energy system. Various research projects to improve biogas technologies have been or are being conducted, including seeking alternative feedstock for biogas production [1-2], optimizing and further developing process technologies [3-4], and increasing the end product (biogas and digestate) utilization efficiency [5-6]. Water scrubbing/absorption and amine-based chemical absorption are the most common upgrading technologies. but the large volumes of solvent that are used require significant thermal energy for regeneration. This shortcoming is promoting research on emerging technologies including membranes, calcium looping, catalyzed sorbents, algae-based capture, direct air capture, and liquefaction [7], but most of these technologies face different technological challenges. Cryogenic low-temperature upgrading technologies are still under development; however, they deliver a high methane purity with minimal methane loss (<1%) and a high purity captured CO_2 that usually shows up to 98% purity [8]. Low temperature CO_2 capture technologies, often called cryogenic carbon capture, relies on phase change, thus separating the CO_2 from the gas in the form of a liquid or solid [9].Though cryogenic distillation is the preferred method, it has been reported to consume a total specific energy of 1.79 MJ/kg CO_2 (0.35 kWh/Nm3 of raw biogas) to produce biomethane at a 95.56% capture rate[10-11]. Most efforts have focused on the avoidance of dry ice formation caused by CO_2 cryogenic separation due to potential operation problems caused by the blockage of pipes or other equipment [12-13].

The Amin of this study is to design, and evaluation of technologies related only to separation of CO_2 in biogas upgrading, mainly the amine absorption and cryogenic separation processes. The concept of this work is based on three aspects:

1) Process technology and product quality.
2) Methane recovery and methane losses.
3) Energy consumption and economy.

Material and methods

The methodology followed in this research can be described in the next consecutive sections as shown in Figure (1), where the Aspen HYSYS 11 simulator, Aspen process economic analyzer, Aspen EDR 11, and Excel 2019 were utilized for design, analyzing, and optimization of the project.

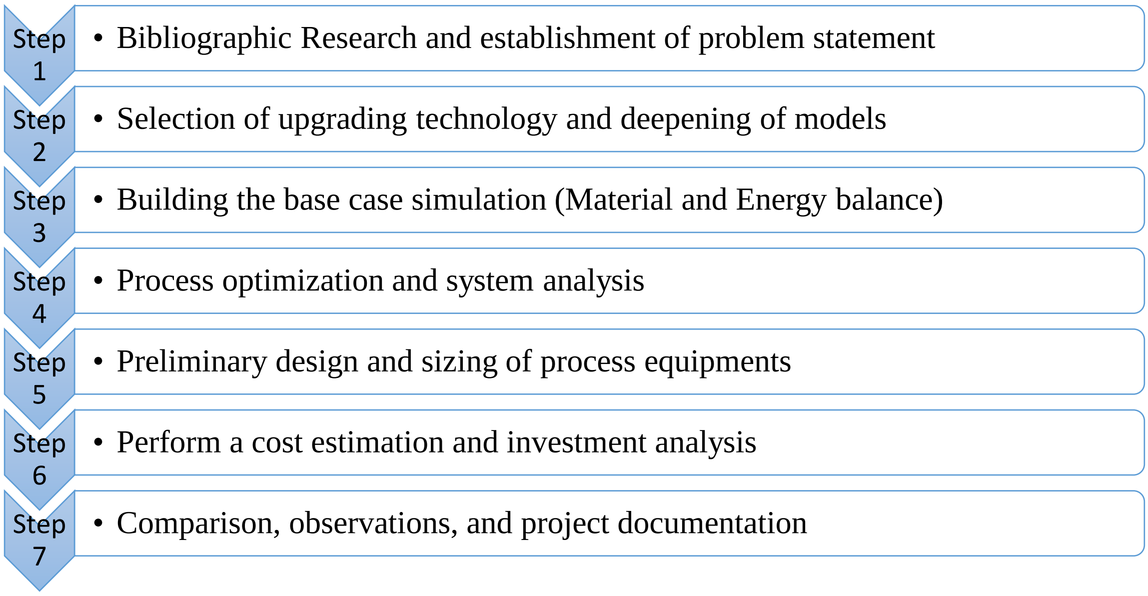

Figure (1): Research methodology.

In the **first stage** of the project, the problem statement is well established and understood, where the plant section to be designed and analyzed, is a part of biogas plant, that treating a stream from a digester system see Table (1), in order to obtain bio-methane with CO_2 concentration compatible with injection into the grid.

Table (1) : Input biogas stream.

Pressure (bar)	1.013
Temperature (C^0)	15
Flow rate (Nm^3/h)	1060
Composition (Vol.%, Dry base)	
Methane	68 %
Carbon dioxide	32 %
Hydrogen sulphyde	NR
Water	Saturated at input T and P

For more realistic, feed specification is collected from a real biogas production plant, which is located in Emilia Romagna / Italy, while the product specification required is decided and selected based on the Italian standard and policies, in order to be injected into the local grid see Table (2).

Table (2): Output biomethane specification.

Pressure (bar)	8
Temperature (C^0)	<20
Composition (mol %)	
Carbon dioxide	$\leq$ 3 %
Water dewpoint	$\leq$ 20 C^0 @ 8 bars

In the **second stage** of the project, select the most propriety technology for biogas upgrading, Amine absorption and cryogenic separation were selected as a case study based on the fact that, the first one is considered as a commercially available technique, while the latter is considered as a most developed and under investigation technique, which would help making the comparison more realistic and effective and consequently the research.

In the **third stage** of the research, material and energy balance are performed using Aspen HYSYS V11 where the base case simulation is built based on the information that has been taken from bibliography in order to meet the product requirements.

In the **fourth stage** of the research, taking the advantage of the useful tools and features available in Aspen HYSYS V11(optimizer, case study tool, and stream utility) which used along with Excel 2019, process optimization is implemented, furthermore, system analysis is performed using stream analysis package, in order to check the operability problems in each node in the plant (i.e., CO_2 freeze out and hydrate formation).

In the **fifth stage**, preliminary design and equipment sizing are performed based on the results of the optimum case simulation using EDR software, vessel and tray sizing features. where the design criterion is made to meet the commercial standards, which would help reduce the extra costs.

In the **sixth stage**, Once the criteria are satisfied and the design is done, the data (such as equipment geometry, configuration, type material of construction…) is transferred into APEA software, which used along with excel 2019, to perform a cost estimation and investment analysis, where net present cost (NPC) is calculated, to include both capital and operating cost for more realistic and reliable result.

In the **seventh stage** the comparison between both cases are carried out, and the observation is extracted and discussed, in order to make the best decision about the best case.

Finally, the project documentation (Results, PFD, and equipment data sheet and sketches), and writing the final report and recommendationsThe materials and methods should be typed in Times New Roman with font size 10 and justify alignment. Author can select Normal style setting from Styles of this template. The simplest way is to replace (copy-paste) the content with your own material. Method and analysis which is performed in your research work should be written in this section. A simple strategy to follow is to use keywords from your title in first few sentences.

Results and discussion

1- Results of Amine Absorption Process

- **Result of material and Energy balance**

Dashboard of the process is shown in Table (3), which is screening the main parameters controlling the entire process, while the results of material and energy balance for the main streams in the process especially the boundary streams is shown in Table (4).

Table (3): Material streams condition and composition.

Name	Feed	Lean Amine	Rich Amine	5	6
Vapor Fraction	1.000	0.000	0.000	0.009	1.000
Temperature [C^{O}]	102.589	44.000	63.700	107.500	43.984
Pressure [bar]	2.600	2.200	2.500	2.450	1.000
Molar Flow [kmol/h]	48.098	650.000	663.441	663.441	15.567
Mass Flow [kg/h]	1196.457	14783.511	15393.315	15393.315	647.371
Liquid Volume Flow [m^3/h]	2.547	14.471	15.217	15.217	0.783
Heat Flow [kcal/h]	-8.41E+06	-1.92E+08	-1.97E+08	-1.94E+08	-5.89E+06
Comp Mole Frac (Methane)	0.66860	0.00000	0.00003	0.00003	0.00128
Comp Mole Frac (CO_2)	0.31463	0.00065	0.02196	0.02196	0.90685
Comp Mole Frac (H_2O)	0.01677	0.94527	0.92503	0.92503	0.09188
Comp Mole Frac (DEAmine)	0.00000	0.05408	0.05299	0.05299	0.00000

Table (4): Continues.

Name	7	WATER MU 1	DEA MU 1	PURGE 1	final product
Vapor Fraction	0.000	0.000	0.000	0.000	1.000
Temperature [^{O}C]	113.113	64.344	64.344	64.737	20.000
Pressure [bar]	1.500	1.450	1.450	1.450	7.950
Molar Flow [kmol/h]	647.874	2.124	0.002	0.000	33.233
Mass Flow [kg/h]	14745.944	38.265	0.233	0.000	560.995
Liquid Volume Flow [m^3/h]	14.434	0.038	0.000	0.000	1.776

Heat Flow [kcal/h]	-1.87E+08	-6.01E+05	-1.05E+03	0.00E+00	-2.82E+06
Comp Mole Frac (Methane)	0.00000	0.00000	0.00000	0.00000	0.96705
Comp Mole Frac (CO_2)	0.00070	0.00000	0.00000	0.00000	0.02972
Comp Mole Frac (H_2O)	0.94504	1.00000	0.00000	1.00000	0.00323
Comp Mole Frac (DEAmine)	0.05426	0.00000	1.00000	0.00000	0.00000

Table (5) shows the results of the energy and power consumption for each individual unit in the process.

Table (5): Energy and power consumption.

Equipment	**Power**
K-100	43.82 kW
P-100	0.4339 Kw
Reboiler	1297 Kw
E-101	332.4 Kw
Total heat and cooler power	1711 Kw
Total compressor power	98.88 Kw

- **Comparison between base case and optimum case**

The optimization was done on the amine solution case study in order to select the amine strength and flow rate. Different amine flow rate at three amine strength (20wt%, 25wt%, 30wt%) were selected to examine and study their influence on the CO_2 fraction in the sweet gas as well as reboiler duty. The results of the Comparison between the optimum case and base case for amine absorption process were summered in Table(6) and graphically depicted in Figures (3and 4).The total energy and power consumption in the optimized case are reduced by 73% and 11% respectively in comparison with the base case, in the other hand the methane losses are in the entire system is reduced by 27% and consequently the methane recovery in the upgraded biogas stream is increased from 99,91% to 99,93%, while the CO_2 mole fraction remains within the limits (<3%), and moreover, even though the methane purity is slightly decreased.

Table (6): Comparison between the optimum case and base case for amine process.

	Base case	**Optimized case**
Total duty (kW)	6436.5	1711
Total power (kW)	111.5	98.88
Methane recovery	99.91**%**	99.93**%**
Methane losses	0.086%	0.062%
Upgraded biogas composition		
Comp. mole percent (CO_2)	2.24%	2.9%
Comp. mole percent (Methane)	97.4%	97%

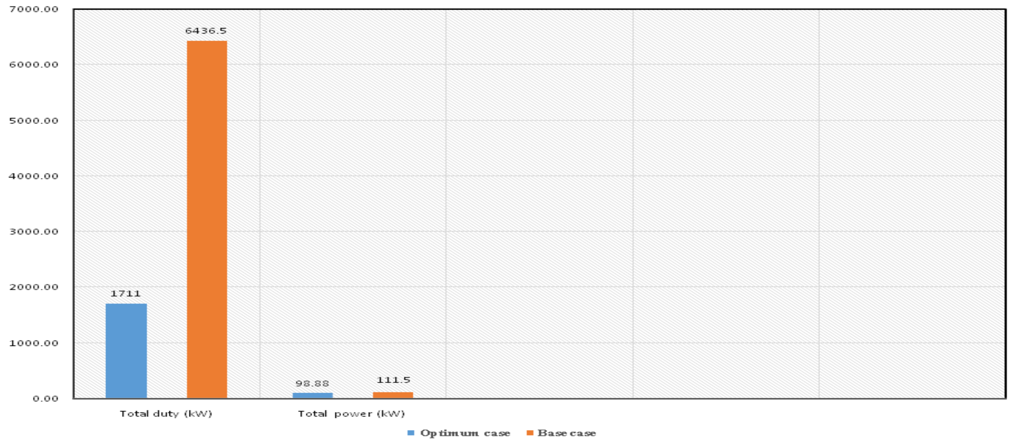

Figure (2): Comparison between the optimum case and base case for amine process.

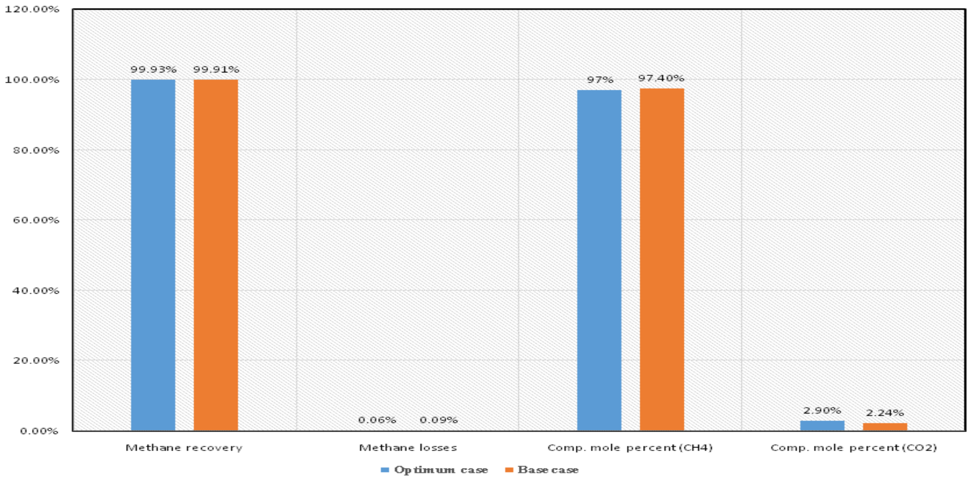

Figure (3): Comparison between the optimum case and base case for amine process.

2- Results of cryogenic separation process

- **Result of material and energy balance**

The material and energy balance of the main streams are shown in the Table (7).

Table (7): Material streams condition and composition.

Name	Dry biogas	feed1	9	13	14
Vapor Fraction	1.000	1.000	1.000	1.000	0.000
Temperature [^{0}C]	15.000	13.728	15.000	-40.000	-40.000
Pressure [bar]	1.030	1.030	72.000	71.850	71.850
Molar Flow [kmol/h]	47.292	51.554	50.769	43.770	6.999
Mass Flow [kg/h]	1183.339	1270.729	1256.553	1042.281	214.272
Liquid Volume Flow [barrel/day]	381.939	412.184	410.038	353.570	56.468
Heat Flow [kcal/h]	-2.01E+06	-2.16E+06	-2.14E+06	-1.78E+06	-4.21E+05
Comp Mole Frac (Methane)	0.67894	0.67815	0.688642	0.72218	0.47891
Comp Mole Frac (CO_2)	0.32106	0.30664	0.311358	0.27782	0.52109
Comp Mole Frac (H_2O)	0.00000	0.01521	0	0.00000	0.00000
Comp Mole Frac (H_2S)	0.00000	0.00000	0	0.00000	0.00000

Table (8): Continues.

Name	20	17	18	Solid	final product
Vapor Fraction	0.498	0.000	0.721	0.000	1.000
Temperature [^{0}C]	-61.662	-61.000	-112.855	-112.855	20.000
Pressure [bar]	30.000	71.700	8.050	8.050	7.900
Molar Flow [kmol/h]	6.999	43.770	43.770	12.231	31.539
Mass Flow [kg/h]	214.272	1042.281	1042.281	515.949	526.332
Liquid Volume Flow [barrel/day]	56.468	353.570	353.570	98.480	255.090
Heat Flow [kcal/h]	-4.21E+05	-1.81E+06	-1.81E+06	-1.16E+06	-6.23E+05
Comp Mole Frac (Methane)	0.47891	0.72218	0.72218	0.06523	0.97693
Comp Mole Frac (CO_2)	0.52109	0.27782	0.27782	0.93477	0.02307
Comp Mole Frac (H_2O)	0.00000	0.00000	0.00000	0.00000	0.00000
Comp Mole Frac (H_2S)	0.00000	0.00000	0.00000	0.00000	0.00000

The results of the energy and power consumption for each individual unit in the process are shown in the Table (9).

Table (9): Energy and power consumption.

Equipment	Power
E-100	136.06 Kw
E-104	44.072 kW
E-107	22.980 kW
E-108	3.0757 kW
K-100	125.6 Kw
K-101	116.1 Kw
Total coolers and heaters duty	206.19 Kw
Total compressors power	241.81 Kw

- **Comparison between base case and optimum case**

As shown in Table (8), due to the implementation of heat integration process the total energy consumption in the optimized case is reduced by 44% in comparison with the base case, in the other hand, implementation of the methane recovery stage reduces the methane losses in the entire system by 76% and consequently the methane recovery in the upgraded biogas stream is increased from 85.15% to 95.91%, however, it causes slight increasing in the total power compression from 230.7 kW to 241.7 kW, moreover,

The CO_2 mole fraction in the upgraded biogas remains within the limits (<3%), even though the methane purity is slightly decreased.

Table (10): Comparison between base case and optimum case for cryogenic separation process.

	Base case	Optimized case
Total duty (kW)	371.8	207.9
Total power (kW)	230.7	241.7
Methane recovery	85.15%	95.91%
Methane losses	14.61%	4.09%
Upgraded biogas composition		
Comp. mole percent (CO_2)	1.35%	2.31%
Comp. mole percent (Methane)	98.65%	97.69%

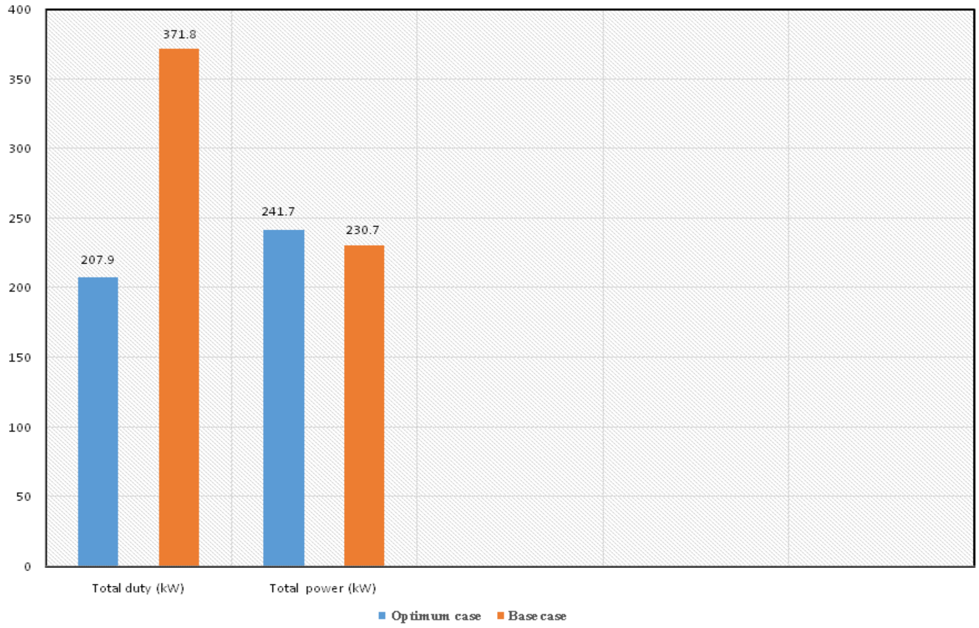

Figure (4): Comparison between base case and optimum case for cryogenic process.

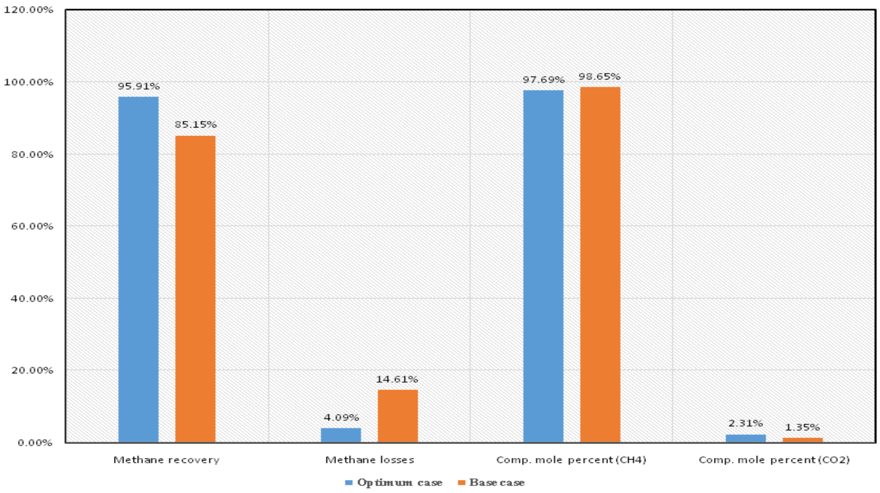

Figure (5): Comparison between base case and optimum case for cryogenic process.

- **Result of stream analysis and type**

The result of stream analysis in terms of CO_2 freeze out formation, two phase critical pressure and temperature as well as the state of aggregation are shown in the Table (11 and 12) respectively. It is clearly seen that the CO_2 freezer would only occur at the desired point.

Table (11): CO_2 freezer analysis.

Analysis	**Stream temperature (^{0}C)**	**Freezing temperature (^{0}C)**	**Status**
CO2 Freeze Out (12)	-40	-66.8	Not formed
CO2 Freeze Out (20)	-61.6	-61.8	Not formed
CO2 Freeze Out (16)	-48	-70.6	Not formed
CO2 Freeze Out (17)	-61	-70.6	Not formed
CO2 Freeze Out (18)	-112.9	-59.16	Formed

Table (12): Envelop analysis.

Analysis	**Stream temperature (^{0}C)**	**Stream pressure (bar)**	**Critical Pressure (bar)**	**Critical Temperature (^{0}C)**	**State**
Envelope (12)	-40	71.8	73.21	-44.38	Vapor + Liquid
Envelope (20)	-61.6	29	88.54	-16.31	Vapor + Liquid
Envelope (16)	-48	71.7	70.02	-48.58	Vapor
Envelope (17)	-61	71.65	70.02	-48.58	Vapor
Envelope (18)	-112.9	8.050	70.02	-48.58	Vapor + Solid

3- Comparison between amine absorption and cryogenic separation

Table (13) and Figures (13 and 14) shows the results of techno-economic comparison between amine absorption and cryogenic separation biogas upgrading, where the energy required in the amine process is much higher than that in the cryogenic process due to the high energy required for regeneration of the amine, while the power consumption is higher in the cryogenic process than amine process, because it is carried out at elevated pressure. Methane recovery in the amine process is higher than in the cryogenic process, even though the upgraded biogas purity is slightly less, but the CO_2 fraction in both cases is still within the limits. Economic analysis shows that the amine process has a lower installation cost than the cryogenic process but higher operation cost, however, the net present cost shows a preference for the amine process over the cryogenic process.

Table (13): Comparison between amine absorption and cryogenic separation.

	Amine absorption	**Cryogenic separation**
Total duty (kW)	1711	206.19
Total power (kW)	98.88	241.81

Methane recovery	99.93%	95.91%
Methane losses	0.062%	4.09%
Operating cost (USD/Year)	2,398,660	1,931,910
Fixed capital cost (USD)	2,883,800	3,659,600
Net present cost (USD)	8,456,510	9,681,910
Upgraded biogas composition		
Comp. mole percent (CO_2)	2.9%	2.31%
Comp. mole percent (CH_4)	97%	97.69%

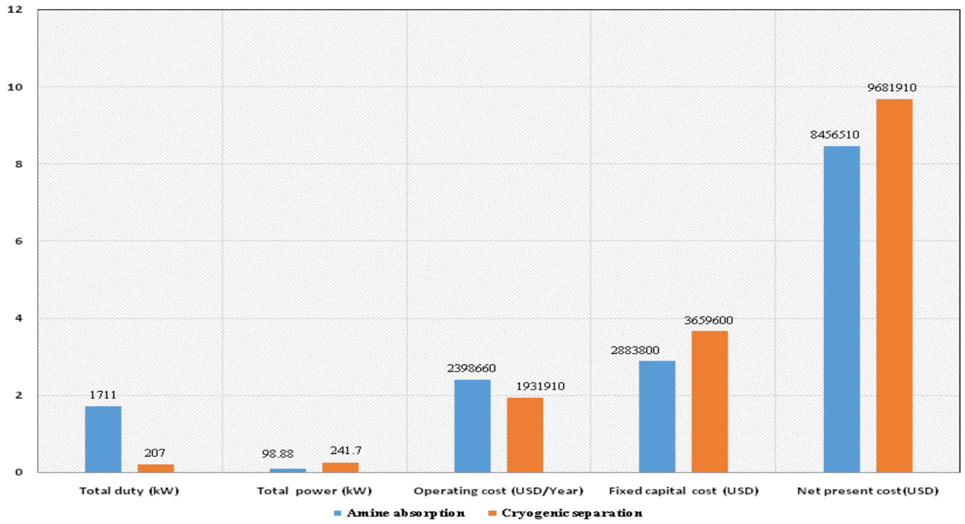

Figure (6): Comparison between amine absorption and cryogenic separation in terms of power, duty and cost.

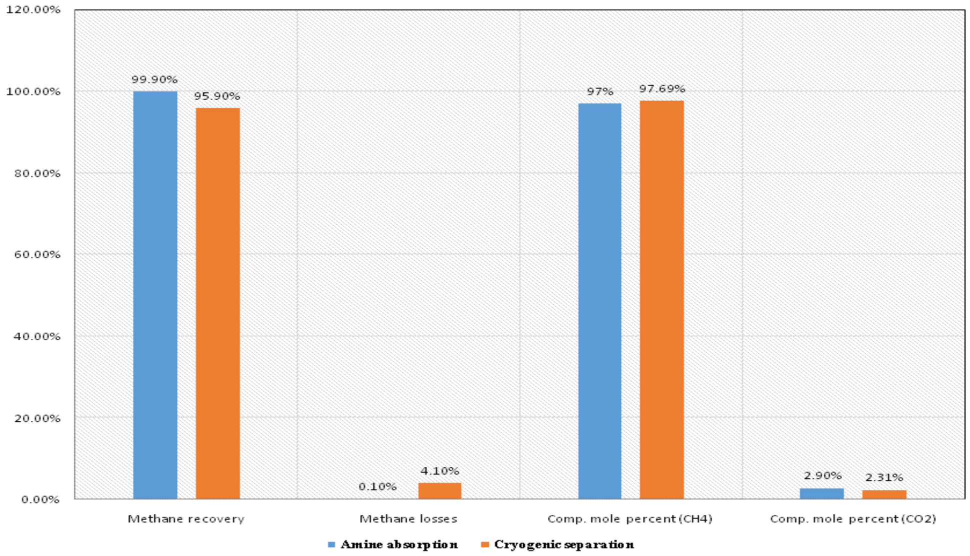

Figure (7): Comparison between the amine absorption and cryogenic separation in terms of methane recovery, loss and purity.

Conclusion

Objective of the present research was a techno-economic comparison between amine absorption and cryogenic separation process. The two biogas upgrading techniques were examined in order to check the applicability and select the best option. Three aspects were chosen for the assessment: (1) process technology and product quality, (2) methane recovery and methane losses (3) energy consumption and economy.

The simulation results show that both techniques can be applied, and they were similar in terms of product quality, based on, the amine absorption has more preference over the cryogenic separation in terms of methane recovery and economy.

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