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Technical and economic assessment of processes for the LNG production in cycles with expander and refrigeration

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Abstract

Optimized liquefied natural gas (LNG) process can be helpful for better energy and cost saving for gas transportation and storage. In this study, different layouts of LNG units are examined technically and economically so that with the specific and combined refrigerants, the least amount of energy can be consumed in the LNG unit. Two optimized LNG production processes were selected and compared. In Case 1, the expander is used for preventing energy loss in joule Thomson phenomena, and in Case 2, precooling was performed for better integration of heat. The study used Aspen HYSYS software to simulate the process and Aspen Capital Cost Estimator (Icarus) for economic analysis. According to the economic analysis of the energy and the process of these two cases, Case 2 is better in economic terms and energy consumption. This simulation is for an LNG unit with a capacity of 1000 tons per day. Total costs (including direct and indirect) in Case 1 and 2 are 152 and 130 USD/Tone, respectively. This issue is related to use of the compressors and turbo-expanders in Case 1.

Keywords LNG unit · Refrigeration cycles · Technical and economic analysis

Abbreviations

LNG	Liquefied Natural Gas
CAPEX	Capital expenditures cost
OPEX	Operating expenditures cost
NG	Natural Gas
CNG	Compressed Natural Gas
GTL	Gas to Liquids
NGL	Natural Gas Liquids
LPG	Liquefied Petroleum Gas
MR	Mixed refrigerant

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MR	Mixed refrigerant
N2	Nitrogen
CO2	Carbon dioxide
H2S	Hydrogen sulfide
H2O	Water
MEA	Mono ethanolamine
DEA	Diethanolamine
DEG	Diethanolamine
TEG	Three ethylene glycol
I-BUTANE	Isobutane
N-BUTANE	Normal butane
N-PENTANE	Normal pentane
APCI	Air Products and Chemical Incorporated
DMR	Double Mixed Refrigerant
PPMR	Propane Pre-Cooled Mixed Refrigerant
C3MR	Multi-Component Refrigerant
MCR	Multi-Component Refrigerant
POCLP	Phillips Optimized Cascade LNG Process
MFCP	Mixed Fluid Cascade Process
PFHE	Plate-Fine Heat Exchanger
CAMEL LNG	Companies Algerine de Methane Liquide
SMR	Single Mixed Refrigerant

1 Introduction

One of the energy sources is natural gas in underground reservoirs (Jabareen, 2008; Tlili, 2015; Raza & Shah, 2020). Today, due to the lack of this valuable energy resource in the whole world, finding an optimal process to transport this energy source has become very vital today (Jacobsen, 2009; Abdoli et al., 2018; Thomas & Dawe, 2003; Javanmardi et al., 2006).

In the last two decades, natural gas has been the fastest-growing energy source in most parts of the world, with low greenhouse gas emissions and high energy efficiency (Barza et al., 2020; Barza et al., 2018; Parfomak, 2003). In the last three decades, however, only the natural gas liquefaction industry has been successful in achieving the very large remote gas fields that could not be accessed by pipelines (Stenning & CranStenning, 2000; Chatti et al., 2005). Today, the LNG supply chain has developed and competes with the markets that were previously occupied by pipelines (Sloan & Koh, 2007; Gudmundsson et al., 1998).

On the other hand, the need for gas as a clean fuel in petrochemical units is increasing day by day around the world (Mokhatab & Purewal, 2006; Mokhatab & Economides, 2006; Pillarella et al., 2007; Manrique et al., 2019). But its transfer to long distances through the pipeline has many technical and economic limitations. One way to solve this problem is to liquefy natural gas (Wang et al., 2019; Ancona et al., 2020). In this regard, attention to natural gas (NG) as a source of clean energy is expanding. With about 16 percent of the world's natural gas reserves, Iran is the second-largest gas reserve in the world, and its lifespan is estimated to be more than 100 years (Sanaye & Ghoreishi, 2019; Salehi, 2018; Al-Sobhi et al., 2018; Fazlollahi, 2016). For this reason, the need for optimal use of this energy is felt for domestic consumption (instead of petroleum products) (Sabbagh et al., 2020; Nagy, 2016). One of the most important issues in the natural gas industry is the issue of natural gas transmission and storage. Natural gas transmission is done in two ways: liquefaction and piping. Gas transmission over long distances (above 4000 km) through piping is not appropriate and liquid transport must be applied (Nagy, 2016; Zhang et al., 2020). LNG is the best technology for gas transmission over long distances (Zhang et al., 2020). As the distance of gas transmission to the consumer market increases, the use of LNG becomes more economical (Park et al., 2020).

LNG is obtained from the liquefaction of natural gas in refrigeration cycle up to − 162 °C. It is an odorless, colorless, non-corrosive, and non-toxic liquid. LNG is comprised from the methane, ethane, propane, butane and nitrogen. In the process of liquefaction, the volume of gas decreases by about 600 times. Thus, gas can be transported in liquid form to supply in distant markets and places, where it is not possible to transport gas through the pipeline (Park et al., 2020; He & Ju, 2015; Castillo & Dorao, 2010). Liquefied natural gas is produced when natural gas is cooled in a process called "liquefaction" to approximately − 162 °C. During this process, liquid natural gas cools below its boiling point. In this case, some hydrocarbons, water, carbon dioxide, oxygen and some sulfur compounds settle in leave the gas (Mokhatab et al., 2013; Kumar et al., 2011).

Propane pre-cooled mixed refrigerant (C3MR) is currently the leading process for natural gas liquefaction. It is typically designed with high efficiency for base-load plant and used for medium and large-scale plants. In this regard, for many years, there was not a new refrigerant for liquefying gases, so C_3MR was the best choice. Interestingly, the same process was again used with minor advances in the process cycle, sometimes with larger turbines and for greater capacities (Sanavandi & Ziabasharhagh, 2016). However, C_3MR technology has now reached technical limitations such as the maximum load in the propane compressor, larger cooler and spiral exchangers. Therefore, at the moment, due to these limitations and to optimize the natural gas liquefaction processes, new processes are expanding and supplying (Sanavandi & Ziabasharhagh, 2016; Primabudi et al., 2019).

The methods used to produce LNG can be divided into two general forms. One is the direct compression and expansion of the gas, and the other is the use of a refrigerant as natural gas refrigeration, which is a better way to use a refrigerant but is more cost-effective. Non-refrigeration methods are important for expansion on offshore platforms and on LNG carriers. Because they take up less space and are therefore more economical (Sanavandi & Ziabasharhagh, 2016; Primabudi et al., 2019; Asadnia & Mehrpooya, 2017). On the other hand, choosing the best method depends on the purpose of the LNG plant. Since in some LNG factories, a lot of electricity is required, current costs play a decisive role in selection and optimization (Lim et al., 2013). Zhou et al. investigated the advantages and disadvantages of expander cycles and multi-component refrigerants with the same conditions. After optimizing these processes, they finally introduced the expander cycle as a suitable cycle for liquefaction in offshore areas (Zhu et al., 2019). Neeraas and Marak examined the disadvantages of five experimental processes and compared the results with each other, concluding that the expander cycles were not suitable for small-scale applications due to their simplicity and safety. On the other hand, the multi-component refrigeration processes, in particular dual multi-component refrigerants, are suitable for large-scale applications (Neeraas & Marak, 2011).

Narasimhan et al. (2011) selected a Jules Thomson refrigeration process for a single-stage mixed refrigerant and investigated the effect of a combination of refrigerant components and equipment on cycle performance. The purpose of this experiment was to find the best and most suitable combination for the initial charge of the cycle by examining different combinations and their effect on various cycle parameters. They conducted study with seven different hydrocarbon refrigerant compounds and concluded that one compound may have a favorable effect on one part but adverse effects on others. Also, with an optimal compound, it is not always possible to optimize the system because the cycle performance will depend on the equipment used in the system in addition to the composition. Mortazavi et al. (2014) investigated dual-mixture refrigerants and simulated the process to determine the optimal operating conditions for the process. In their study, the optimal conditions for the DMR cycle were evaluated through considering the efficiency. For this, a model of the cycle was developed for single mixed refrigerant (SMR) cycle.

Ghorbani and coworkers (2018) investigated the integration of LNG structure in the modified refrigeration cycle for precooling, and mixed component refrigerants for main cycles in gas liquefaction process. This precooling system has been simulated and evaluated for optimization of energy and reduction of cost. Their results show that this precooling system can reduce the amount of capital cost, specific power and prime cost of product by 31.9, 38.9 and 15.31%, respectively.

In another study, Ghorbani and et al. (2018) modified the LNG production process with an absorption refrigeration system integrated with precooling compression refrigeration cycle. They found the LNG production flow rate and energy consumption can decrease by 6.1 and 0.6%, respectively. Also, their results state that electrical efficiency, net overall thermal efficiency, exchanged heat with refrigeration cycle and mass flow rate of LNG are reduced by 2.2, 7.1, 1.6 and 4.3%, respectively.

Therefore, it could be found that the refrigeration cycle and precooling system can be affected on performance of liquefaction system, power consumption and efficiency of refrigeration cycle, etc. The results of this impacts can be changed investment, capital cost and economic analysis of LNG production process.

Also, the setting of influential factors contributes to choose the most suitable process for establishing Mini LG: simplicity of operation, process safety, the life cycle of plant and easiness of operation, and the arrangement and type of equipment, general plot plan and energy consumption. The liquefaction process with turbo-expander in mixed refrigerant cycle can be good choices to be used in Mini LNG. However, using of precooling system in this process can be effective of energy consumption (Neeraas & Marak, 2011; Narasimhan & Venkatarathnam, 2011; Mortazavi et al., 2014; Ghorbani et al., 2018; Ghorbani et al., 2018).

According to the above explanations and due to the complexities involved in the LNG productions with related refrigeration cycles, the main objective of this research was to apply technical, economic, and energy analyses to specify the best conditions to minimize energy consumption and optimize capital investment. To our best knowledge, this is the first study to simulate, model and optimize the various refrigeration and liquefaction conditions for minimizing energy consumption, maximizing the liquefied gas transport capacity, and optimizing the capital cost of processing plants. In this regard, Aspen HYSYS, Refprop, Aspen Capital Cost Estimator, and Energy analyzer software have been used for process simulation, economic evaluation and energy analysis, respectively. Therefore, the employed technique and developed procedures can be used as useful tools for design and optimization of appropriate liquefaction and transportation technology with effective performance for various industrial applications such as LNG and compressed natural gas (CNG), etc.

2 Methods and procedures

2.1 Technical and economic simulation and analysis

In this study, the LNG processes (with the capacity of 1000 tons per day) are investigated, considering the optimized refrigerants to obtain energy and cost in the LNG production unit. The technical analysis of LNG production processes with various refrigerants was performed. In this process, the content of different refrigerants was also investigated. Moreover, the economic analysis of these processes, leading to higher efficiency LNG production, was performed. All technical analysis was performed by Aspen HYSYS simulation. Also, economic analysis was performed using Icarus software and finally compared and validated with existing models.

The refrigeration cycle of the natural gas liquefaction unit, like other refrigeration processes, is a continuous process, meaning that refrigerant completes a full cycle, including condensation, heat exchanger, suppression valve, and condenser, to cool natural gas. Applying the slightest change in the natural gas liquefaction process will cause fundamental changes in the various equipment of the liquefaction unit. Therefore, there are ideas to improve the performance of the liquefaction unit, which is necessary to simulate the liquefaction unit of natural gas. In this process, the refrigerant enters the heat exchanger and exits from two separate points, expands by the turbine, and then re-enters the exchanger. Finally, the refrigerant is compressed and cooled in two stages after leaving the exchanger. It is then re-compressed in two compressors. Finally, it is cooled and entered the exchanger.

In this paper, Aspen HYSYS V10 software was used to simulate processes. One of its important features is that it can answer any engineering issues in different industries. This software is very powerful for modeling stable models. Peng Robinson is used as a fluid package in both simulations. This package is the most practical model in this software, which covers a wide range of temperatures and pressures, and is a reliable and proven package for the design of refineries.

After simulating the process, the result is import to Aspen Capital Cost Estimator or Icarus software for economic analysis.

Aspen Capital Cost Estimator (ACCE or ICARUS) was applied to size, map and estimate the cost of plants (equipment and bulk materials, etc.). The ACCE is applied to predict the direct and indirect costs and investment requirements of various projects. Its pricing basis, economic models and database library have been updated from qualified databases and libraries such as Richardson's WinRace International. This software provides the possibility of process and mechanical design of heat exchangers and preparation of construction plans, evaluation and troubleshooting of existing exchangers, simulation of existing exchangers and technical and economic estimation of construction of a special heat exchanger (Lee et al., 2012; Nguyen et al., 2021; Rezaie et al., 2020; Saleh et al., 2019; Shayan et al., 2020; Nguyen et al., 2020).

2.2 Description of the LNG production process

2.2.1 Description of case 1

Case 1 is designed to produce LNG (energy intake and temperature reduction). In this regard, the feedstock is imported at a temperature of 32 °C and a pressure of 55.13 bar with a certain flow. Cold flow through the rotating cycle lowers the temperature. On the other hand, MR, as a mixture of methane, ethane, propane, and nitrogen (Fig. 1), is used as the coolant. In addition to cooling the feed, it is used as a compressed MR cooler. Due to the high temperature and pressure inside of the compressor, the temperature must be reduced. This continues to an increase in pressure and a decrease in temperature to 28 °C. After leaving the LNG, the feed enters the heat exchanger, and the feed gas is cooled by MRI refrigerant and exchanged at – 108 °C. Also, the temperature is reduced from – 90 to – 100 °C. The feed is cooled in the second heat exchanger. In essence, the refrigerant of this heat exchanger is the coldest refrigerant in the conversion cycle; therefore, the temperature reaches – 113.5 °C.

To separate the LNG from the gas flow, the outlet flow from the pressure reducing valve must be inserted into the separator to separate the desired product. It should be noted that when the separator separates the LNG flow from the gas phase, the output is at the atmospheric pressure.

Due to its low temperature, the exhaust gas is used for cooling. This gas is extracted as methane and used as fuel for turbochargers.

MRI is a cyclic process that begins with the compression of a gas. MRI is known as the first stage of compression, in which the temperature will be 25 °C and the pressure 10.5 bar. The values of temperature and pressure are exactly the same of temperature and pressure of the gas. After passing through the first stage of the compressor, the temperature and pressure would reach 98.82 °C and 20 bar, respectively. MRI then enters the cooler and lowers the temperature to – 25 °C. The cooled gas enters the second stage of the compressor, and this cycle rotates. The schematic of the Case 1 simulation is shown in Fig. 1.

2.2.2 Description of case 2

The applied gas in Case 2 has similar features like the gas in Case 1. In Case 2, there is a pre-cooler which increases the pressure. Increase in the pressure results in a higher temperature. The cooler is used to balance the temperature similar to its initial value. The schematic of the Case 2 simulation is shown in Fig. 2.

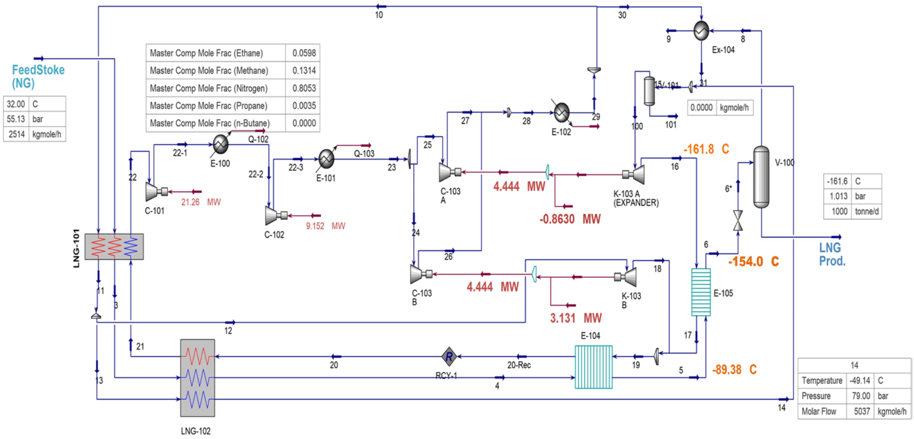
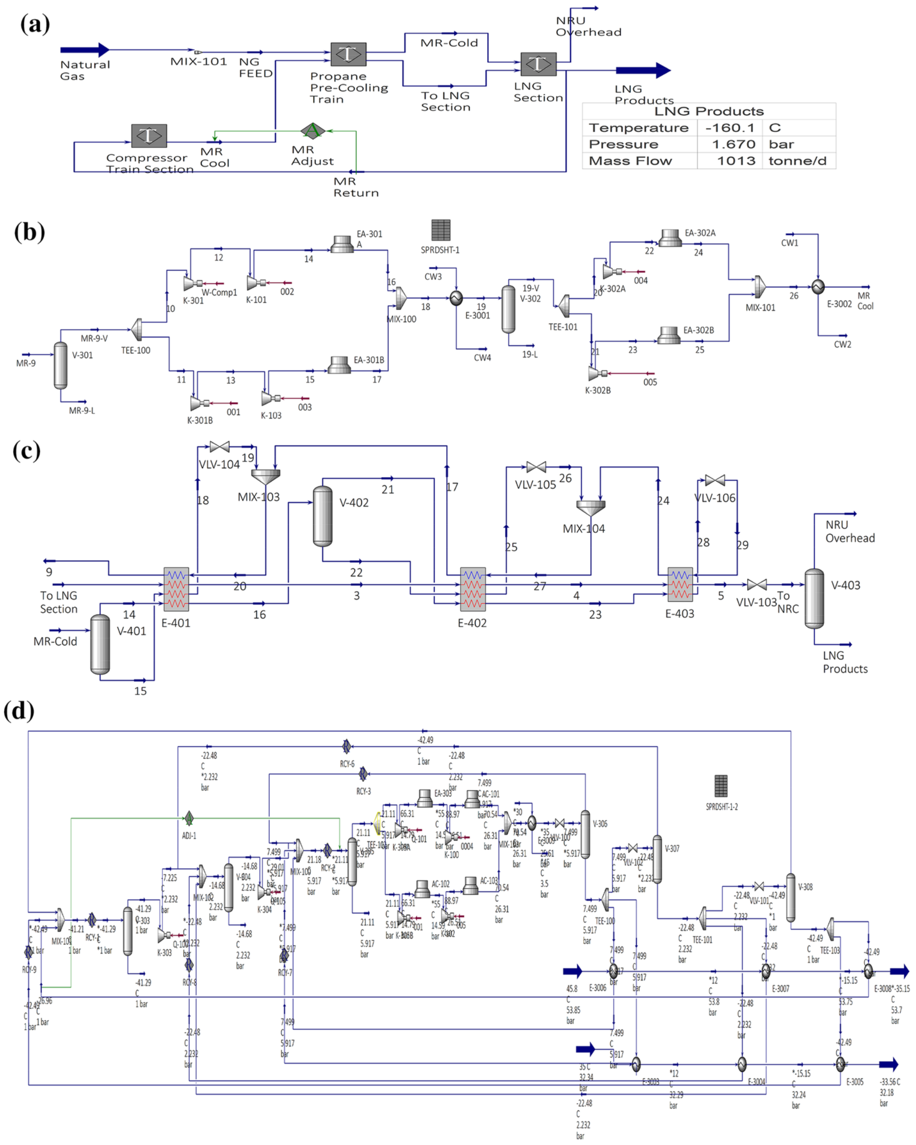


Fig. 1 Schematic process flow diagram and simulated LNG production in Case 1



LNG Products		
Temperature	-160.1	C
Pressure	1.670	bar
Mass Flow	1013	tonne/d

Fig. 2 Schematic process flow diagram and simulated **a** LNG production and sub-flowsheets of LNG process; **b** Compressor Train Section; **c** LNG Section; **d** Propane Pre-Cooling Train in Case 2

The propane cycle is a set of coolers and compressors. The pressure of propane gas was increased and re-pressurized in several stages. When the pressure rises, it is necessary to lower the pressure with the propane cycle. This causes the surrounding energy to be taken up into LNG type exchangers and the natural gas temperature to be reduced when the pressure is lowered. This decrease in temperature finally reaches to -35 ˚C.

Then in the Mix-ref section of the combined refrigerant cycle, as in the combination of Case 1 in the LNG unit, the simulation process takes place, so that the LNG temperature decreases and using Mix-ref, which is high pressure, it appears in three steps:

- Step 1 → Temperature of – 111°C
- Step 2 → Temperature of – 111.8°C
- Step 3 → Temperature of – 154°C

In the last section, there is a Joule–Thomson valve, which causes the pressure to be equal to the 1.6 bar and the temperature to – 160 °C. In this section, LNG is produced 1000 tons per day.

The compressors in this path compress the refrigerant and prepare it for LNG cooling. There are three stages for the compressor. First, the gas is compressed, and finally, the compressed gas is liquefied. In the LNG section, the refrigerant is evaporated at different stages and in different exchangers (or so-called flashes). Then, in each heat exchanger, it takes up the energy of the natural gas fluid to evaporate, leading in the occurrence of cooling and liquefaction process. The difference between Case 1 and Case 2 is that, in Case 2, propane cycle has been added and the initial pre-cooler is the temperature changes ranging from – 133 to – 160 °C, resulting in reduced energy exchange load. Another difference is that Case 1 uses an expander instead of a Jules–Thomson valve, which converts wasted power into compressor power.

3 Results and discussion

The problem with liquefaction cycles is their high energy consumption. The goal was to reduce energy consumption in gas liquefaction processes. The components involved in the cycle are numerous and varied and working on each may result in controversial results. What is considered from the beginning was the optimal percentage of refrigerant used in the refrigeration cycle, which inevitably includes an expander and a compressor. Expander energy has been used to provide the required power for the compressor.

3.1 Technical evaluation and comparison

In Case 1 simulation, a combined refrigerant process was observed in Aspen HYSYS software, providing the energy required for the compressors from the expander and the pressure in the refrigerant cycle.

A part of the energy optimization in Case 1 is provided by the expander for compressor power (K-103). The expander (K-103B) provides about 1.3 MW of the required energy for the compressor. In addition to refrigerators, one part of the energy was provided for cooling. In the Case 2 simulation, since there is a pre-cooler cycle, some energy loads were taken from this cycle. As a result, the energy load for the LNG section is not high and therefore the costs do not increase. In fact, it can reduce the economic burden. However, Case 1 expander is not in this process, and this is the difference between the two Cases.

Table 1 Direct and indirect costs of LNG in (a) Case 1 and (b) Case 2

(a) Overall Project Summary-Case 1

		Unit	Man-hours	Wage rate (USD)	Labor cost (USD)	Unit Material	Material cost (USD)	Total (USD)
(2) Equipment	15 ITEM(S)	496.4	7,446	32.70	243,462	2,645,080	39,676,200	39,919,662
(3) AG Pipe	1,407 M	9.0	12,704	31.97	406,190	1,033	1,453,422	1,859,612
(4) Piling	71 EACH	8.2	582	28.38	16,532	922.30	65,483	82,015
(4) Concrete	693M3	8.6	5,957	25.87	154,138	259.54	179,936	334,074
(4) Grout	1.8M3	166.0	296	24.59	7,267	3,942	7,016	14,283
(5) Steel	2.2 TONNE	46.8	101	30.01	3,033	8,262	17,845	20,878
(6) Instrumentation	314 EACH	21.1	6,638	32.53	215,956	2,801	879,389	1,095,344
(7) UG Electrical	348 M	1.7	584	29.11	16,993	30.07	10,473	27,466
(7) AG Electrical	17,753 M	0.57	10,148	31.49	319,509	206.08	3,658,524	3,978,033
(8) Pipe Insulation	1,638 M	1.6	2,674	23.97	64,100	95.85	156,972	221,072
(8) Equip Insulation	412M2	5.0	2,063	23.94	49,390	85.36	35,164	84,554
(9)Paint	1,919M2	0.61	1,165	23.93	27,869	6.50	12,472	40,341
Direct Totals			50,358		1,524,438		46,152,897	47,677,335
Const Equip & Indirects								1,221,100
Const Mgt, Staff, Supv			7,746					710,600
Freight								1,846,100
Taxes and Permits								2,884,601
Engineering			20,579					2,318,400
Other Project Costs			1,091					3,231,356
Contingency								10,780,109
Indirect Totals			29,416					22,992,266
Project Totals:			79,774		1,524,438		46,152,897	70,669,600

Table 1 (continued)

(b)Overall Project Summary-Case 2

		Unit	Man-hours	Wage rate (USD)	Labor cost (USD)	Unit Material	Material cost (USD)	Total (USD)
(2) Equipment	40 ITEM(s)	249.3	9,972	32.71	326,145	749,790	29,991,600	30,317,745
(3) AG Pipe	3,683 M	6.3	23,282	31.97	744,298	497.79	1,833,149	2,577,447
(4) Piling	111 EACH	9.7	1,072	28.38	30,438	922.30	102,375	132,813
(4) Concrete	745M3	9.9	7,345	25.80	189,492	268.11	199,635	389,128
(4) Grout	3.2M3	181.5	586	24.59	14,418	3,965	12,807	27,225
(5) Steel	17.0 TONNE	46.2	785	30.01	23,550	8,216	139,661	163,211
(6) Instrumentation	804 EACH	20.2	16,258	32.52	528,715	2,548	2,048,594	2,577,309
(7) UG Electrical	858 M	1.2	1,004	28.83	28,945	21.80	18,709	47,654
(7) AG Electrical	28,314 M	0.63	17,749	31.52	559,466	173.07	4,900,396	5,459,862
(8) Pipe Insulation	4,467 M	1.4	6,284	23.98	150,692	64.35	287,471	438,163
(8) Equip Insulation	1,514M2	3.3	4,929	23.81	117,365	61.59	93,254	210,619
(9)Paint	8,358M2	0.55	4,620	23.81	109,995	5.71	47,686	157,681
Direct Totals			93,886		2,823,520		39,675,338	42,498,858
Const Equip & Indirects								2,260,600
Const Mgt, Staff, Supv			13,261					1,222,200
Freight								1,587,000
Taxes and Permits								2,479,701
Engineering			50,685					5,710,801
Other Project Costs			2,085					3,370,212
Contingency								10,643,288
Indirect Totals			66,031					27,273,802
Project Totals:			159,917		2,823,520		39,675,338	69,772,661

3.2 Economic analysis

After simulating the LNG production unit, a study using Aspen Icarus software was performed to obtain the initial estimate of the economic viability of the process. Both Aspen HYSYS and Icarus software are manufactured by the same company, so the process information can import from Aspen HYSYS to the Icarus. In Table 1, all the information about the construction and installation of the given equipment is given.

The investments made by the software for LNG production are reported in the following tables. Engineering design includes all the processes, mechanics, instruments, electrical, and other disciplines performed to design a unit. Procurement includes all the activities for purchasing, installing, and transporting equipment and bulk materials. Installation is in-site construction, involving materials, person per hour, and human resources. In industry, these activities are called EPC. Tables summarizing project costs by the contractor involve more precise costs, including equipment, piping, construction, reinforcement, insulation, electrical work, and painting. Finally, the total cost of the project is derived from the sum of the total, indirect, and direct costs. Of course, it should be noted that engineering costs as well as other miscellaneous costs are also included.

According to the results in Table 1, the direct, indirect, and total capital costs of LNG in Case 1 were 47,677,335, 22,992,266 and 70,669,600 USD, respectively. Also, the direct, indirect and total costs of LNG in Case 2 were estimated at 42,498,858,

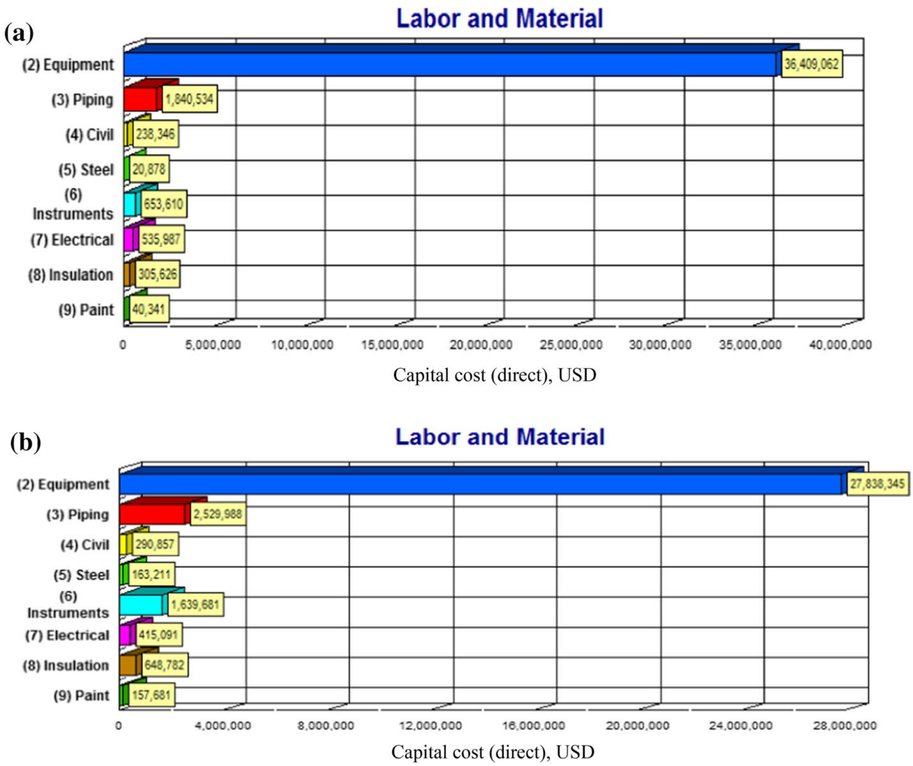


Fig. 3 Costs of total material and costs of installing various LNG equipment in **a** Case 1 and **b** Case 2

27,273,802 and 69,772,661 USD, respectively. Therefore, it is observed that in Case 2, costs were significantly reduced compared to Case 1. This is because Case 2 does not have an expander, and cooling is done in two steps. Costs of total material and costs of installing various LNG equipment in (a) Case 1 and (b) Case 2 are given in Fig. 3.

According to this figure, in the payroll chart in Cases 1 and 2, the highest cost is allocated to the cost of installing the equipment. Checking the material cost, it could be found that the highest cost is related to the purchase of equipment. In Case 1, there is an expander, so it costs more than Case 2. Equipment cost diagrams for different types of LNG are shown in Fig. 4.

In this figure, the cost of each piece of equipment is given separately. It could be found that the highest price is related to the main tower (C-101) and the lowest is related to the exchanger. Prices of all equipment in LNG in Case 1 and Case 2 are given in Fig. 5a and b, respectively. Since different pieces of equipment are required to produce LNG, this figure shows how much of the project cost is related to both the purchase cost and the wage of different equipment. As can be seen in these figures, the highest

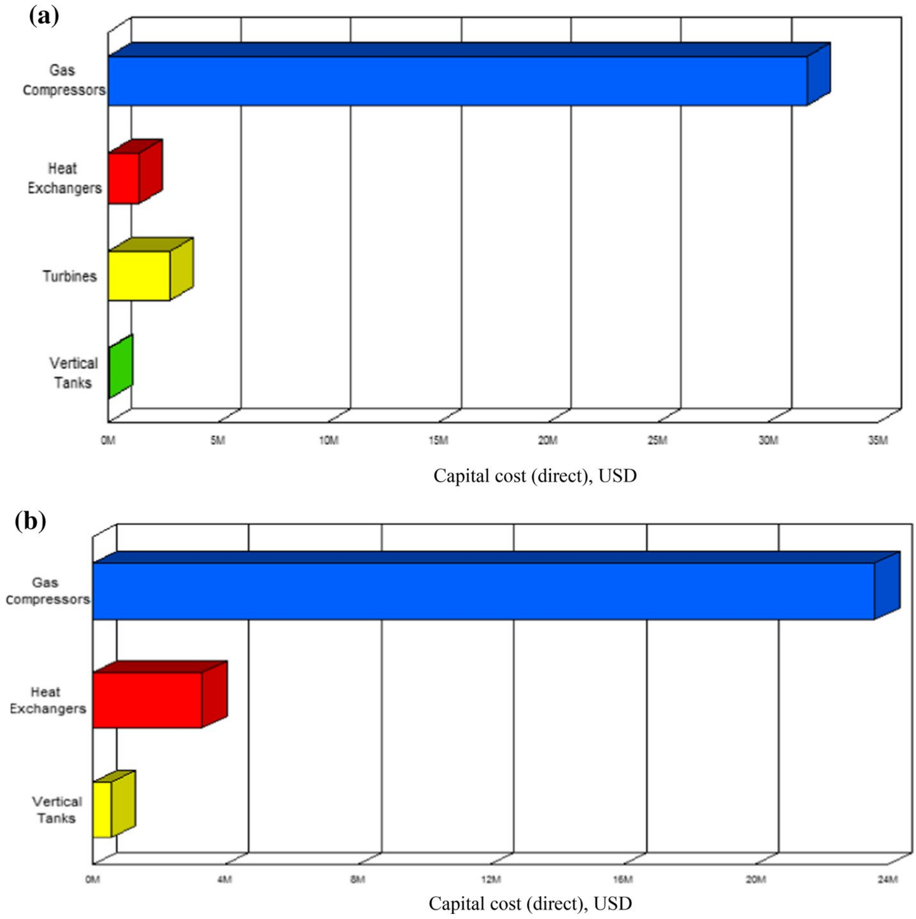


Fig. 4 Equipment cost diagram according to the different types of LNG in **a** Case 1 and **b** Case 2

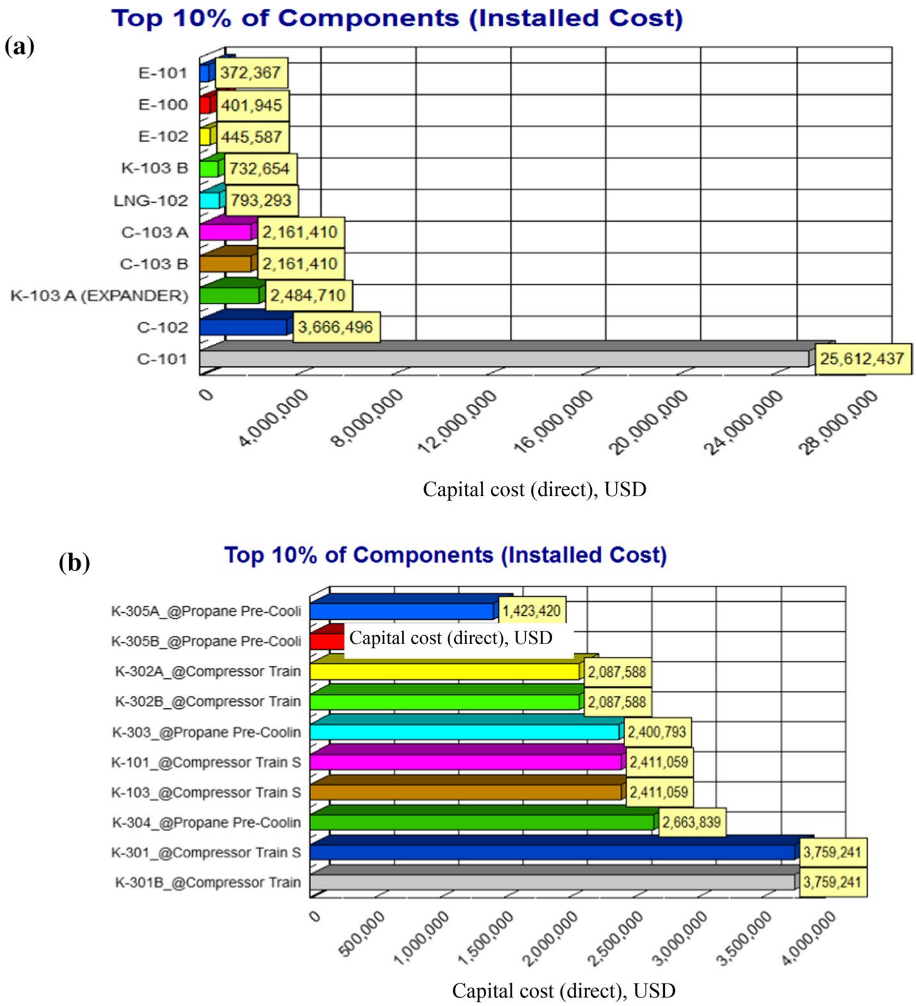


Fig. 5 Prices for each equipment separately in LNG in **a** Case 1 and **b** Case 2

cost is related to gas compressor exchangers and the lowest cost is related to vertical containers.

3.3 Process energy analysis

In Case 1, the energy consumption of all facilities is 40.68 MW, and in Case 2, it is 20 MW. Moreover, the exhaust gases of Case 1 are 392.8 tons per day, but in Case 2, they are 193.1 tons per day. The energy consumption in Case 1 is twice that of Case 2. Energy consumption in different cases is shown in Table 2.

As can be seen, the actual energy consumption of Case 1 is much higher than Case 2. This is because, in Case 1, turbo-expander and compressors have a lot of power consumption. Case 1 has more cooling energy than Case 2, which is due to the higher total number of facilities. In

Table 2 Energy consumption in (a) Case 1 and (b) Case 2

Property	Actual	Target	Available savings	% of Actual
Total Utilities [MW]	40.68	41.76	− 1.08	− 2.66
Heating Utilities [MW]	0	0	0	0
Cooling Utilities [MW]	40.68	41.76	− 1.08	− 2.66
Carbon Emissions [tonne/d]	392.8	403.4	− 10.6	− 2.7
Property	Actual	Target	Available savings	% of Actual
Total Utilities [MW]	20	20.14	− 0.14	− 0.73
Heating Utilities [MW]	0	0	0	0
Cooling Utilities [MW]	20	20.14	− 0.14	− 0.73
Carbon Emissions [tonne/d]	193.1	194.5	− 1.4	− 0.72

Case 2, as a result of adding pre-cooler cycle, energy consumption is reduced and optimized. In this section, reduction in the total number of facilities results in lower amount of exhaust gases. Moreover, because less fuel is burned in heaters and boilers, the exhaust gases are also reduced.

3.4 Comparison of case 1 and case 2 duties

Based on the previous section, it was found that the number of exchangers in Case 2 would be increased. Also, the number of exchangers is much higher. Therefore, the total energy consumption would be higher. Details of heat exchanger in the given cases are shown in Table 3.

In Case 1, the number of coolers is less than Case 2. In Case 2, the main cooling is done with air. For this reason, less water circulation can be seen in coolers. Although the number of exchangers in Case 2 is higher, they are more economical and smaller, but in Case 1, the exchangers are larger, and their shells are much bigger. Given the overall situation, Case 2 can perform better for LNG production. Neeraas and Marak examined the disadvantages of five experimental processes and compared the results with each other, concluding that the expander cycles were not suitable for small-scale applications due to their simplicity and safety. On the other hand, the multi-component refrigeration processes, in particular, dual multi-component refrigerants, are suitable for large-scale applications (Shayan et al., 2020). Zhu et al. also selected a pre-cooling process and examined the effect of its composition and equipment on cycle performance (Nguyen et al., 2020). Their purpose in conducting this experiment was to obtain the best and most appropriate composition by examining the different compounds and their effects on the different parameters of the cycle. They concluded that one compound may have a positive effect on one part but harms others, and the use of smaller equipment in terms of energy consumption creates more optimal conditions for the cycle.

4 Conclusion

Natural gas liquefaction processes vary in terms of energy consumption, investment, and technical complexity, especially in low capacity production. In this research, two case studies were performed for evaluating two high performance liquefaction processes and controlling the related level of energy consumption as well as saving the capital investment.

Table 3 Details of heat exchanger in (a) Case 1 and (b) Case 2

Heat Exchanger	Type	Ideas for Changes	Base Duty [MW]	Hot Inlet Temperature [C]	Hot Outlet Temperature [C]	Cold Inlet Temperature [C]	Cold Outlet Temperature [C]	Base Area [m2]	Hot Side Fluid	Cold Side Fluid	Value [kJ/h-m2-C]
E-105@Main	Process Exchanger	No	2.93	−90.7	−154.0	−161.8	−130.0	1703	FeedStoke (NG)_To_6	16_To_17	396.6
E-104@Main	Process Exchanger	No	7.02	32.0	−90.7	−132.2	−46.7	7661	FeedStoke (NG)_To_6	19_To_22	80.7
E-100@Main	Cooler	No	21.44	308.9	25.0	−25.0	−24.0	2201	22-1_To_22-2	Refrigerant 1	231.4
E-101@Main	Cooler	Yes	9.553	153.7	25.0	−25.0	−24.0	812.3	22-3_To_23	Refrigerant 1	421.5
E-102@Main	Cooler	Yes	9.684	150.9	28.0	−25.0	−24.0	889.2	28_To_29	Refrigerant 1	384.8
Ex-104@Main	Process Exchanger	No	1.95	28.0	−79.0	−161.6	682.4	−32,770	30_To_31	8_To_9	−32,767.0

Heat Exchanger	Type	Base Duty [MW]	Hot Inlet Temperature [C]	Hot Outlet Temperature [C]	Cold Inlet Temperature [C]	Cold Outlet Temperature [C]	Hot Side Fluid	Cold Side Fluid
E-3006@TPL1	Process Exchanger	1.072	45.8	12.0	7.5	8.0	NG FEED_To_To LNG Section@TPL1	HT-NG IN_To_HT-NG OUT@TPL1
E-3003@TPL1	Process Exchanger	2.609	35.0	12.1	7.5	8.0	MR Cool_To_MR-Cold@TPL1	HT-MR IN_To_54@TPL1
E-3005@TPL1	Process Exchanger	6.375	−16.1	−33.6	−42.5	−42.0	MR Cool_To_MR-Cold@TPL1	LT-MR IN_To_56@TPL1
E-3008@TPL1	Process Exchanger	0.7081	−15.2	−35.2	−42.5	−27.0	NG FEED_To_To LNG Section@TPL1	LT-NG IN_To_LT-NG OUT@TPL1

Table 3 (continued)

Heat Exchanger	Type	Base Duty [MW]	Hot Inlet Temperature [C]	Hot Outlet Temperature [C]	Cold Inlet Temperature [C]	Cold Outlet Temperature [C]	Hot Side Fluid	Cold Side Fluid
E-3007@TPL1	Process Exchanger	0.8936	12.0	−15.2	−22.5	−22.0	NG FEED_To_To LNG Section@TPL1	MT-NG IN_To_MT-NG OUT@TPL1
E-3004@TPL1	Process Exchanger	4.315	12.1	−16.1	−22.5	−22.0	MR Cool_To_MR-Cold@TPL1	MT-MR IN_To_55@TPL1
EA-303@TPL1	Cooler	0.7088	66.3	55.0	30.0	35.0	6-4_To_6-6@TPL1	Air
AC-101@TPL1	Cooler	3.387	89.0	70.5	30.0	35.0	6-8_To_6-10@TPL1	Air
AC-102@TPL1	Cooler	0.7088	66.3	55.0	30.0	35.0	6-3_To_6-5@TPL1	Air
AC-103@TPL1	Cooler	3.387	89.0	70.5	30.0	35.0	6-7_To_6-9@TPL1	Air
EA-301 A@TPL3	Cooler	1.682	86.7	55.0	30.0	35.0	14_To_16@TPL3	Air
EA-301B@TPL3	Cooler	1.682	86.7	55.0	30.0	35.0	15_To_17@TPL3	Air
EA-302A@TPL3	Cooler	4.221	128.0	55.0	30.0	35.0	22_To_24@TPL3	Air
EA-302B@TPL3	Cooler	4.221	128.0	55.0	30.0	35.0	23_To_25@TPL3	Air
E-3001@TPL3	Process Exchanger	2.028	55.0	35.0	30.0	45.0	18_To_19@TPL3	CW3_To_CW4@TPL3
E-3002@TPL3	Process Exchanger	2.219	55.0	35.0	30.0	45.0	26_To_MR Cool@TPL3	CW1_To_CW2@TPL3
E-3009@TPL1	Process Exchanger	17.14	70.5	35.0	30.0	45.0	13_To_4@TPL1	CW1_To_CW2@TPL1

Table 4 Results of CAPEX, OPEX, Total Annualized Cost (TAC) and Cost per tone

		Case 1	Case 2
Direct Cost	USD	47,677,335	42,498,858
Indirect Cost	USD	22,992,266	27,273,802
CAPEX	USD	**70,669,600**	**69,772,661**
OPEX	USD/yr	**32,326,072**	**25,315,161**
Total Annualized Cost (TAC)	USD/yr	**50,968,534**	**43,721,013**
Cost Per Tone	USD/T	**152**	**130**

For this purpose, two technologies were proposed to produce liquefied natural gas. Evaluation of the technical conditions and economic analysis have been done by Aspen HYSYS and Aspen Capital Cost Estimator software, respectively. Based on process simulation, there are many heat exchanger and cold boxes in Case 2 for the sake of precooling system and several refrigeration cycles. Therefore, the energy consumption in this case is better than Case 1 due to energy saving in several stages. Also, Case 2 works better for the liquefaction process with a pre-cooling cycle, in term of operating economy. It was also observed that Case 2 creates better conditions in terms of the need for capital and various costs. Total capital costs (including direct and indirect) in Case 1 and 2 are 70,669,600 and 69,772,661 USD, respectively. This issue is related to use of the compressors and turbo-expanders in Case 1. Overall comparison of two cases in CAPEX, OPEX, Total Annualized Cost (TAC) and Cost per ton are reported in Table 4. Based on these results, total costs (including OPEX and CAPEX) in Case 1 and 2 are 152 and 130 USD/Tone, respectively. In addition, Case 2 can be considered for the LNG production due to increase the investor's flexibility and reliability and also lower energy loss and pollutants.

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