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ECONOMIC ANALYSIS ON PRICO PROCESS FOR NATURAL GAS LIQUEFACTION BASED ON TCI CRITERIA

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ABSTRACT

Liquefied Natural Gas has become a global fuel with an annual trade volume growth of more than 7%, an expected growth of 6.7% per year until 2020 and with a current trade volume of over 240 million tons. There were seven main liquefaction technologies in use, the most common one being the PRICO process, also known as Single Mixed Refrigerant (SMR). PRICO LNG process comprises of only single mixed refrigerant and one NG stream, thus makes it the simplest LNG process exists so far. This paper applies economic analysis to a PRICO process to determine the Total Capital Investment (TCI). The analysis in this paper using the results that was obtained from energetic analysis by executed the simulation using DWSIM software. The results obtained after calculated the TCI later is discussed with a few criteria of TCI itself.

Keywords: LNG; PRICO; economic; total capital investment; DWSIM.

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1. INTRODUCTION

The Energy Outlook Report [1] forecasts that world energy demand will be about 30% higher in 2040 compared to 2010 that natural gas will grow fast enough to overtake coal for the number-two position behind oil and that natural gas will be the fastest-growing major fuel source over this period, growing at 1.6% per year from 2010 to 2040. In their Energy Perspectives 2012 report [2], the U.S. International Energy Agency predicts natural gas will remain important to the global energy system for decades.

Natural gas is cooled down (to temperatures around 110 K at 1 atm) in order to liquefy it and transport it overseas in large quantities. This procedure reduced the volume approximately 600 times. Liquefied natural gas can also be used domestically.

There are four main stages in the LNG value chain, if piping and operations between these stages are excluded: exploration, liquefaction, shipping and storage and regasification. The liquefaction plant is the most expensive part of the total capital investment, which is why new technologies have constantly been developed to increase efficiency and decrease costs. Technologies include cascade technologies, non-cascade technologies, ones with only pure refrigerants, ones with both pure and mixed refrigerants and ones with one or more mixed refrigerant. Some technologies make use of a phase separator and some do not, and they can also be categorized according to whether there is a pre-cooling process or not.

2. LITERATURE REVIEW ON LNG PROCESSES

The specific and detailed study or publication about LNG processes is limited and at the same time not openly accessible [3]. However, C3MR process is the most popular process that used in the LNG industry, about 52% of the total world liquefaction capacity [4].

As presented by [5], four objectives functions have been developed to use for operation optimization. The analysis has been performed on the refrigerant system and the results shows the major exergy losses were contributed by the compression system and driving forces across the Main Cryogenic Heat Exchanger (MCHE). In [6] discuss two refrigeration cycles that were used in the LNG processes: Propane cycle and MCR cycle. The process was modeled in the Aspen HYSYS software. The total power consumption has been reduced successfully by

9.08% and the power consumption saving using heat exchanger with 1K pinch temperature in the cryogenic column is lower by 17% than from using heat exchanger with 5K pinch temperature.

Conventional and advanced exergetic analysis has been done on five selected LNG processes (C3MR is one of them) as demonstrated by [7]. The results show exergy destruction within compressors and multi stream heat exchanger were higher than the other components such as cooler and valve. The authors also reported that the Linde C3MR process have high percentage of avoidable inefficiency and the results indicate that the process have more room for improvement in energy consumption aspects. In [8] in his work has developed four different enhancement option by (1) replacing LNG expansion valves by two phase expanders, (2) replacing the expansion valve of MCR with two phase expanders, (3) replacing all of the expanders with two phase expanders, (4) replacing the propane cycle expansion valves with liquid turbines and the other with two phase expanders. The results show the compressor power reduction, expansion work recovery and LNG production increase can be attained by 2.68 MW, 3.82 MW and 1.24% respectively by replacing the conventional expansion process with expanders.

Two different cases has been designed and developed with different flowsheet configuration, but same component(s) by [9] and named as Case 1 and Case 6. The results of energetic and exergetic analyses shows that Case 6 gives the maximum value of coefficient of performance (COP) and exergetic efficiency compared to baseline case (Case 1), which are 15.51% and 18.76%. The outcomes show that by lessening the cooling duty at the middle stages of propane evaporator around 13.5% energy saving can be accomplished compared with the baseline case. In this work however, no consideration is made from economic analysis aspects.

By using Aspen Plus which is a steady-state simulation software, in [10] developed 10 new LNG plants driver cycles enhancement with different configuration. In their work, the authors optimized all 14 enhancement options design variables to show their potential of saving energy. By comparison with the current available technologies, five of newly designed driver cycle configurations have higher efficiency that the most efficient existing conventional driver cycle. As a result, it was shown that the best designed driver cycle enhancement option improved the base driver cycle energy efficiency by 38%.

In [11] has made a technical comparison between different precooling cycles for LNG processes was done by using computational simulation by using Aspen HYSYS in their work. Technical performance differences such as relative power and relative UA whether choosing a pure refrigerant component (propane) or a mixed refrigerant for precooling cycle of LNG processes were discussed in their work. As reported, a three stage propane configuration was to be a better way to use under warm and cold climate condition than a two stage mixed refrigerant (C2/C3) arrangement in terms of energy efficiency. In another work, in [12] evaluated the usage of pure propane and ethane/propane mixed refrigerant cycles for a precooling cycle using Linde-Hampson cycle as a base case. According to the authors, the results indicated that a precooling cycles based on propane configuration component cycles has the highest advantage in comparison with an ethane/propane MR cycle.

The theoretical performance of a natural gas liquefaction process that was modeled and analyzed with Engineering Equation Solver (EES) based on the exergetic performance coefficient (EPC) has been investigated by [13]. The authors carried out the EPC analysis by using the propane, ethylene, and methane refrigerant. The results obtained showed that the maximum irreversibility were occurred in the propane cycle and evaporator section and the results also show propane cycle have the highest rate of exergy destruction, which is 37% compared with the other two cycles which are 28% and 35% respectively. In [14] proposed a new methodology for LNG liquefaction that focus on minimizing the energy consumption that based on the thermodynamics analysis, mathematical programming, and computational simulation. The authors then programmed their simulation with GAMS solved by using LINDOGlobal solver and examined the optimization results by using Aspen Plus in order to ensure its solution feasibility. The results that they achieved for C3MR case study has shown that this methodology greatly narrow down the energy consumption by 13%.

In [15] conducted a synthesis of pinch and exergy analysis in order to find the maximum value of exergetic efficiency by simulating the C3MR model in HYSYS. They also carried out the exergoeconomic analysis using total revenue requirement method. The authors then developed a genetic algorithm from MATLAB to optimize the propane mixed refrigerant process by linking it with HYSYS software. The results obtained show the exergetic efficiency, exergy amount of fuel, exergy lost and destruction were smaller than the base case design with value of 6.79%, 1.6683 kW, 0.2276 kW and 1.2545 kW respectively. In another literature, in [16] proposed a process that regard with three stage propane precooling cycle that was modeled Aspen HYSYS software by 1 MTPA production capacity. They then performed the cycle optimization variables in order to reduce the specific energy consumption. This shown that the specific energy consumption has been successfully reduced from 1028.94 kJ/kg at initial condition to 973.93 kJ/kg at optimized condition, which represents 5.35% of specific energy consumption saving.

As stated by [17], Single Mixed Refrigerant (SMR) of known as PRICO process is the most simple process out of the four known processes. The process was first studied in the year 1981 in Algeria. For over the last 23 years, three liquefaction trains that using this process has been built and operated.

Fig. A3 (see Appendix) shows the original flow sheet of SMR process [17] that are contains of a single LNG heat exchanger, a separate feed, a compressor with an associated after-cooler, suction scrubbers, a separator and pump. In [3] reported that are not many research publication work that deals with liquefaction proces, but SMR process (PRICO) is become quite popular among researchers recently. In [17] claims that this operation experience caused an improvement in the efficiency of process, which is 38% compared to original design. It stated again in the same paper, SMR process has the lowest equipment used compared to the other three processes. In this process, gas enters the LNG exchanger at the feed conditions and was cooled against the cold refrigerant stream. It is then moved to the LNG storage of temperature conditions that is below -155°C. In [18] discussed that eight composition of the mixed refrigerant that can be used for PRICO process. The author also reported that the effect of properties of the mixed refrigerant to the fundamental characteristics of the PRICO process. They show that by increasing the concentration of nitrogen within the MR can lead to an improvement in the heat-transfer characteristics of all heat exchanger. This paper aims to analyze the PRICO LNG process from economic perspective by using TCI method.

3. TOTAL CAPITAL INVESTMENT (TCI) METHOD

Economic analysis was conducted based on the Total Revenue Requirement (TRR) method [19]. It is crucial to accurately estimate the PEC in order to execute a detailed economic analysis. The TRR is calculated on a year-by-year basis based on the estimated FCI and the assumption for the financial, economic, market input values and operating. The non-uniform budgetary values that allied with the investment (operating maintenance, carrying charges and fuel costs of the system analyzed) were levelized. Next, all of them will be adapted into the same series of constant payments (annuities). For the economic analysis, the following assumption are made:

- The operating and maintenance costs are a function of the *CC* and are varied between 1 and 10 %.
- The electricity costs are assumed to be vary between 0.05 and 0.20 $/kWh.
- The LNG plant operates with 100 % capacity during 7446 hours per year (capacity factor = 85 %).
- The average cost of money, $i_{eff} = 10\ \%$.
- The plant economic life, $n = 20$ years.
- The average general inflation rate, $r_n = 2.5\ \%$.

The TCI of a LNG plant processes can be treated as a one-time cost, not like the cost of operating, fuel and maintenance costs that are characterized as continuous expenditures. This is particularly when the construction of plant, design and start-up phase must truly be alarmed. Fig. 1 shows and summarize the main element of the TCI of an LNG plant.

I. Fixed Capital Investment (FCI)

A. Direct costs (DC)

1. Onsite costs (ONSC)
    - Purchase equipment cost (PEC)
    - PEC installation (45% of PEC)
    - Piping (35% of PEC)
    - Instrumentation and control (20% of PEC)
    - Electrical components and material (20% of PEC)
2. Offsite costs (OFSC)
    - Land (10% of PEC)
    - Civil, structural and architectural work (50% of PEC)
    - Service facilities (65% of PEC)

B. Indirect costs (IC)

- Engineering and supervision (35% of PEC)
- Construction cost (15% of DC)
- Contingencies (10% of IC)

II. Other Outlays (OO)

- Startup cost
- Working capital
- Cost of licensing, R&D
- Allowance for funds used during construction (AFUD)

Fig.1. Total capital investment criteria

There are two main components that can be extracted from TCI criteria; Fixed Capital Investment (FCI) and Other Outlays (OO). FCI is the monetary value costs desired for land and all needed purchases, construction and installation of amenities and equipment of the plant. This can be carried out by assumed that the term for FCI is a zero-time term of design, setting up and erection for the plant total costs. FCI is separated into two categories; direct costs and indirect costs. The costs that are covering the major permanent components, labour, materials and other things used in the erection, fabrication and setup of the plant fixed amenities is called the former costs. Meanwhile, the costs that covering temporary facilities needed for project and all other remaining expenses is called the latter costs [20]. The total capital investment is calculated by the following equation after considering all the information provided.

$$TCI = DC + IC + OO \tag{1}$$

3.1. Purchase Equipment Costs (PEC) Estimation

The first step in economic analysis is to estimate the PEC. First, the erection materials and the operating settings of the process must be identified. The estimation and calculations that put into action here can be better in accuracy and reliability with as much quality data as possible. It is more important to contemplate advices, consultation or at least price tags from supplier for costly appliances when the project scale is bigger. If not, the manufacturer's quotation will be not available because of confidentiality and estimation that taken from seasoned and qualified professional will be preferred. All the calculation from extensive cost records of trustworthy firms also included. If the best top two favoured options cannot be obtained, maybe because of time or budget limitations by using the charts available from [20], the PEC can also be determined.

By using the guidance from high volume of information in cost and design, the charts is then built. It is necessary to know the parameters for example heat exchangers heat transfer area or compressors power, to simply study the charts for the necessary cost of the appliances. By using the charts, it is also permitted the effects of the appliances characteristics to be considered such as pressure and temperature. The equipment base cost (C_b) which can be obtained from charts is adjusted by having all of these effect as elements as example material factor (f_m), temperature factor (f_T) or pressure factor (f_p) [20]. As addition, bare module factor also can be comprised to the appliances final module cost of as shown in the Equation (2).

$$PEC = C_B \ f_d \ f_m \ f_T \ f_p \ f_{BM} \tag{2}$$

Generally, for stainless steel, the $f_m = 2.5$ and electrical motor driver, $f_d = 1$. For compressor, the base cost is denoting to the year 2009 (CEPCI 394) [21].

$$C_B = \exp\{ 7.223 + 0.8[\ln(P_c)] \} \tag{3}$$

The charts that available from the charts normally are costs log-plotted contrary to the equipment size, causing in a straight line through the chart. Line slope (α) or what economists called as FCI scaling factor is applied for evaluation of cost of a particular equipment ($C_{PE,Y}$) at a particular parameter, for example size (X_Y) with the existence of the PEC of the same appliance ($C_{PE,W}$) at a dissimilar size (X_W) as presented below in the next equation.

$$C_{PE,Y} = C_{PE,W} \left(\frac{X_Y}{X_W}\right)^a \tag{4}$$

The amendment in the reference year and proportions may well modify the scaling factor. Except if dependable information is available to used, scaling factor be presumed as $a = 0.6$ that often known as the sixteenths rule [20]. Cost index is another key parameter for economic analysis. The cost index (CI) or called as inflation indicator can be stated as

$$\text{Cost}_{\text{ref. year}} = \text{Cost}_{\text{original}} \left(\text{CI}_{\text{ref. year}} / \text{CI}_{\text{original}}\right) \tag{5}$$

The cost index can be used to right the costs for appliances, repository, labour and material. This index are commonly denoted to the Marshall and Swift (M&S) Equipment Cost Index that based on the assembly expenditures for a lot of chemical process industries and Chemical Engineering Plant Cost Index (CEPCI) that based on the erection expenditures for chemical plants.

3.2. FCI (Fixed Capital Investment) Direct Costs Estimation

FCI usually can be classed into two components; onsite costs (ONSC) and offsite costs (OFSC). These two components are estimated through assessment based on the comprehensive flow charts of a system and for the rest of the computations, a factor procedure is applied. Factor procedure is applied for corresponding element in terms of percentage of PEC (n% of PEC). These values are recognized as a product of practice from numerous plants in the chemical engineering industrial practice. The setup of the PE involves the costs for shipment and assurance to make sure the appliances received to the site from the maker, the unloading cost, management, ground works, supports, labour and additional expenditures that important to fully set up the appliances. If any other information is not provided, the average value of 45 % can be used [20].

One of the expenses that represents materials and labour costs is piping that is compulsory for the erection of the whole piping network in the plant. The cost of piping accounted around 10-70 % of PEC. The control and instrumentation cost depend on the complexity of the PE. The greater standard of automation and control, often bring about in more satisfaction in the appliances design. Usually, it range between 6-40 % of the PEC. The expenses that associated to materials, setup and labour for placement lines, power centers, substation, alternative control repository, switch gears and area lightning are the expenses that referred to electrical equipment and materials expenses. About rate of 20 % from PEC is relevant. Land of the plant relies greatly on the plant location and about 10 % from PEC value is anticipated to cover such budget. Service amenities also included but not only restricted to utility supply such as water and electricity. 65 % of PEC is accounted for such expenses [20].

3.3. Indirect FCI Cost Estimation

Costs that allied with management, erection and unforeseen event of the plant are classified as indirect cost (IC). Supervision and engineering contain of the expenditure for the whole plant plan and other requirement such as management and check-up, scale models procurement and administration, advisor fees and travel. This expense, might budget about 25-75 % of the PEC. The construction cost cover about 15 % of the PEC that usually concerns for mobile appliances and operation, appliances and tools, employees household office on-site as well as indemnities. Lastly, contingencies cost is usually covers 5-20 % of the FCI that accounts on all unpredictability and hazards in the real costs calculation such as change in weather, difficulties in transportation and unexpected price changes and also operation stoppage. This often depend on the complexity, dimensions and exceptionality of the plant.

3.4. Other Outlays

The charges involved in the working funds, startup investment and allowance for funds used during construction are referred as Other Outlays. These charges are second part of the total capital investment (TCI). Startup costs mostly involve the expenses of equipment, materials and overheads which are funded only throughout the startup phase of the plant prior to its operation. The startup costs of a thermal system are representable as a total of the unescalated costs such as one month of permanent O&M charges, one month of unfixed operating costs calculated at full load, one week of fuel at full load and 2% of the plant facilities investment [22].

Additionally, to these outlays, working capital is the capitals needed for the period of the plant operation. It is essential for the operating costs prior to receiving the payment from the product sale. Working capital includes the investment for [23]:

a) Raw materials, fuels and provisions carried in stock
b) Finished goods in stock and semi-finished goods in the process of being manufactured
c) Money kept on hand for operating expenses, taxes and other current obligations
d) Accounts receivable

e) Accounts payable

The allowance for funds used during construction (AFUDC) characterizes the time value of the money through the construction based on an interest rate equivalent to the weighted cost of capital. Taking into account the construction period of a plant, portion of the outlay is necessary to cover design studies, civil, acquisition, engineering effort and setting up of equipment without having any income from the plant [22-23].

4. RESULTS AND DISCUSSION

4.1. Purchased Equipment Cost (PEC)

It is important to estimate the size of heat exchanger in order to determine the purchased equipment cost (PEC). The area of heat transfer of heat exchanger is used as sizing parameter. For heat exchanger, we considers the UA values that are obtained from DWSIM software simulation results on this process [24]. Noted that, U-Heat transfer coefficient and A-Heat transfer area. PEC for heat exchanger is estimated by using the Equation (2). For the compressors, we used the net required power (P_c) that are also obtained from simulation to estimate the PEC of each compressor. The PEC of heat exchanger and compressor is shown in Table 1.

Table 1. Purchased equipment costs

No.	Type	Name	Variable	Value	Unit	PRICO $C_{PE,Y}$ (10^6 \$)
1	Heat Exchanger	HEX1 & HEX2	Area	5164	m^2	80.6
2	Compressor	C1	Power	49.62	MW	71.53
3	Compressor	C2	Power	50.15	MW	72.14
Total PEC						224.27

The U values of heat exchanger is obtained from the literature for HEX1 and HEX2. The U values for both heat exchangers are 1500 and 1200 W/m^2K respectively [25]. For compressor, the PEC is calculated by apply the equation below.

$PEC = F_D F_M C_B$ (6)

In above equation, F_D and F_M represent the effect of driving type and material used for construction respectively. $F_D = 1$ since electric motor drive is used and $F_M = 2.5$ because of the usage of stainless steel for the driver. While, C_B represent the base cost of the compressor purchase cost for a CEPCI 394 in 2009 is given by Equation (3).

4.2. Estimation of TCI

The total PEC that obtained is 224.27 x 10^6 \$ with the appropriate cost indexes included. The fixed capital investment (FCI) for the plant is calculated at the value of 987.79 x 10^6 \$. The TCI is calculated at 1104.69 x 10^6 \$ and the detailed result on it is shown in Table 2.

4.2.1. Calculation of Startup Costs (SUC) and Working Capital (WC)

Plant startup costs is a part of other outlays. After estimated the FCI, startup costs and working capital need to be estimated. Startup costs is the sum of the unescalated expenses such as one month of fixed O&M, one month of variable O&M costs at full load, one week of full load and 2% of the plant facilities investment.

$$SUC_{Jan1,2012} = \frac{0.336x10^6}{12} + \frac{0.331x10^6}{12} + \frac{98.163x10^6}{52} + 0.02(1364.21x10^6) \tag{7}$$

After the escalation of the cost to the end of December 31, 2015 is

$$SUC_{Dec\,31,2015} = 35.49x10^6\$ \tag{8}$$

The working capital is the sum of the unescalated expenses of 2 months of fuel cost and variable O&M costs at full load and 3 months of labour cost, plus with a contingency of 25% of those costs.

$$WC_{Jan1,2012} = \frac{(1.25)\,98.163x10^6}{6} + \frac{0.154x10^6}{4} = 20.489x10^6 \tag{9}$$

After the escalation of the cost to the end of December 31, 2015 is

$$WC_{Dec\,31,2015} = WC_{Jan\ 1,2012}\ x\ (1 + i_n)^4 = 24.916\ x\ 10^6 \tag{10}$$

4.2.2. Estimation of Allowance for Funds Used During Construction (AFUDC)

The plant facilities investment (PFI) is shown in Equation (11). The cost of land is not included in the economic analysis so that PFI is equal to the plant FCI. With an annual rate of 5% to

December 31, 2014, 40% of the plant facilities investment should be escalated, and the rest 60% should be escalated to December 31, 2015 according to the parameters that assumed in economic analysis.

PFI = FCI – Cost (11)

The total AFUDC calculated is 56.49 x 10^6 at the end of year 2015

TNI = Cost + WC = 56.497 x 10^6 \$ (12)

Table 2. Total capital investment (TCI)

I. Fixed-Capital Investment (FCI)	**10^6 \$**
A. Direct Costs	
1. Onsite Costs	
PEC	224.27
PEC installation (45% of PEC)	100.92
Piping (35% of PEC)	78.5
Instrumentation and control (20% of PEC)	44.85
Electrical, equipment and materials (20% of PEC)	44.85
Total Onsite Costs	493.39
2. Offsite Costs	
Land (10% of PEC)	22.427
Civil, structural and architectural work (50% of PEC)	112.135
Service facilities (65% of PEC)	145.78
Total Offsite Costs	280.342
Total Direct Costs	773.73
B. Indirect Costs	
1. Engineering and supervision (35% of PEC)	78.5
2. Construction costs (15% of DC)	116.1
3. Contingencies (10% of IC)	19.46
Total Indirect Costs	214.06

Total Fixed- Capital Investiment (FCI)	987.79
II. Other Outlays	
Starup costs	35.49
Working capital	24.92
Cost of licensing, R&D	0
Allowance for funds used during construction (AFUDC)	56.49
Total other outlays	116.9
Total Capital Investment	1104.69

We treat the total depreciable capital investment as

$$TDI = TCI – TNI = 1048.2 \times 10^6 \$ \quad (13)$$

After we calculated the TDI, we can estimate the modified accelerated cost recovery system (MACRS) for the tax life of the system which is 15 years. According to the MACRS, the depreciation must be calculated for another one year, which makes that a system that has tax life of 15 years should be calculated for 16 years [26] (please refer to Fig. A1 in Appendix for such information).

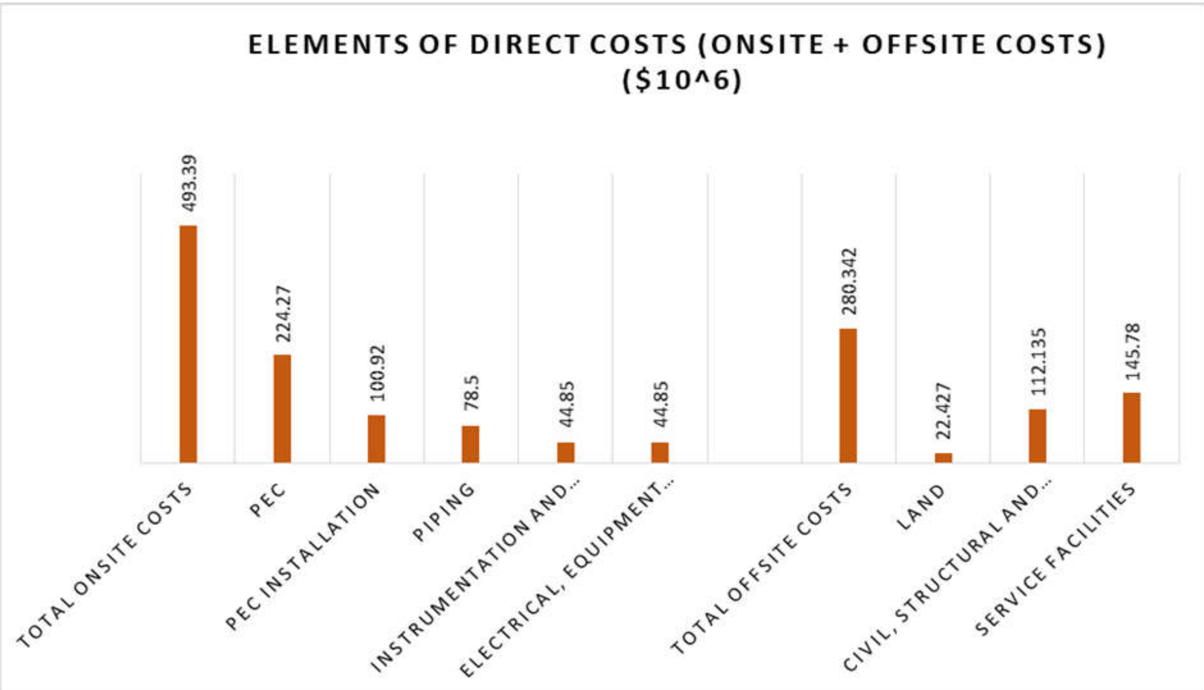

Fig.2. Elements of direct costs

Fig. 2 shows the element in direct costs in bar chart format. As we can see, total onsite costs is higher compared to total offsite costs. This is because the cost that associated with equipment, piping, instrumentation and control have the higher costs compared to offsite costs such as land, civil and service facilities. The equipment such as heat exchanger and compressors have high use of energy in the plant process. This is what cause that the cost for onsite is higher than offsite costs.

5. CONCLUSION

This paper analyzed the economic analysis on PRICO LNG process. The analysis was executed by applying the Total Capital Investment (TCI) method using results from energetic analysis simulation from DWSIM software. From the analysis, the TCI that was obtained to be 1104.69 x 10^6 \$. Several improvement can be considered for the future development of PRICO process in the LNG industry such as energy consumption through exergy and environmental analyses.

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APPENDIX

		Fixed facilities investment			Common equity		Preferred equity		Debt	
Construction year	Calendar year	Jan 1 2012 ($)	Amount of escalation	Escalated investment	Escalated investment	AFUDC	Escalated investment	AFUDC	Escalated investment	AFUDC
1	2014	545.609	55.925	601.533	210.537	31.581	90.230	10.557	300.767	30.077
2	2015	818.413	129.002	947.415	331.595	0.00	142.112	0.00	473.708	0.00
	Subtotals	1364.021	184.927	1548.927	542.132	31.581	232.342	10.557	774.474	30.077
Total AFUDC		**72.214**								
Total AFUDC in 2012		**56.497**								

Fig.A1. Total AFUDC

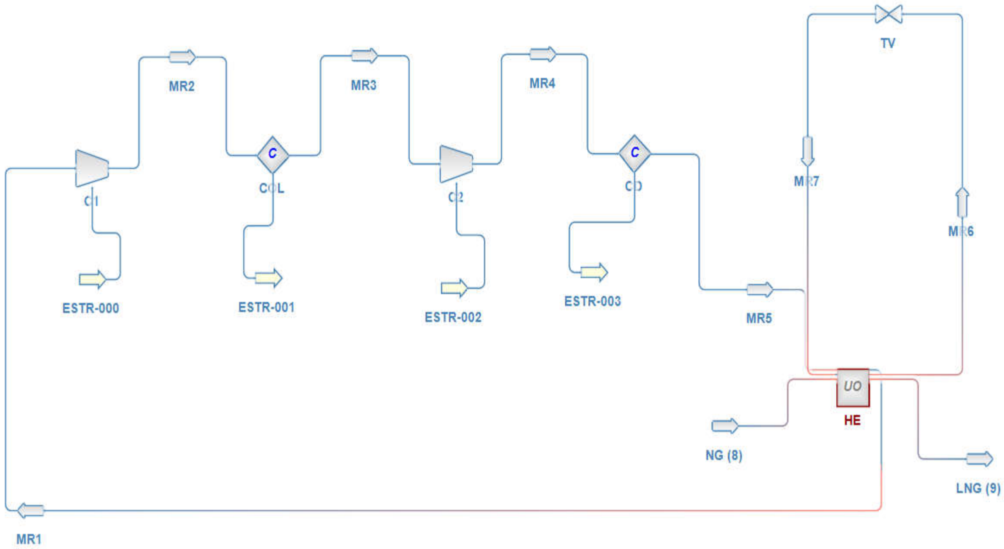

Fig.A2. Flowsheet of PRICO process as simulated in DWSIM

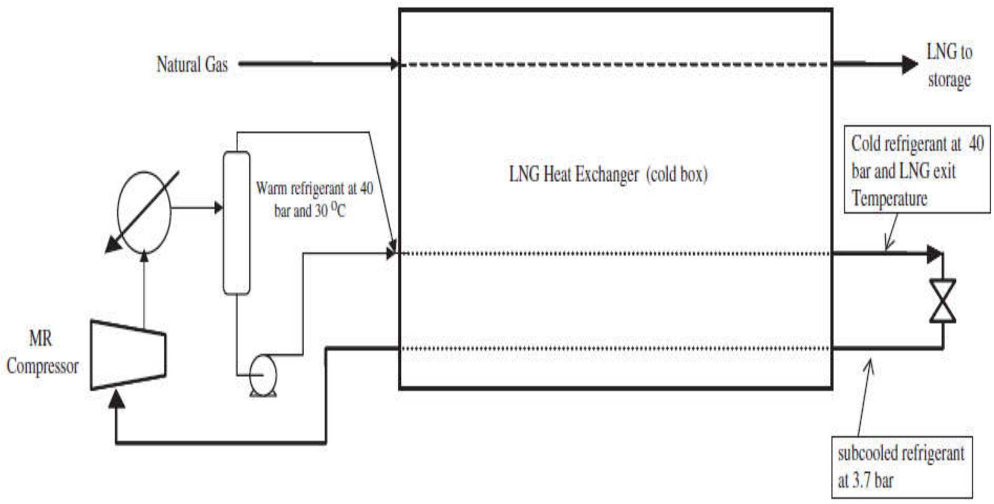

Fig.A3. SMR (PRICO) original flowsheet [17]

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