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Optimization of LNG Cold Energy Utilization via Power Generation, Refrigeration, and Air Separation

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ABSTRACT

Natural gas is conventionally transported in its liquid form or Liquid Natural Gas (LNG). It is then transported using cryogenic insulated LNG tankers. At receiving terminals, LNG is regasified prior to distributing it through gas distribution system. Seawater has been used as the heat source, which leads to vast amount of cold energy discarded into the water. This work presents the use of LNG cold energy around Melaka Refining Company (MRC). The cold energy is utilized in power generation, propylene refrigeration cycle, and air separation plants. These systems are designed and simulated using a commercial process simulation software. Capital cost (CAPEX) function and revenues of each system are further developed as a function of LNG flowrates. These developed correlations are then used in an optimization problem to seek for the most profitable scenario. The results show that utilizing LNG for air separation unit yields the highest profit compared to power generation and refrigeration plants.

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1. INTRODUCTION

Natural gas is often discovered and extracted from remote areas far from the consumers. For short distances, the gas ia normally transported via pipelines. On the other hand, for long distances, natural gas ia shipped through vast oceans (Yumrutaş et al., 2002). Prior to shipping, natural gas is converted to liquefied natural gas (LNG) which is then transported using cryogenic insulated LNG tanks. The refrigeration process consumes relatively high amount of energy to achieve temperature of -162°C to liquefy the natural gas into LNG (Mehrpooya et al., 2015). Via this liquefaction process, the volume of LNG is reduced to about 600 times smaller than NG at atmospheric pressure.

At receiving terminals, the LNG has to be evaporated flow back to gas at ambient temperature, making it be transported through gas distribution systems. Thermal energy from seawater is widely used to regasify LNG, which destroys the physical exergies (Franco & Casarosa, 2014). Regasification process needs approximately about 800 kJ/kg of energy to convert LNG back into gas. This energy is commonly known as the cold energy. So far, there are several ways of utilizing this cold energy. For example, it can be used for power generation, ethylene and propylene refrigeration cycle, air separation, and other low temperature applications (Sung & Kim, 2017).

For power production, direct expansion conversion is essentially the simplest configuration (Franco & Casarosa, 2014). **Figure 1** shows the illustration of a direct expansion cycle. In the figure, VNG is a short form of vaporized natural gas.

LNG liquid is pumped to a sufficiently higher pressure (stream 1 to 2), evaporated (stream 2 to 3) by a heat source (e.g. seawater), and then expanded to drive the turbine-generator to generate electricity (stream 3 to 4). The temperature of the gas is further increased to reach ambient temperature (stream 5 to 6) prior to being distributed to users.

To further improve the energy efficiency, Rankine cycle has been used to gasifiy the LNG (Lu & Wang, 2009), shown in **Figure 2**.

LNG is pumped at a sufficiently high pressure and then evaporated in a heat exchanger that condenses the refrigerant in the Rankine cycle. The condensed refrigerant is pumped, evaporated, and then expanded to drive a turbine generator to produce electricities.

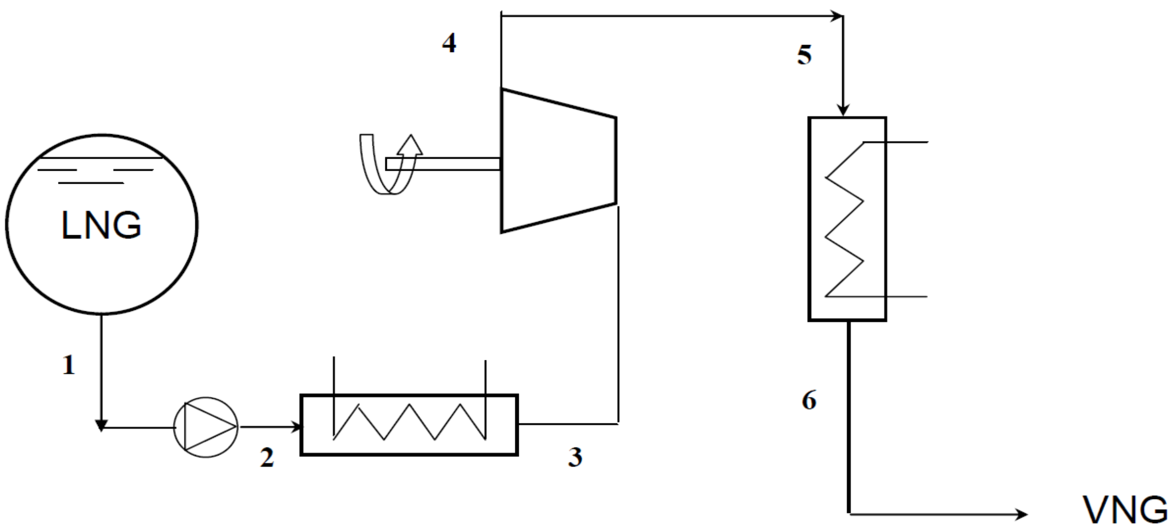

Figure 1. Direct Expansion Cycle

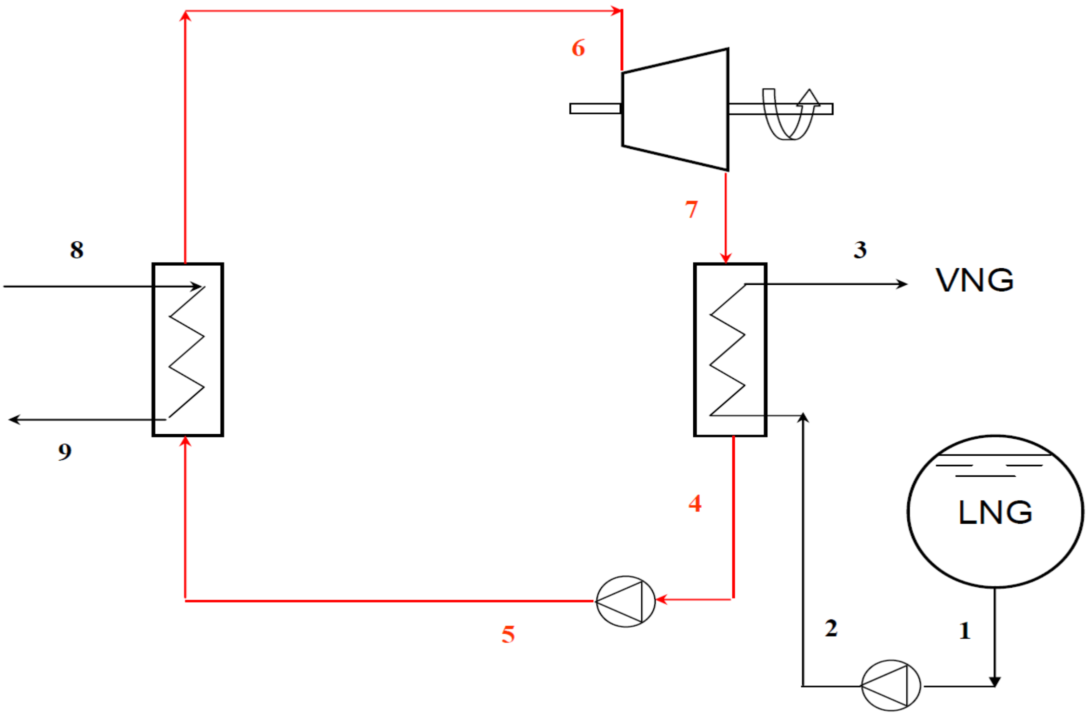

Figure 2. Rankine Cycle

In a refrigeration application, the above Rankine cycle can be utilized. It is basically the same system which consists of compression, condensation, expansion and evaporation (Yumrutaş et al., 2002). The refrigerant absorbs the heat in the evaporator downstream of the pump (see **Figure 3**).

In an air separation unit, oxygen and nitrogen from the air are separated at low temperature levels. In this regard, cold energies of the LNG has been proposed to be utilized. **Figure 4** shows that LNG is used as a cooling medium for the air pre-cooler in order to cool down the air to a very low temperature of around -150^{o}C. Thus, using LNG cold energy allows the ASU to run with minimum power which would reduce the cost of operating nitrogen and oxygen (Xu et al., 2014).

Malaysian Refining Company (MRC) is known for its highest production rate in Malaysia at 300,000 barrels per day (bpd). The company has built its first Malaysia state-owned Petronas' LNG terminal at Melaka. The LNG terminal has a capacity of 3.8 million metric ton per annum (mmtpa). Apart from that, the terminal has two permanently moored floating storage unit (FSU) which has the capacity of 130,000 m^3 each.

The objective of this paper is on utilizing cold energy from the LNG terminal in Melaka. For this purpose, cold energy users around the refinery are first identified. These users are then integrated with the LNG evaporation unit. Each system is simulated and their economic performances are evaluated to seek for the most profitable application.

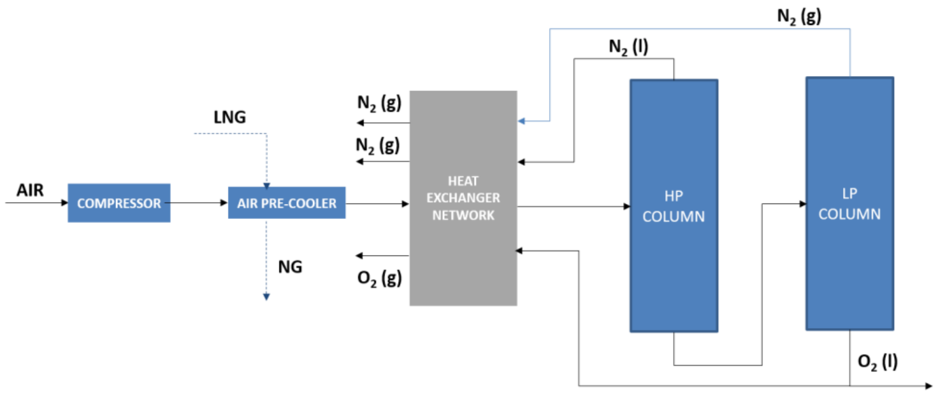

Figure 3. Air Separation configuration with LNG pre-cooling.

2. METHODOLOGY

First, potential users around Melaka LNG terminal are identified. The users should have low operating temperature units in order to utilize the cold energy from LNG. The distance between the regasification terminal and to the user is limited to within 10 km radius. In the next phase, cold energy recovery system for power generation, propylene refrigeration and air separation are designed and simulated using Aspen HYSYS. The use of Aspen HYSYS in evaluating process technologies and techno-economic analysis is well-known and has been widely used (Abdurakhman et al., 2017; Putra, 2016a; Putra, 2016b). In the simulation, the profit and the capital cost of each recovery system design are calculated on the basis on LNG flowrate. The capital cost (CAPEX) of the plant would be computed using Aspen Process Economic Analyzer software. Optimization in GAMS was performed to find the most profitable option to recover this cold energy.

3. RESULTS AND DISCUSSION

3.1. LNG Capacity

The amount of LNG accounted in Melaka LNG Terminal is 3.8 million metric ton per annum (mmtpa). Taking into consideration that Melaka has two floating storage units, a continuous supply of LNG that can be expected for several applications. Thus, the flowrate of LNG as follows:

$$3{,}800{,}000\frac{ton}{yr}\times 1000\frac{kg}{ton}\times\frac{1}{365}\frac{yr}{days}\times\frac{1}{24}\frac{day}{hr}\times\frac{1}{60}\frac{hr}{min}\times\frac{1}{60}\frac{min}{s}=120\frac{kg}{s}$$

This provides a basis for the maximum flowrate of LNG that can be used and the available cold energy. The LNG simulations for each application are carried out in order to obtain profit and the capital cost (CAPEX) in the function of LNG flowrate. LNG generally consists of a mixture of various gas as shown in **Table 1** (Liu & Guo, 2011).

3.2. Cold Energy Users

The first phase of the project was to gather information on the cold energy users around Melaka Refinery complex within 10km radius from the regasification terminal. The distance is limited by 10 km to minimize piping cost and lost of energy from the pipeline. The list of cold energy users is shown in **Table 2**.

3.3. Power Generation

There are various cycles of power generation and working fluid options available to utilize LNG cold energy. As previously discussed, in the literature by using the cooling capacity of LNG there are two types of cycles which can be implemented to generate power which are organic rankine cycle and direct expansion cycle. The heat of seawater is used as energy input, but often a high temperature heat source is used (in the range 60 and 1300°C). Thus, for this project organic rankine cycle (ORC) combined with direct expansion cycle (DEC) using high temperature waste heat source is applied. This power cycle is considered as promising systems for waste energy utilization and environmental protection (Miyazaki et al., 2000).

Table 1. LNG Composition

Component	Composition (mole)
Nitrogen	0.0007
Methane	0.8877
Ethane	0.0754
Propane	0.0259
n-Butane	0.0056
i-Butane	0.0045
n-Pentane	0.0001
i-Pentane	0.0001

Table 2. List of Cold Energy Users

No.	Industrial Type	Cold Energy Usage
1	Oil Refinery	Low temperature separation, chilled water production, and power generation
2	Chemical Plant	Air separation
3	Food Manufacturer	Refrigeration for frozen food

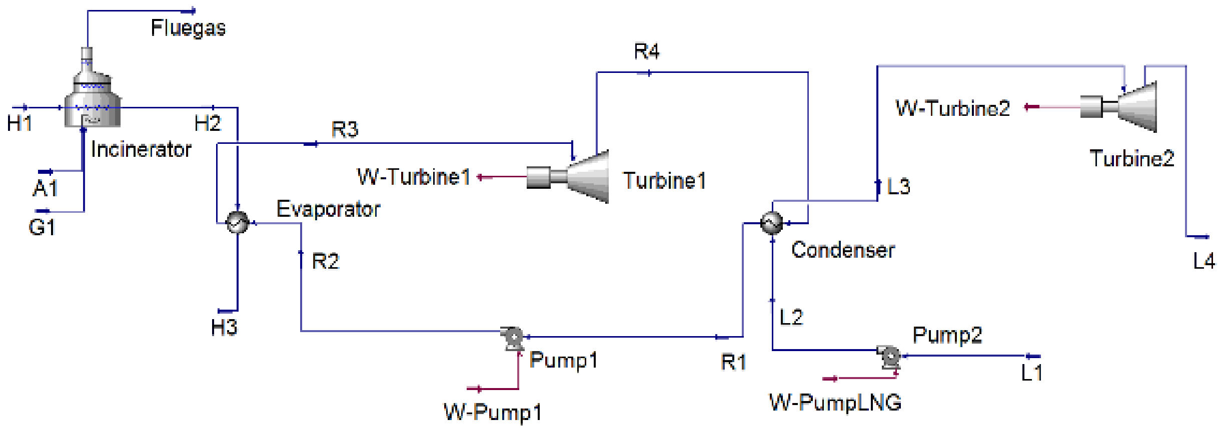

Figure 4. Aspen HYSYS Simulation of ORC with DEC

The simulation diagram in **Figure 5** shows the combined power cycle using refuse incineration and LNG (L1 – L4) as the cooling medium. In the simulation, fired heater is used instead of incinerator due to the model unavailability in HYSYS. The working fluid (R1 – R4) is an ammonia–water system (70:30) in this cycle. Ammonia–water is used to recover the LNG cold energy at low condensing temperature, where pure water cannot be used (Miyazaki et al., 2000). The air (H1 – H3) at 25°C ambient temperature is heated up to 600°C by the garbage incineration process which provides heat source to the evaporator. The working fluid is superheated to 300°C at 3 MPa in the evaporator and enters the turbine 1 where the power is generated.

No temperature cross-over is expected in the evaporator because the gas temperature ranges from 600 to 350°C while the working fluid temperature in the boiler ranges from -30 to 300°C. The pinch point in the evaporator is specified as 10°C in the present model. The working fluid from the turbine 1 is then cooled down as low as -30°C by the condenser with the LNG as the cooling medium. LNG at a low temperature of -162°C is evaporated in the condenser after exchanging heat prior to entering turbine 2 where more power is generated. The main assumptions used in this process simulation are shown in **Table 3**.

The simulation is carried out to determine the net power generation and also the capital cost (CAPEX) using Aspen Process Economic Analyzer software for various capacities on the basis of different LNG flowrate.

From **Figure 5**, it can be clearly seen that as the LNG flowrate increases, the power generation and capital cost required to build the power generation system also increases. From the results, the power generation increases as LNG flowrate increases because higher flowrate of LNG has the cold energy to cool down bigger amount of working fluid (R4) which in return generates higher amount of power in the turbine. Thus, a linear line is then plotted to obtain the best fit line. The equation based on LNG flowrate (x; in kg/s) obtained from the results is:

$$CAPEX = 31814x + 2 * 10^6$$
$$Power = 0.2711x - 0.0133$$

3.4. Refrigeration

Propylene refrigeration cycle, uses the work of compressor mainly to reduce the temperature of the refrigerant to low temperature in order to act as a cooling medium for processes that operates in cryogenic. The propylene refrigerant is supplied to the processes that need the streams to be cooled down to low temperatures at which cooling water or chilled water are unable to cool it down. The integration of LNG cold energy enables propylene refrigerant to be brought to low temperatures such as -35, -20, and 5°C without the need of compressor work.

Table 3. Assumptions for Combined Power Cycle

Parameters	Value
Adiabatic efficiency of the turbines	80%
Adiabatic efficiency of the pumps	70%
Minimum approach temperature (ΔT_{min})	10°C
Pressure Drop in heat exchangers	0.3 bar
Temperature of heating source	950°C
Temperature of LNG entering the LNG pumps	-162°C
Pressure of the product natural gas	30 bar
Temperature of the product natural gas	20°C
Ammonia-water concentration	0.7

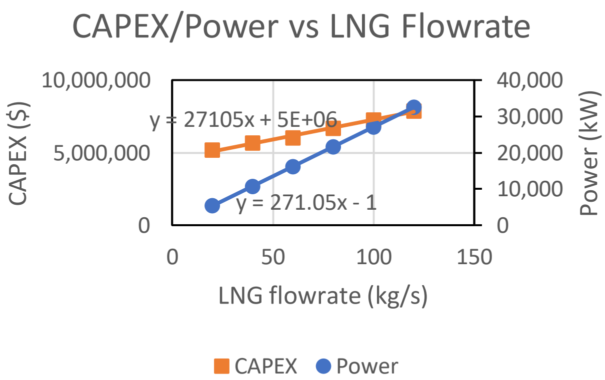

Figure 5. Graph of CAPEX/Power vs LNG Flowrate (CPC)

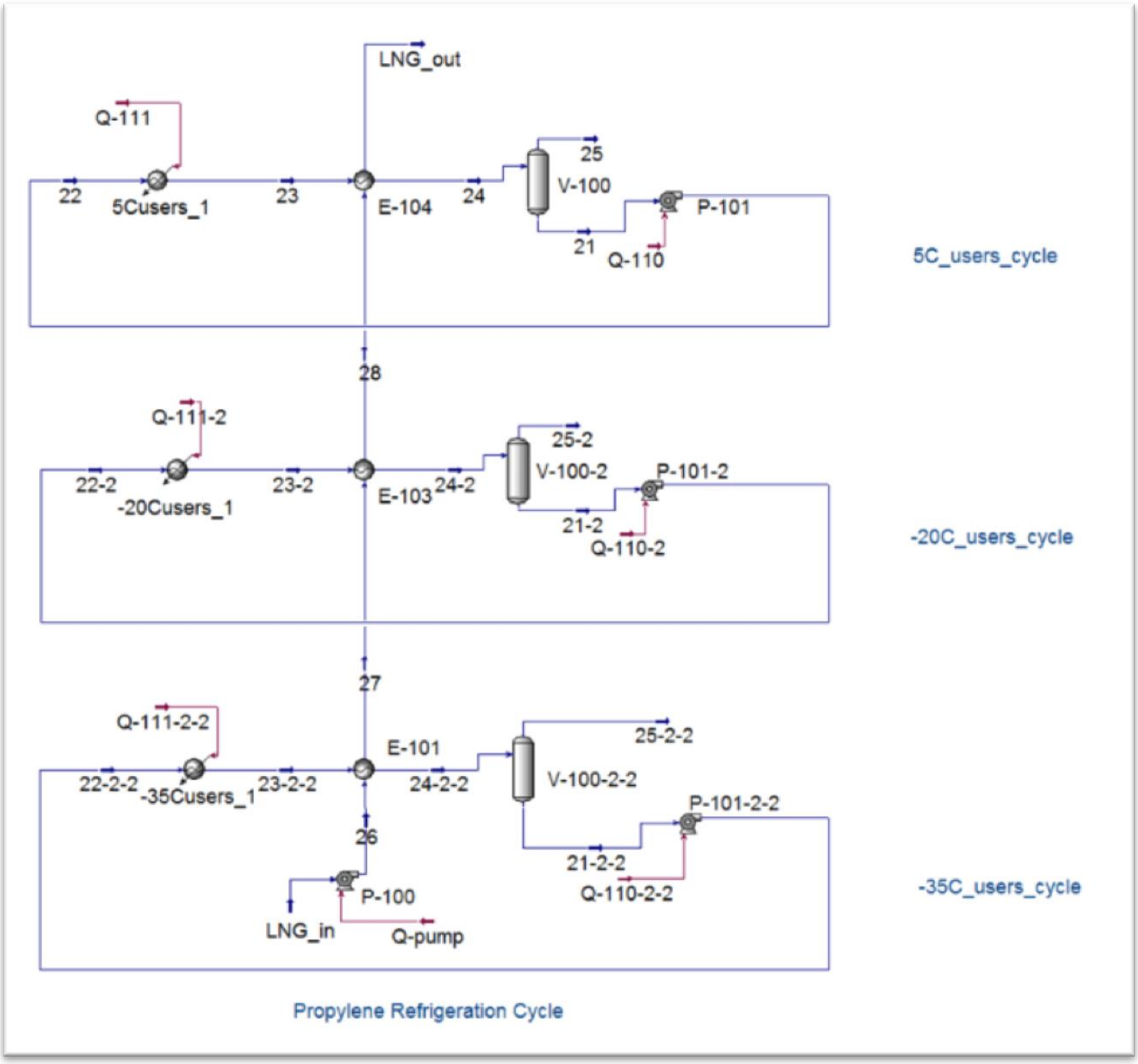

Figure 6. Aspen HYSYS Simulation of Propylene Refrigeration Cycle

The propylene refrigeration cycle consists of three system which are operating at -35°C, -20°C and 5°C. All the cycles operate the same way except for having different operating temperatures. The propylene (22) is first pumped to the heat exchanger where propylene is used to cool down the heat medium. Then, the propylene is brought back to its original operating temperature by using LNG as the cooling medium in the heat exchanger. This refrigeration system allows us to run the system without the need of external power from compressor since the cold energy from LNG is sufficient enough to cool the refrigerant down back to its original operating temperature. Lastly, the propylene is channelled to flash drum to separate any gas from the liquid refrigerant prior to repeating the cycle again. The main assumptions used in this process simulation are shown in **Table 4**.

The simulation of the propylene refrigeration plant is carried out to determine the amount of heat that can be removed from the hot stream by LNG and also the capital cost (CAPEX) of the plant for different LNG flowrate.

The same trend is observed from the graph which results is linearly increasing of heat removed and CAPEX with increment of LNG flowrate. This is because, higher LNG flowrate contains more cold energy which is able to remove heat from higher amount of propylene refrigerant. The linear equation of the two lines in the curve based on LNG flowrate (y; in kg/s) is:

$$CAPEX = 40229y + 5 * 10^6$$

$$Q_{removed} = 770.68y - 3.4667$$

Table 4. Assumptions for Propylene Refrigeration Cycle

Parameters	Value
Adiabatic efficiency of the turbines	80%
Adiabatic efficiency of the pumps	70%
Minimum approach temperature (ΔT_{min})	10°C
Pressure Drop in heat exchangers	0.3 bar
Temperature of LNG entering the LNG pumps	-162°C
Pressure of the product natural gas	30 bar
Temperature of the product natural gas	-5°C

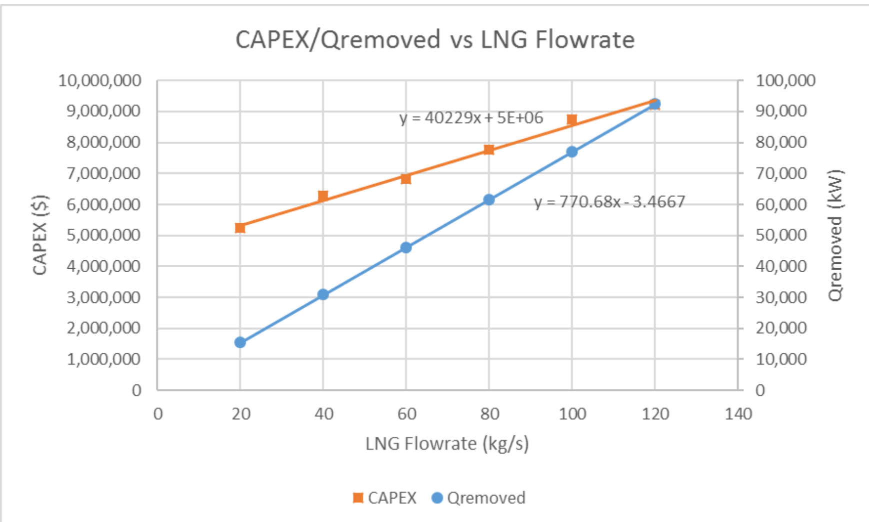

Figure 7. Graph of CAPEX/Qremoved vs LNG Flowrate (Refrigeration)

3.5. Power Generation

Air separation unit separates the air into its primary components which are nitrogen and oxygen with the co-production of argon. The most common method of air separation is through cryogenic process. This is because the boiling point of these gases ranges from -170 to -190°C at atmospheric pressure. In order to obtain low temperature cold energy, a lot of power is required. The integration of LNG not only saves energy but also creates economic benefits by efficiently utilizing the cold energy obtained from the LNG gasification (see **Figure 8**).

The simulation of air separation process using LNG is shown in **Figure 9**. The process mainly consists of air compressor, heat exchangers, turbine and a distillation column (containing the upper and lower tower). The air (A) first enters into the compressor at ambient temperature of 25°C to be pressurized till 1200 kPa. Then, the air is precooled using LNG (L) from temperature of 354 to -150.5°C. The turbine is used to generate electricity while expanding the air stream to 620 kPa which lowers its temperature to -169.2°C. The stream then passes through cold box to lower its temperature till -172°C using nitrogen and argon product as the cold source. After the cold box, the air enters into the distillation column which produces liquid oxygen, O_2 at the bottom of column while nitrogen, N_2 at the top of the column. Crude argon is also drawn from the middle part of the column which is not considered as product in this case because it needs to undergo further distillation.

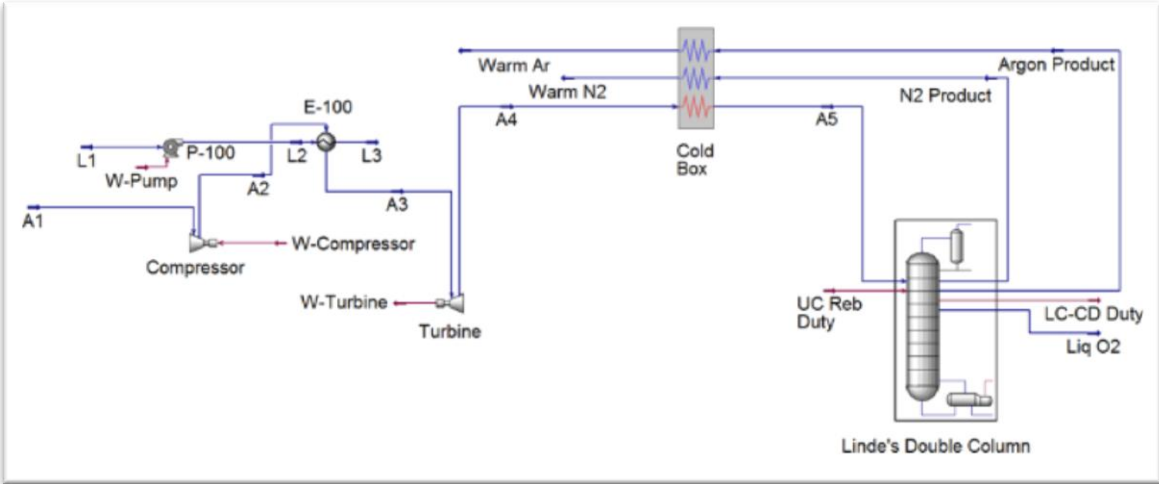

Figure 8. Aspen HYSYS Simulation of Air Separation Unit

Table 5. Assumptions for Air Separation Unit

Parameters	Value
Adiabatic efficiency of the turbines	80%
Adiabatic efficiency of the pumps	70%
Minimum approach temperature (ΔT_{min})	10°C
Pressure Drop in heat exchangers	0.3 bar
Temperature of LNG entering the LNG pumps	-162°C
Pressure of the product natural gas	30 bar
Temperature of the product natural gas	20°C

The simulation of the air separation unit is carried out to determine the amount of O_2 and N_2 produced (Argon needs to undergo further distillation) and also the capital cost (CAPEX) together with the power consumption of the plant for different LNG flowrate.

The CAPEX and power consumption of the plant increases when the flowrate of LNG increases. Besides that, the flowrate of oxygen and nitrogen also increases as the flowrate of LNG increases. This is because, higher flowrate of LNG is able to cool larger amount of air which is then separated into oxygen and nitrogen. The equation line obtained from the graphs as follows:

$$CAPEX = 203469z + 1 * 10^7$$
$$\text{Power} = 1067z - 2.0333$$
$$m_{oxygen} = 0.3568z - 0.0013$$
$$m_{nitrogen} = 1.1814z$$

where z is the LNG Flowrate (kg/s)

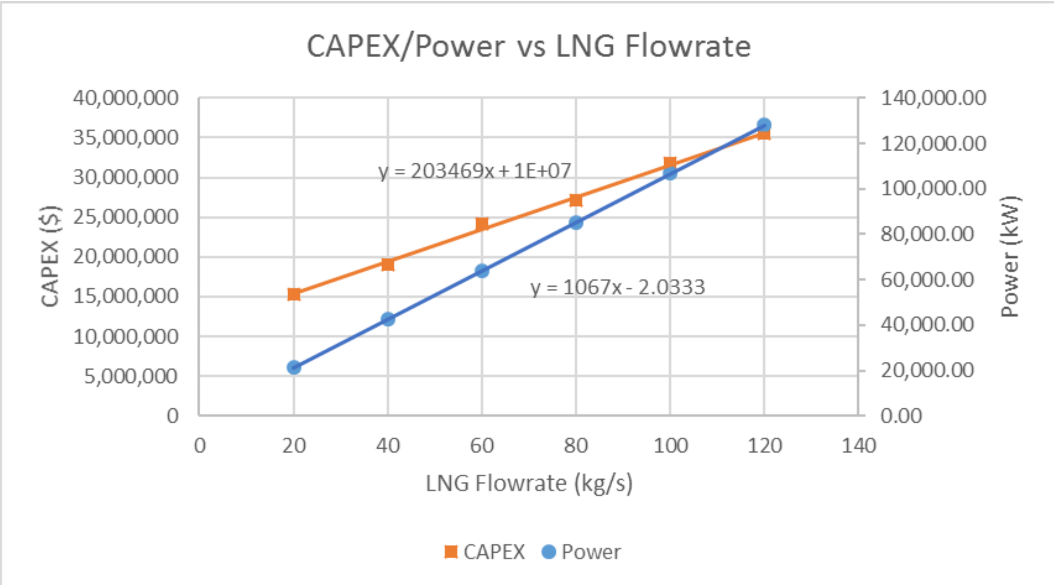

Figure 9. Graph of CAPEX/Power vs LNG Flowrate

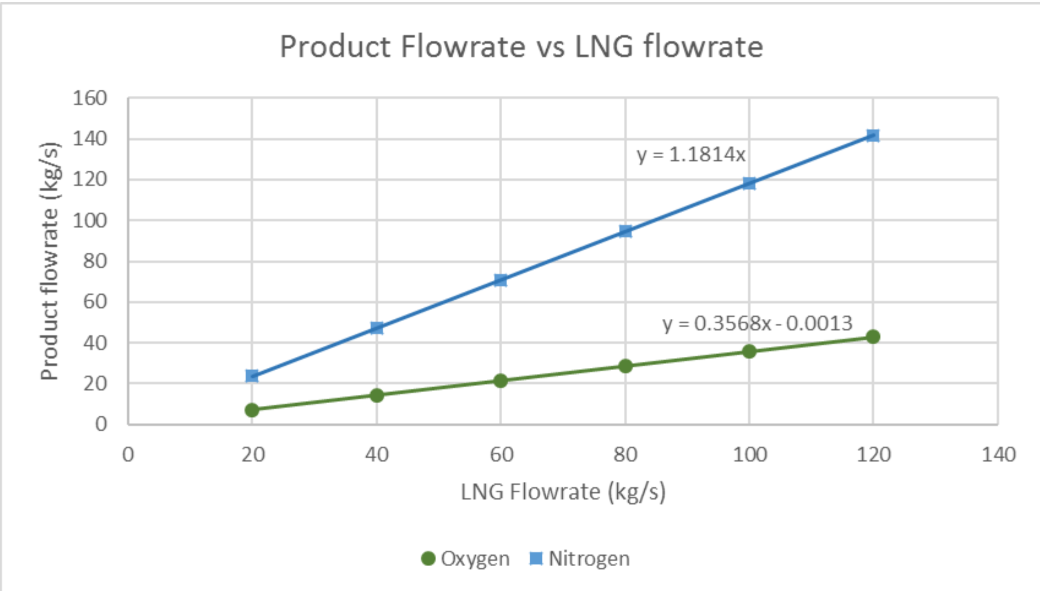

Figure 10. Graph of product flowrate vs LNG flowrate

3.6. Cost Analysis

In the previous sections, 3 applications of LNG cold energy have been simulated and the equation to calculate the cost/profit has been established on the basis of LNG flowrate. These 3 applications are now optimized in terms of profit to give the most profitable scenario in utilizing the LNG cold energy. However, the cost estimate only takes into consideration of equipment cost, operating cost, and profit from the products. The parameters involved in the calculations are in **Table 6**. This cost analysis is important for deciding the scaling up process (Nandiyanto, 2018).

Linear Programming (LP) formulation is used to optimize for the most profitable application. This is because the equations that are obtained from the results are all linear. The capital expenditure (CAPEX) is converted into annual payment in order to obtain annual profit for the applications. The formula used for this calculation is:

$$Annual\ Payment = \frac{i(CAPEX)}{1-(1+i)^{-n}}$$

The combined objective function of the linear programming (LP) formulation is:

$$\begin{aligned} Annual\ Profit &= f(x,y,z) \\ &= C_1[-\frac{0.1(27105x + 5*10^6)}{1-(1+0.1)^{-20}} + (271.05x - 1)*A*h] \\ &- C_2[\frac{0.1(40229y+10^6)}{1-(1+0.1)^{-20}} + (770.68y - 3.4667)*A*h] \\ &- C_3[\frac{0.1(203469z + 1*10^7)}{1-(1+0.1)^{-20}} - (1067z - 2.0333)*A*h \\ &+ (0.3568z - 0.0013)*3600*h*B + (1.1814z)*3600*h*D] \end{aligned}$$

Table 6. Cost Parameters

Parameter	Value
Plant Life, n	20 years
Operating hours, h	8600 hours/year
Electricity price, A (Buy/Sell)	$ 0.06/kWh
Oxygen price, B	$ 0.2/kg
Nitrogen price, D	$ 0.3/kg
Interest rate, i	10 %
Binary variable, C_1, C_2, C_3	0 or 1

where C_1, C_2 and C_3 act as binary variable whereby:

- If x=0, C1=0 and if x>0, C1=1
- If y=0, C2=0 and if y>0, C2=1
- If z=0, C3=0 and if z>0, C3=1

The constraints for the equation are the minimum and maximum flowrate of LNG, corresponding to x+y+z ≤ 120 and x+y+z ≥ 20. Thus, using LP solver from excel spreadsheet the optimized value obtained for x, y and z respectively are x = 0; y = 0; and z = 120 kg/s.

The results obtained shows that fully utilizing LNG cold energy for air separation unit (ASU) yield the highest profit. This is mainly because selling O_2 and N_2 as a product produce significant amount of profit even though the capital cost of the plant is highest compared to the other two applications. The annual profit of annual separation unit (ASU) is:

$$Annual\ Profit\ (Air\ Separation\ Unit) = \$\ 1{,}511{,}739{,}692$$

Besides that, power generation and propylene refrigeration running at maximum capacities is able to obtain annual profit of:

$$Annual\ Profit\ (Power) = \$\ 15{,}813{,}553$$

$$Annual\ Profit\ (Refrigeration) = \$\ 46{,}564{,}385$$

It can be clearly seen that power generation yields lesser profit compared to propylene refrigeration system. This is because, refrigeration system fully utilizes LNG cold energy in the heat exchanger to cool down the hot stream. However, in refrigeration, the power is only limited to low operating temperature system while the electricity produced from power generation can be utilised for various types of applications.

4. CONCLUSION

In the present paper, LNG cold energy from regasification process in Melaka's LNG terminal has been utilized. Three options have been considered, namely power generation, refrigeration, and air separation units. It turns out that the air separation unit yields the highest profit. Future recommendation for the implementation of this project involves optimizing the applications for different temperature and pressure parameters to further improvise the design. It is also possible to state that although the analysis reported in the present paper is based on Melaka's LNG terminal, the results obtained here can be used as a benchmark for other LNG regasification terminals around the world.

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6. AUTHORS' NOTE

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article. Authors confirmed that the data and the paper are free of plagiarism.

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