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Thermodynamic Analysis of LNG Regasification Process

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Liquified Natural Gas (LNG) plays a vital role in the transition toward a sustainable energy future due to its reduced emissions compared to coal. Due to the low storage temperature (-162 °C) during LNG shipping, there is an ample amount of cold exergy (800-900 kJ/kg) embodied in LNG. The regasification process of LNG usually does not utilize this cold exergy. In this study, a detailed thermodynamic analysis of the LNG regasification process with secondary literature data is done. This process is modelled in Aspen Plus for a 2.77 MMTPA LNG regasification plant using the Peng-Robinson equation of state to calculate the thermodynamic properties. It is found that 1,024 kJ/kg of LNG is available in the form of physical exergy, which is equivalent to 0.131 kWh of power. From the obtained results, the energy and exergy flows are represented through Sankey and Grassmann diagrams. The maximum exergy loss is 40 %, originated from the LNG heat exchanger. The present study delineates the pathway for future work of cold exergy utilization to the potential cold consumers (e.g., data centre cooling, food storage etc.) with minimum destruction of exergy.

1. Introduction

Worldwide energy demand is rising, together with the necessity to reduce emissions and pollution due to population growth and economic development. In addition to these factors, high energy prices are pushing us towards the sustainable use of energy resources. It is necessary to have affordable, flexible, and low carbon primary energy sources in the energy mix. Liquefied Natural Gas (LNG) plays a vital role in the transition toward a sustainable energy future due to its reduced Greenhouse Gas (GHG) emissions compared to coal and oil, by 50 % and 20 % (IGU, 2021).

LNG is a clear, colourless, and non-toxic liquid, which results from the liquefaction of natural gas. LNG liquefaction process decreases the volume of the gas by 600 times which makes it economical for overseas transportation (Lim et al., 2020). LNG is stored in large, insulated tanks and transported at -162 °C near atmospheric pressure. After reaching the delivery terminal boil of gases are reliquefied and LNG is regasified to its gaseous phase and delivered through pipelines (Shakrina et al., 2021). LNG regasification is done typically through heating mediums like air and seawater via various types of vaporisers (Naveiro et al., 2021). In the regasification process, the temperature difference between the cold LNG and the atmosphere is very large (approximately 185 °C) which makes it attractive from an exergetic point of view. Apart from the chemical exergy of LNG, it possesses plenty of high-quality physical exergy, i.e., 800-900 kJ/kg of LNG at -162 °C (Zhao et al., 2020).

Various studies on LNG cold energy utilization have been reported which include power generation through the Organic Rankine cycle, Brayton cycle and combined cycle (Cao et al., 2021). In power generation cycles LNG cold is utilized as a cold sink and its cold energy is used to condense the working fluid of the power generation cycle. A study on the power generation potential of LNG regasification terminals shows that up to 0.240 kWh of electric power can be generated per kg of LNG regasified (Çengel, 2020). In addition to power generation, LNG cold exergy utilisation in air separation (Wu et al., 2020) and power generation with cryogenic carbon capture (Liu et al., 2020) have also been reported in the literature. In the air separation process, LNG cold is utilized to precool the air entering the compressor which reduces the compressor work. LNG cold energy-based cascaded system is proposed which provides cooling at different temperature levels, power, heating, natural gas, and liquid carbon dioxide (Liu et al., 2020). A study identified potential future applications of LNG cold energy utilization in cooling for data centres, seawater desalination, energy storage, and cold

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chain (He et al., 2019). Recent studies reviewed and assessed the improvements related to LNG cold energy utilization systems. These systems are not able to efficiently utilize the available cold energy in LNG. To understand the losses and process irreversibilities occurring from each component of the LNG regasification system, the regasification process needs to be thermodynamically analysed in a detailed manner. Thermodynamic analysis can be used to evaluate, analyse, and optimize the energy usage in the LNG regasification process and the utilization potential of the available cold energy. In addition to thermodynamic analysis, very limited carbon footprint analysis of the LNG regasification process is reported in the open literature. Carbon footprint analysis provides opportunities to mitigate carbon emissions.
In this study, a detailed thermodynamic analysis of the LNG regasification process (seawater as the heating medium) is performed with a carbon footprint analysis. The process is modelled in Aspen Plus, and the results of the thermodynamic analysis are shown through Sankey and Grassmann diagrams.

2. Thermodynamic analysis of LNG regasification process

LNG is regasified at high pressures owing to the pipeline pressure requirement of the natural gas supply chain. There are temperature and pressure differences with respect to the ambient conditions. This difference with the environment is called cold energy and it is obtained when LNG is regasified from its cryogenic state (-162 °C) to the final gaseous state at the ambient conditions (25 °C).
Energy and exergy analysis estimates the extent of LNG cold energy accessible in the receiving terminals and the potential of LNG cold energy utilization. Energy analysis treats all forms of energy as equivalent without differentiating between the different grades of energy. It is based on the first law of thermodynamics and is qualitative. On the other hand, exergy analysis is based on the degradation of energy, and it differentiates between the different grades of energy. Exergy analysis is based on the second law of thermodynamics (Kotas, 1988). The process of exergy analysis is especially suited for achieving the goal of efficient usage of energy resources. Also, it allows the spots, categories, and actual magnitudes of waste and loss to be monitored (Moran et al., 2014).
The general energy balance can be expressed as:

$$En_{in} = En_{out} \tag{1}$$

$$\dot{Q} + \sum(\dot{m}_{in}.h_{in}) = \dot{W} + \sum \dot{m}_{out}.h_{out} \tag{2}$$

where En_{in} is the rate of net inlet energy transfer in kJ/s; En_{out} is the rate of net outlet energy transfer by heat, work, and mass in kJ/s; $\dot{Q}$ is the rate of net heat input in kJ/s; $\dot{W}$ is the rate of net work output in kJ/s; m is the mass flow rate in kg/s and h is the specific enthalpy in kJ/kg.

The general exergy balance can be expressed as:

$$Ex_{in} = Ex_{out} + Ex_{des} \tag{3}$$

LNG regasification is an open system flow process so, the overall exergy associated with the flowing stream of matter can be expressed as (Dinçer and Rosen, 2021)

$$Ex_{total} = Ex_{Ph} + Ex_{Ch} + Ex_{KE} + Ex_{PE} \tag{4}$$

where Ex_{Ph} is physical exergy; Ex_{Ch} is chemical exergy; Ex_{KE} is kinetic exergy; Ex_{PE} is potential exergy
Since no combustion occurs in the LNG regasification process, there is no occurrence of a dead state, and the chemical exergy of LNG is constant throughout the process. LNG regasification is physical exergy conversion process only.
Physical exergy is due to an imbalance caused by the difference in temperature and pressure with respect to T_o and p_o.

$$\dot{\boldsymbol{Ex}}_{\boldsymbol{Ph}} = \dot{\boldsymbol{m}}[(\boldsymbol{h} - \boldsymbol{h_o}) - \boldsymbol{T_o}(\boldsymbol{s} - \boldsymbol{s_o})] \tag{5}$$

where s is the specific entropy in kJ/kg.K and the subscript *o* indicates properties at dead state (T_o and P_o).
Using the Eq(1) to Eq(5) and thermodynamic data, the energy and exergy balance of the LNG regasification process is performed. The reference state (T_o and p_o) for the exergy calculations is 25 °C and 1 bar.

3. System description

After unloading from the carriers at the terminals, LNG is stored in insulated containers which are used as feed tanks to the regasification process.

3.1 LNG regasification process

Figure 1 is redrawn with the data (LNG stream temperature, pressure, and mass flow rate) from Noh et al. (2018). LNG is stored at -162 °C near atmospheric pressure in an insulated tank. Boil off-gases (BOG) generated during the transportation and unloading process are compressed to 10 bar pressure and mixed with the pressurized (10 bar) LNG stream from pump P1. As the mass flow rate of the LNG is very high as compared to the BOG, it gets condensed and converted back to LNG during the mixing process. Then, LNG is pressurized to 60 bar with pump P2 and supplied into the vaporizer (heat exchanger) as a cold fluid. Seawater is used to heat the LNG and it is pressured with pump P3 to 3 bar and supplied to the vaporizer as a hot fluid. In the vaporizer, LNG is converted to high pressure (60 bar) NG for further transportation and seawater is released into the sea with a minor temperature drop at a temperature of 17 °C.

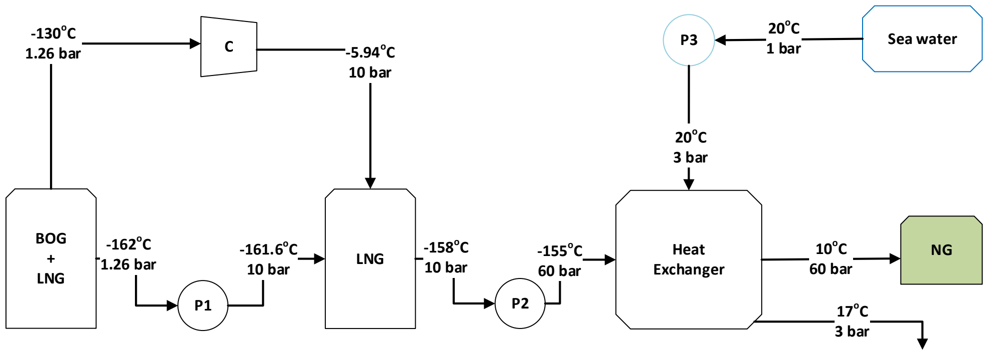

Figure 1: LNG Regasification process (Noh et al., 2018]

3.2 Modelling

The LNG regasification process shown in Fig. 1 is modelled using the Aspen Plus V8.4 software, which is a process simulation tool. LNG is considered as 100 % methane in the entire analysis. The Peng-Robinson equation of state is used to calculate the thermodynamic properties. For the process simulation, the adiabatic efficiency of the pumps and compressor is taken as 80 %.

4. Results and discussion

During the regasification process, most of the cold energy available in the LNG is dissipated into the seawater. Through energy and exergy analysis, the amount of energy and exergy dissipated in the heating fluid is analyzed. LNG, inlet seawater, and electricity to run the pumps and compressor contribute to the input energy and exergy; NG, and discharged seawater contribute to the output energy and exergy of the system. There are energy losses and exergy destructions from different components. Table 1 shows the thermodynamic properties of the LNG regasification process. All these data are taken from the NIST database for methane (Friend et al., 1989). Additionally, energy and exergy at each point are also estimated. The negative sign in the energy column represents the amount of cold energy present in the corresponding stream.

Table 1: Thermodynamic property, energy, and exergy data at all the points of Figure 1

Stream	$\dot{m}$ (kg/s)	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kg.K)	$\dot{E}n$ (MJ/s)	Ex_{ph} (kJ/kg)	$\dot{E}x_{ph}$ (MJ/s)
LNG	89.03	−162.0	1.26	-912.69	-6.69	-81.26	96,501	96.50
LNG	89.03	−161.6	10	-910.02	-6.69	-81.02	96,617	96.62
BOG	1.4	−130.0	1.26	-333.06	-1.67	-0.47	232	0.23
BOG	1.4	−5.94	10	-79.81	-1.46	-0.11	499	0.50
LNG	90.43	−158.0	10	-897.50	-6.58	-81.16	96,335	96.33
LNG	90.43	−155.3	60	-880.95	-6.54	-79.66	96,753	96.75
NG	90.43	10	60	-100.96	-2.39	-9.13	55,396	55.40
Seawater	5,164	20	1.01	84.01	0.30	433.83	5,804	5.80
Seawater	5,164	20	3	84.20	0.30	434.81	6,785	6.78
Seawater	5,164	17	3	71.64	0.25	369.95	13,364	13.36

4.1 Energy and exergy analysis

The energy and exergy balance of each component is made according to the equation (2) and (3). All the energy balances are shown in Table 2. It is observed that major energy is being lost from the heat exchanger and minor energy losses are happening from all other components. The energy losses estimated in pumps P1, P2, P3, and Compressor C1 are 0.452 MJ/s, 2.83 MJ/s, 0.288 MJ/s, and 0.677 MJ/s. LNG vaporizes from the heat available in the seawater however, there is a heat gain in the heat exchanger from the atmosphere which is estimated as 5.67 MJ/s which is considered in the energy lost section of the Sankey diagram.

Table 2: Energy and exergy balance of LNG regasification system

Component	Energy balance	Exergy balance
Pump: P1	EP1, in + WP1, in = EP1, out + EP1, Lost	ExP1, in + WP1, in= ExP1, out + ExP1, des
Pump: P2	EP2, in + WP2, in = EP2, out + EP2, Lost	ExP2, in + WP2, in= ExP2, out + ExP2, des
Pump: P3	EP3, in + WP3, in = EP3, out + EP3, Lost	ExP3, in + WP3, in= ExP3, out + ExP3, des
Evaporator: HE	EHE, LNG in + EHE, SW in = EHE, NG out + EHE, SW out + EHE, Lost	ExHE, LNG in + ExHE, SW in = ExHE, NG out + ExHE, SW out + ExHE, des
Compressor:C1	EC1, in + WC1, in = EC1, out + EC1, Lost	ExC1, in + WC1 = ExC1, out+ Exdes
Tank: T1	ET1, LNG in + ET1, BOG in = ET1, LNG out	ExT1, LNG in + ExT1, BOG in = ExT1 LNG, out+ ExT1, des

On the other hand, exergy analysis shows the exergy destruction at each point of the process. Exergy destruction happens due to the consumption of exergy in components throughout the process. In this work, LNG cold exergy gained by the seawater during the vaporization process is considered as exergy destruction. Exergy gained by seawater results in a minor drop in temperature (20 °C to17 °C) of seawater. This decrease in seawater temperature does not show any potential for work so, it is considered as exergy destructed. The largest exergy destruction occurs in the heat exchanger (34,777 kJ/s) which accounts for more than 90 % of the overall exergy destruction. There is only minor exergy destruction in P1, P2, P3, C1 and T1 (0.01 MJ/s, 0.91 MJ/s, 0.287 MJ/s, 0.05 MJ/s and 0.781 MJ/s).

Figure 2 shows the Sankey diagram depicting the energy flow of the LNG regasification process. The cold energy available in LNG has a negative magnitude. So, for balancing any of the components from the Sankey diagram, the energy flow of LNG is taken as negative with respect to the reference conditions of 25 °C and 1 bar. The pumps and compressors have electric power requirements for their operation and are considered as energy input. Seawater has a high mass flow rate of 5,164 kg/s and high energy also. It is observed that considerably high energy flows are released into the seawater from LNG. Overall, 9.92 MJ/s of energy is lost out of which the maximum is contributed by pump P2 and the heat exchanger. Pump P2 has higher losses because it is exposed to the atmosphere.

Figure 3 shows the Grassmann diagram for the exergy flows of the process considered. The exergy flows of electric power are the same as the energy flows because electric energy is fully convertible to work (the minor conversion losses are ignored). LNG contains the highest exergy flows because of the large temperature difference from the reference conditions. Exergy destruction from each component of the regasification system is shown in Figure 4, which indicates that the exergy destruction associated with the heat transfer losses of the different components (pumps and compressor) are very low and the heat exchanger is the highest. 92 % of the overall exergy destruction is contributed by the heat exchanger.

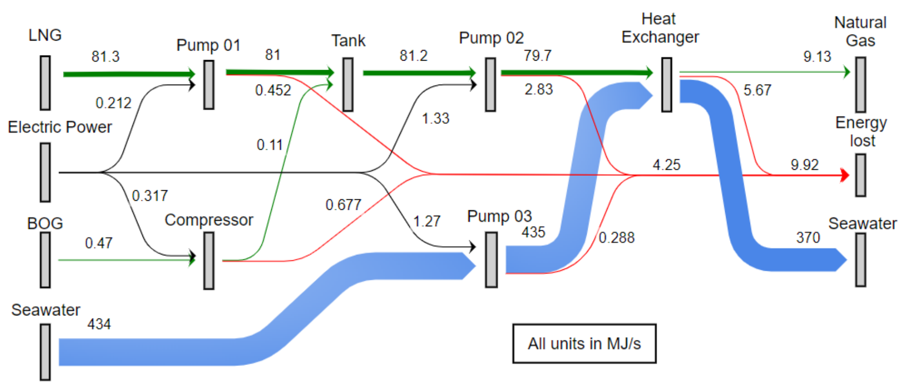

Figure 2: Sankey diagram for the LNG regasification process in Figure 1

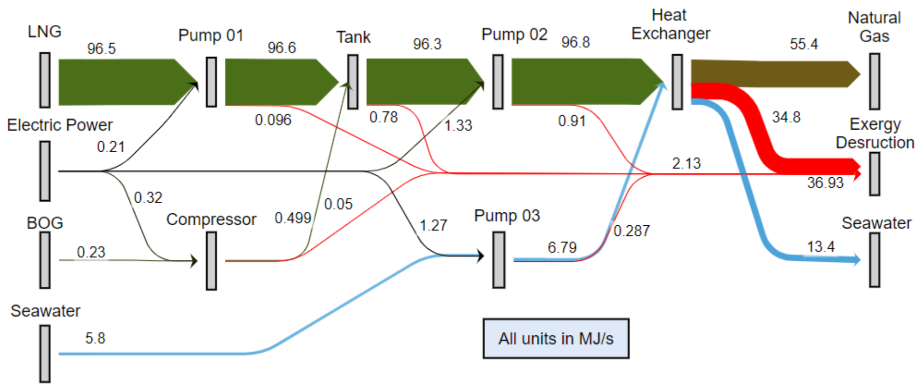

Figure 3: Grassmann diagram for LNG regasification process in Figure 1

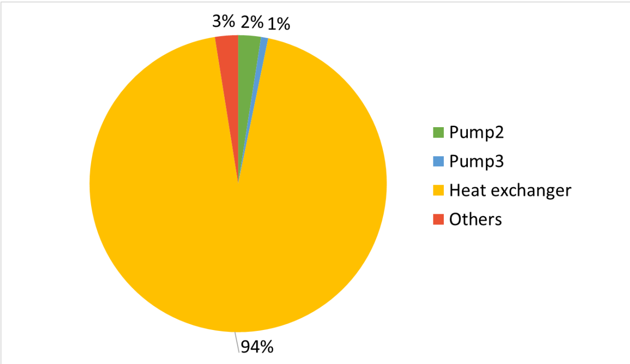

Figure 4: Exergy destruction across different components of Figure 1

4.2 Carbon footprint analysis

Currently, the LNG regasification capacity in India is 42 MMTPA. In addition to this, 24 MMTPA is under construction and 10 MMTPA is planned for the next few years. From the exergy analysis, it is evident that LNG contains approximately 1,084 kJ/kg of cold exergy, out of which 613 kJ/kg is carried away by LNG itself. The remaining 471 kJ/kg of exergy is transferred to the seawater which is also not useful. This is the conventional practice in most of the LNG regasification units. For the existing 42 MMTPA of capacity, these losses translate to 2,588 TWh of exergy annually. If this cold exergy is recovered and utilized, then it would lead to savings of 230 Mt of CO_2 emissions this assumes that an average of 0.89 kg of CO_2 is emitted per kWh of electric power produced in India (Mallapragada et al., 2019).
Table 3 shows the carbon footprint of the input energy to the LNG regasification process. Energy input is in the form of electric power (3,427 kWh) to run the compressor and pumps. With the grid emission factor of 0.89 kg CO_2/kWh, it is calculated that 3,050 kg of CO_2 is emitted into the atmosphere to generate the power required to regasify the LNG. Specifically, 9.37 t-CO_2 is generated in regasifying per t-LNG.

Table 3: Carbon footprint of the LNG regasification process

Parameter	values	Units
Input electrical energy in the LNG regasification (Pumps and compressors)	3,427	kWh
Mass flowrate of regasified LNG	325.55	t-LNG/h
Grid emission factor	0.89	kg-CO_2/kWh
Total emissions	3,050	kg-CO_2/h
Specific emissions	9.37	t-CO_2/t-LNG

5. Conclusions and future perspective

In this study, a detailed thermodynamic analysis of the LNG regasification process is performed which showed that 1,024 kJ/kg-LNG is available in the form of physical exergy. Both the energy and exergy analysis results showed a large potential for energy recovery or storage From the Sankey and Grassmann diagrams, energy losses and exergy destructions are distinctly noticeable at each component of the system. It is observed that the vaporizer (heat exchanger) is the part where maximum exergy (92 %) destruction occurs. It is advisable that a cold recovery system should be installed that can efficiently store or transfer the cold energy of LNG for any other useful application. The carbon footprint analysis shows that cold exergy utilization of LNG decreases the carbon footprint of the energy required to regasify the LNG. In addition, it will also decrease the carbon footprint through the exergy recovery. The present study delineates the pathway for future work on cold exergy utilization. Further study on LNG cold energy utilization for cooling in data centres and food storage units will be targeted with the least destruction of exergy.

References

Cao Y., Dhahad H. A., Togun H., Anqi A. E., Farouk N., Farhang B., 2021, Proposal and thermo-economic optimization of using LNG cold exergy for compressor inlet cooling in an integrated biomass fueled triple combined power cycle, International Journal of Hydrogen Energy, 46 (29), 15351–15366.

Çengel Y. A. 2020, Power generation potential of liquified natural gas regasification terminals, International Journal of Energy Research, 44(4), 3241–3252.

Friend D.G., James F. E., Hepburn I., 1989, Tables for the Thermophysical Properties of Methane. National Institute of Standards and Technology, 1–490. <www.nist.gov>, accessed 22.08.2021

Dinçer I., Rosen M. A., (Ed), 2021. Exergy: energy, environment and sustainable development, Elsevier Amsterdam, Netherlands,1-89.

He T., Chong Z. R., Zheng, J., Ju Y., Linga P., 2019. LNG cold energy utilization: Prospects and challenges. Energy, 170, 557–568.

IGU, 2021. World LNG report 2021. International Gas Union, <www.igu.org/resources/world-lng-report-2021>, accessed 16.08.2021.

Kotas T. J. (Ed), 1988. The exergy method of thermal plant analysis, Anchor Brendon Ltd., Essex, United Kingdom, 99–150.

Lim K.C., Hashim H., Ho W.S., 2020, Cold Energy Recovery Performance Study for Liquified Natural Gas (LNG) Regasification Process, Chemical Engineering Transactions, 78, 595-600.

Liu Y., Han J., You H., 2020, Exergoeconomic analysis and multi-objective optimization of a CCHP system based on LNG cold energy utilization and flue gas waste heat recovery with CO_2 capture, Energy, 190,1-13.

Mallapragada D.S., Naik I., Ganesan K., Banerjee R., Laurenzi I.J., 2019, Life Cycle Greenhouse Gas Impacts of Coal and Imported Gas-Based Power Generation in the Indian Context, Environmental Science and Technology, 53(1), 539–549.

Moran M.J., Shapiro H.N., Boettner D.D., Bailey M.B. (Eds.), 2014, Fundamentals of Engineering Thermodynamics, Wiley, USA.

Naveiro M., Gómez M.R., Fernández I.A., Gómez J.R., 2021, Exploitation of liquefied natural gas cold energy in floating storage regasification units. Brodogradnja, 72 (4), 47–78.

Noh Y., Kim J., Kim J., Chang D., 2018, Economic evaluation of BOG management systems with LNG cold energy recovery in LNG import terminals considering quantitative assessment of equipment failures. Applied Thermal Engineering, 143, 1034–1045.

Shakrina G., Rivera-Tinoco R., Bouallou C., 2021, Cold Energy Storage for Boil-off Gas On-Board Reliquefaction, Chemical Engineering Transactions, 88, 919-924.

Wu Y., Xiang Y., Cai L., Liu H., Liang Y., 2020, Optimization of a novel cryogenic air separation process based on cold energy recovery of LNG with exergoeconomic analysis, Journal of Cleaner Production, 275, 1-16.

Zhao L., Zhang J., Wang X., Feng J., Dong H., Kong X., 2020, Dynamic exergy analysis of a novel LNG cold energy utilization system combined with cold, heat and power, Energy, 212, 1-13.