Using cold energy of the LNG in the integrated process of gasification and electric energy production

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Abstract

Liquefied Natural Gas (LNG) is very energy intensive due to the many processes in the supply chain, from production up to regasification.. The regasification part is identified as the one where the biggest improvement can be done on the energy efficiency.

Regasification terminals accept LNG cargo from the carriers, regasify it, and distribute it for final consumption. For this process they consume additional energy. The aim of this work is to identify and evaluate options for processes integration in order to decrease or even eliminate the energy spent for regasification in LNG terminals. The possible options are cooling applications and integration with power generation cycles.

In this work, power generation Organic Rankin Cycle (ORC) is evaluated with different working fluids and heat sources. It is combined with Direct Expansion (DE) cycle. The simulations are run in ASPEN Plus software. In all the combinations, the net power balance is positive and seawater requirement decreased. With the increase of the temperature of heat source, the net balance improves. The thermal efficiency coefficient for ORC is in the range 12-21%.

In order to define “the best” application for specific location, site conditions and extensive economic analysis are recommended.

Keywords: LNG terminal, integration, energy, ORC, regasification

Introduction

The trend of constant increase in energy demand continues and it is predicted that it will double by the year 2040 [1]. The popularity of the renewable energy sources is constantly growing but still their share in the primary energy mix is much smaller compared to the fossil fuels. Natural gas (NG) is perceived as a fuel for today and tomorrow. It is ranked 3rd by share in primary energy mix and it has constant grow every year, due to new projects [1].

NG has established itself as a clean-burning, reliable and economic fuel. It has proven track of efficient use and it plays very important role in all scenarios for primary energy mix in the future.

The main reasons for its attractiveness are its characteristics as a fuel, the multiple uses and the great safety record. Although NG comes from different regions in the World, with different composition and characteristics, there are many developed technologies to adapt it to the required conditions at the place of consumption.

It can be transported in gaseous or liquefied state (LNG) so this gives additional flexibility in use. Since in many cases the transport is in liquid state and the use in gaseous, it is essential to have good comparison and overview of the values [2].

Its attractiveness comes from the advantages compared to other fuels. Compared to renewable sources, it is more reliable, more efficient and more market competitive. In comparison with the other fossil fuels it has lower GHG and pollutants emissions, which are among the key indicators for fuels performance currently [3].

Market and Supply Chain

Liquefied Natural Gas (LNG) is perceived as a niche market in NG industry. Although it developed much later compared to regular NG market, its popularity has strong growth and it already has well developed market [4].

The key data about LNG market is presented in Table 1.

Table 1: Most important data for LNG markets in 2016 [4]

Importing countries	39	Quantity Imported	263.6 million tons
Exporting countries	19	Increase vs 2015 Import	7.5%
Regasification capacity	830 MTPA	High demand region	Asia, 73% of total
Liquefaction capacity	340 MTPA	Top exporter	Qatar, 30% of total
New Importing countries	4	Short term trade	74.6 million tons, 28%
New regasification terminals	11	Pacific Basin Exports	45% of total

The supply chain of LNG contains several different stages. Starting from exploration and production up to the final utilization, it is a complex structure.

In order to be market competitive and energy efficient, all the stages of the process has to be optimized. The improvements in the production part comes from developing new technologies (unconventional gas), in the liquefaction part with higher capacity liquefaction trains and new combined technologies and the transport part with higher capacity carriers. All these improvements have made it possible to have a well-developed LNG market, which will continue that trend.

The regasification terminal is the last part of the LNG supply chain. Here LNG is regasified and it is distributed to final consumers. Most of the terminals regasify LNG in energy-inefficient way. Instead of making use of the available cold energy of LNG for certain cooling or power generation process, it is just wasted with the seawater which is generally used as a heat source for regasification.

The terminals are major infrastructure projects, which contain a lot of units and devices inside and require significant amount of area for construction.

The main equipment on conventional terminals is: unloading arms, storage tanks, LNG pumps, BOG handling system, vaporizer and additional equipment [5].

All previously mentioned devices have specific characteristics which are important for their proper function and the function of the terminal. For the storage tanks the most important criteria is safety and proper insulation, for the pumps the supply pressure, for the BOG handling system is most important to be able to deal with variation in the BOG emissions from the tanks. The vaporizers are analyzed by different criteria and their choice will depend on more parameters.

Most common types of vaporizers used are: open rack vaporizers (ORV), submerged combustion vaporizers (SCV) and intermediate fluid vaporizer (IFV). There are some other new and specific solutions such as ambient air vaporizer (AAV).

The choice of a vaporizer will depend on the terminal size, the budget of the project, the site location conditions (climate), environmental regulations and other factors.

Literature review

The interest in utilizing LNG cold energy has a long history. It starts in Japan, the country which is largest LNG consumer in the World and which has longest history in cryogenic projects.

The cold energy of LNG can be used for cooling processes and in power generation. For the first one, it is essential to have the required industry close located to the terminal (up to 2-3 km distance). This largely decreases the flexibility and makes mostly the terminals which are located in industrial complex contenders for process integration.

For power generation purpose there is no such requirement. Every terminal can add a power generation group if there is suitable heat source nearby.

Regarding the cooling processes most common use is for air cooling and separation, food refrigeration and similar.

Among the power generation cycles, the highest interest is in Organic Rankin Cycle (ORC) and combinations with it. Other concepts that are evaluated in research are the combination with Brayton cycle, Kalina, some novel concepts and combination of more cycles.

In-depth review of the cold applications of LNG cold energy is provided in [6], [7] and [8]. Here are displayed the researched systems, the obtained results and comparison.

Two most important parameters for an ORC are the working fluid (WF) and the heat source. In common ORC cycles low to medium heat source is used with a suitable fluid that can make use of the heat source. However when ORC is coupled with LNG regasification, additional requirement is that the working fluid should have high enough condensing temperature to be able to transfer heat to LNG.

As most suitable fluids for ORC and LNG coupling are identified propane, ammonia and ammonia-water mixture [6]. Most of the implemented projects employ propane as working fluid, while ammonia and ammonia-water mixture are very interesting for research work, especially when combining ORC with low heat source.

Simulations run

In order to obtain clear view on the possibilities of LNG integration into power cycles, four different schemes, with additional combinations among them, making it in total 12 combinations. They will be evaluated by 4 different criteria. ASPEN Plus software is used for simulations. The scheme presents conventional terminal, and in different cases, the regasification part is varied for evaluation.

The net power balance might come as the most important parameter for a terminal operator. If they decide to invest into integration process for the purpose of power generation, they will want to have this parameter maximized. The net balance will be obtained after gathering all the devices that are related – turbines (Pt), LNG pumps (Plng), seawater pumps (Psw), BOG compressor (C.bog) and WF pumps (Pp.wf). This is presented in the equation below:

$$P_{net} = \sum Pt + \sum Plng + \sum Psw + P_{c.bog} + P_{p.wf} \tag{1}$$

Since the output of power from turbines is indicated with sign “-“ in front of it in the simulation software, power balance with “-“ upfront will be considered as positive, while without it as negative.

Waste of LNG enthalpy is obtained when the enthalpies of the LNG streams before and after the seawater regasifier are compared. The difference between these two values is the enthalpy that could have been used for some cooling process, but it is wasted with the seawater discharge. Usually this occurs only in one vaporizer (heat exchanger), however in the case with DE cycles, there are 2 places where cold energy is wasted to seawater, so usually this value will be higher.

This value is calculated as a difference between the inlet and outlet stream of the seawater regasifier:

$$\Delta h = h_{in} - h_{out} \tag{2}$$

Seawater requirement is the quantity of seawater needed for the terminal function. Seawater can be used for regasification of LNG, but also as a heat source for an ORC. Depending on the configuration of the scheme, there can be one or two seawater intakes:

$$m_w = m_{w1} + m_{w2} \tag{3}$$

Although the main idea here is the utilization of LNG cold energy, the evaluation of the **thermal efficiency** is run as a standard evaluation of all power cycles. However it has to be indicated that in the evaluated cycles no fuels are used as heat source and therefore no direct emissions are created, so even a low efficiency is not something to be worried about.

The efficiency is calculated by the well-known equation:

$$\eta_{th} = \frac{W_t - W_p}{Q_{ev}} \tag{4}$$

The following assumptions are defined prior to simulations [6]:

- Steady state operation of systems
- All equipment used is well insulated
- Pressure drop and heat lost/gain is neglected in pipes
- Pumps, turbines and compressors have pre-defined isentropic efficiency (0.9 for all)
- LNG is assumed to be pure methane
- The heat exchangers used are counter current, and the temperature difference between the hot and cold stream can't be lower than 5 ^{o}C
- Due to environmental regulations, the difference in the seawater intake and discharge can't be lower than 5 ^{o}C

On Figure 1 is presented conventional LNG regasification terminal which uses seawater regasifier (ORV). This is considered here as base case. The input for this case is displayed in Table 3.

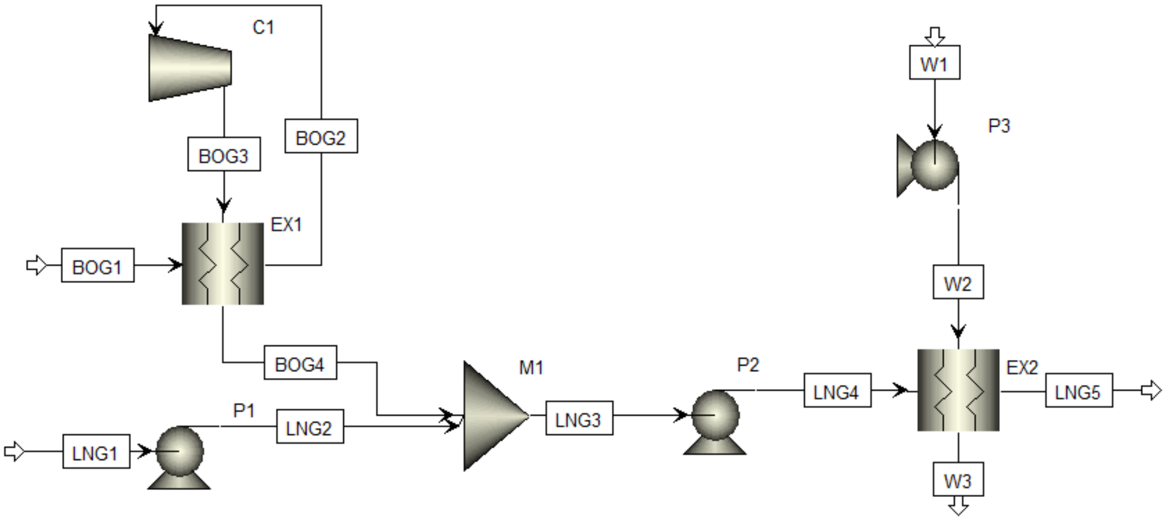

Figure 1: Scheme for Seawater Regasification (ORV)

The first process integration scheme is with adding Direct Expansion Cycle (DE). It is displayed in Figure 2. This combination makes use of the mechanical energy of LNG, while the cold energy is wasted again. The additional parameters needed for this scheme are in Table 4. The input data from Table 3 (for Scheme 1) will be used as default for most of the schemes and simulations, while the additional data needed will be added and defined for every combination. All the components (blocks) used in the simulation require input data, while most of the streams are calculated with the input provided by the user.

Table 2: Entry (Input) data for Case 1 (Figure 1)

Stream/Block	Name on Scheme	Operating parameters

Heat exchanger for BOG	EX1	Vapor fraction	1	
Compressor for BOG	C1	Discharge Pressure	8 bar	
Recondenser for BOG	M1	Operating Pressure	8 bar	
Incoming BOG stream	BOG1	Temperature, Pressure and mass flow	T=-150 °C p=1.2 bars	m=3.65 t/h
Incoming LNG stream	LNG1	Temperature, Pressure and mass flow	T=-162 °C p=1.2 bars	m=150 t/h
Low pressure pump LNG	P1	Discharge Pressure	8 bar	
High pressure pump LNG	P2	Discharge Pressure	80 bar	
Seawater intake	W1	Temperature and mass flow	15 °C	4950 t/h
Seawater Pump	P3	Discharge Pressure	1.5 bar	
ORV	EX2	Gas stream Temperature	10 °C	

The combination with ORC as a key point of this work will be evaluated with different heat sources and working fluids. As heat sources will be evaluated seawater, exhaust steam and exhaust gases. As working fluids will be evaluated propane, ammonia and mixture of ammonia-water (mass ratio 0.6/0.4). Their characteristics will be defined with the data in the suitable scheme.

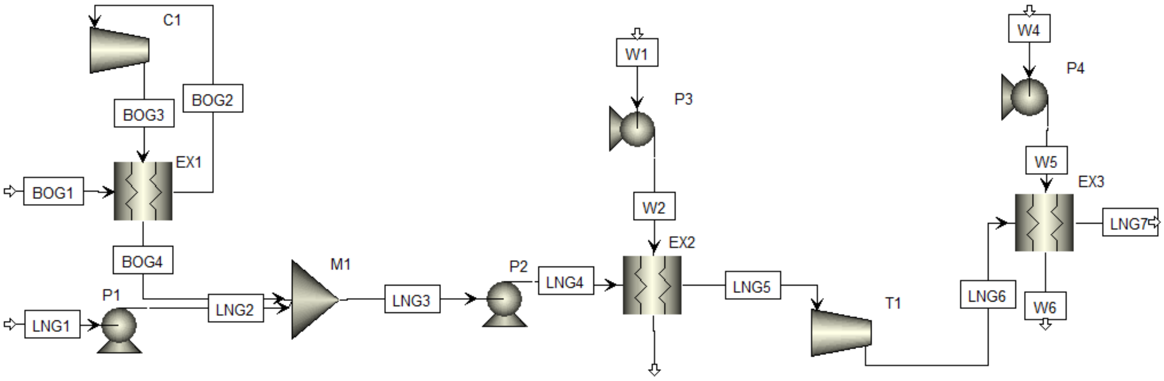

Figure 2: Scheme for Direct Expansion Cycle (DE)

These two parameters of ORC are evaluated due to their critical importance for the performance of the ORC cycles.

Table 3: Input for Case 2 (Figure 2)

Stream/Block	Name on Scheme	Operating parameters	
NG expander	T1	Discharge Pressure	80 bar
Seawater pump	P4	Discharge Pressure	1.5 bar
LNG HP pump	P2	Discharge Pressure	120 bar

The mass flows of WF and heat source will vary in the different combinations. They will depend on the mass flow of LNG that has to be regasified. It has to be emphasized that the regasification of LNG is primary target in these systems, while the additional power generation cycles come as value added.

Table 4: Input data for ORC simulation with Seawater as heat source

Unit/Stream	Propane as Working Fluid	Ammonia as Working Fluid
P5 – pump for WF	P=7 bar	P=7 bar
T1 – turbine for WF	P=1.1 bar Discharge pressure	P=1.1 bar Discharge pressure
EX2 – heat exchanger between LNG and WF of ORC	Vapor=0 (WF condense)	Vapor=0 (WF condense)
EX4 – WF evaporation	Vapor=1 (WF evaporate)	Vapor=1 (WF evaporate)
P4 – seawater pump, heat source	P=1.5 bar	P=1.5 bar
RC2 – WF specifications	P=1.1 bar Vapor=1	P=1.1 bar Vapor=1
RC2 – WF specifications	m= 200 t/h	m=70 t/h

As it is well-known for other conventional cycles, the higher temperature heat source will improve the performance of the cycles [10]

Table 5: Input data for ORC simulation with Exhaust steam as heat source

<table>
<tr><th>Parameters of steam</th><th colspan="2">Quality (vapor fraction)</th><th colspan="2">Pressure</th><th>Temperature</th></tr>
<tr><td>Value</td><td colspan="2">0.9</td><td colspan="2">0.05 bar</td><td>36 ^{o}C</td></tr>
<tr><td colspan="2">Unit/Stream</td><td colspan="2">Propane as Working Fluid</td><td colspan="2">Ammonia as Working Fluid</td></tr>
<tr><td colspan="2">P5 – pump for WF</td><td colspan="2">P=11 bar</td><td colspan="2">P=11 bar</td></tr>
<tr><td colspan="2">RC2 – WF specification</td><td colspan="2">m = 201 t/h</td><td colspan="2">m = 72 t/h</td></tr>
<tr><td colspan="2">H1 – heat source (steam)</td><td colspan="2">m = 42 t/h</td><td colspan="2">m = 45 t/h</td></tr>
</table>

In the evaluated case with exhaust steam as heat source, there is double benefit for the system. The exhaust steam coming from a steam power plant is condensed, while the WF of the ORC is vaporized.

Table 6: Input data for ORC simulation with Exhaust gases as heat source

Parameters of gases	Quality (vapor fraction)	Pressure	Temperature
Value	1	1	200 ^{o}C
Unit/Stream	**Propane as Working Fluid**	**Ammonia as Working Fluid**	**NH_3-H_2O mixture as working fluid**
P5 – pump for WF	P=20 bar	P=20 bar	P=20 bar
Heat source flow	m = 2000 t/h	m = 2000 t/h	m = 2000 t/h

The simulation with exhaust gases with temperature of 200 ^{o}C is the only one where the NH3-H2O mixture can be evaluated. The reason for this is that this mixture has higher evaporation temperature compared to propane and pure ammonia, and can’t run with lower temperature heat source [11].

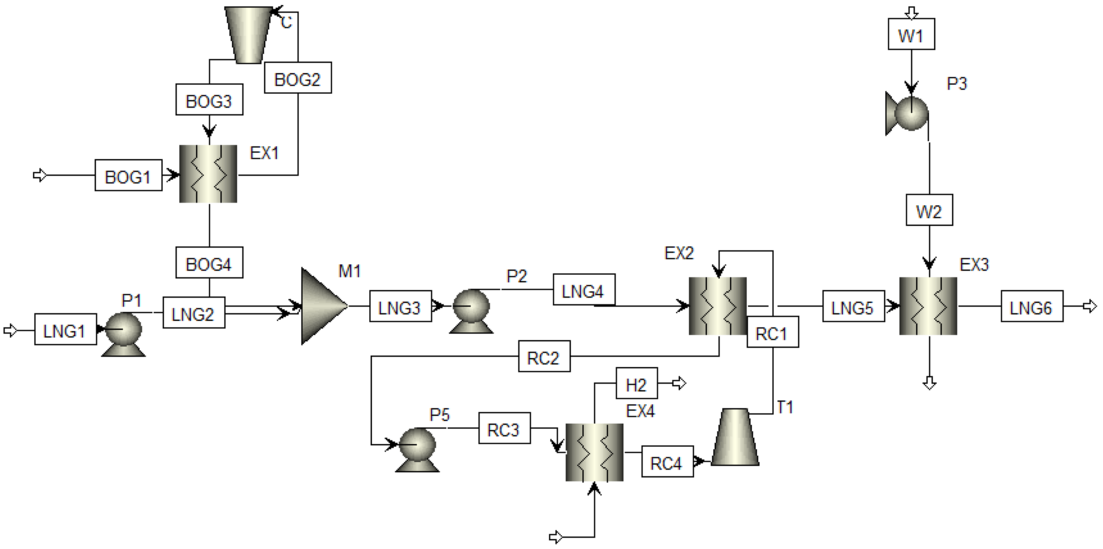

Figure 3: Scheme for Organic Rankin Cycle (ORC)

As a last evaluated scheme is the combination of ORC+DE. In this case the system makes use of both cold energy of LNG and the mechanical energy.

In order to run the simulations, all the blocks (units, devices) require input data. From the streams, the starting ones (LNG1, BOG1 etc) require input, while the others are calculated, based on the input of the first streams and the conditions for operation of the devices.

Based on the results obtained from streams and blocks, the indication parameters are calculated for all 12 cases.

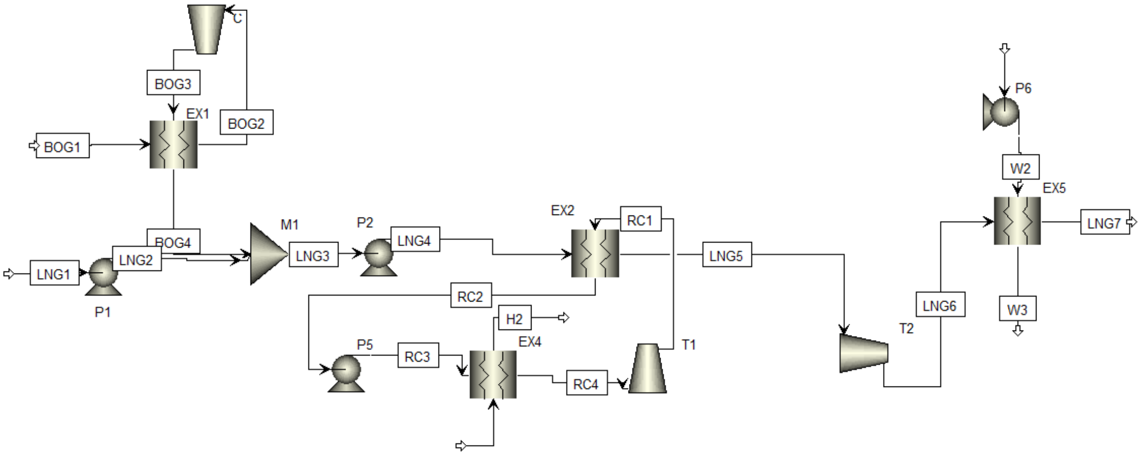

Figure 4: Scheme for Organic Rankin Cycle (ORC) + Direct Expansion Cycle (DE)

The results are displayed in Table 7. It can be noticed that there is no “absolute best” combination, and all of them have certain strong and weak points. Regarding the net power balance, the best result comes for the combination of ORC+DE, with NH3-H2O as working fluid. The best thermal efficiency is when propane is used as working fluid.

Table 7: Final results summary from all schemes

No.	Description	Pnet (MW)	Seawater (t/h)	Enthalpy lost (kJ/kg)	Thermal efficiency (%)
1	Seawater (ORV)	1.23	4950	736.71	/
2	Direct Expansion DE	0.06	5170	764.27	/
3	Seawater ORC propane	-2.52	5650	198.00	14.06
4	Seawater ORC ammonia	-2.21	5650	156.44	12.24
5	Steam ORC propane	-3.82	1350	195.47	17.78
6	Steam ORC ammonia	-3.75	1100	160.90	16.70
7	Gases ORC propane	-4.95	1350	201.06	21.13
8	Gases ORC ammonia	-5.03	1050	155.48	19.99
9	Gases ORC NH_3-H_20	-5.63	0	0.00	17.37
10	Gases ORC+DE propane	-4.37	2000	293.06	21.13
11	Gases ORC+DE ammonia	-4.62	1700	252.70	19.99
12	Gases ORC+DE NH_3-H_20	-7.09	102	14.90	17.37

The Conclusions from this work

All the ORC cycles show positive net balance for power in the terminal. Among them, propane used as working fluid has the best thermal efficiency of cycle, while with NH_3-H_2O mixture as working fluid. In the last combination ORC+DE, with propane and ammonia the net power balance decreases while with NH_3-H_2O increases.

From energetic balance point of view, all the ORC combinations show very promising results for further evaluation. When ORC is employed, in all combinations, the net power balance turns from negative to positive, so the terminal can sell the surplus electricity generated. Although the thermall efficiency of the cycles is low, this shouldn’t be seen as big downside. The reason for this is that in all simulations, low temperature heat is used. Having in mind that there aren’t direct GHG emissions from the cycles (no combustion of fuels), these cycles can be attractive for investment.

For further improvement of this work, in depth analysis of the load fluctuation and economic evaluation are suggested. The load fluctuation of the terminal can decrease the efficiency of the implemented cycle and prolong the payback period.

Economic analysis with detailed cash-flows will give a better overview for potential investors in this type of projects.

Nomenclature and Abbreviations

BOG – boil off gas
DE – direct expansion
GHG – greenhouse gases
ORC – Organic Rankin Cycle
ORV – open rack vaporizers
P – Power

h - enthalpy

LNG – liquefied natural gas

m – mass flow of stream

Q – evaporation heat

WF – Working Fluid

η_{th} - Thermal Efficiency

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