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

Milan Zlatkovikj

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisor: Prof. Henrique Anibal Santos de Matos

Examination Committee

Chairperson: Prof. Edgar Caetano Fernandes

Supervisor: Prof. Henrique Anibal Santos de Matos

Member of the Committee: Eng. Rui Marmota

November 2017

Acknowledgements

Getting close to finalizing this work, I want to express my gratitude to the people that helped me in making it. First of all, I want to thank my supervisor professor Henrique Matos and Antonio Domingues. Their in-depth knowledge of this thematic was the reason it started in the first place.

The experience of process integration and research work from professor Matos helped me in the analytical part of this work. On the other side, Antonio's vast experience in the oil and gas industry helped me to understand how the LNG industry works and the terminals in general. Their technical expertise is undeniable.

However, during this work, I realized that even with the best engineering skills some projects might get stuck, due to other non-related issues, that every student ocassionally evidents. For their help on this matter, I am even more grateful. The encouragement from professor Matos in the periods when the work wasn't going the best has great contribution, that now is finally coming to an end. On the other side Antonio's calmness and patience showed me that for some work time and patience are a must.

I would like to thank to the colleagues that worked during the same period in LabSOP at Tecnico. It was good to talk to people that already went through the process and their guidance was certainly helpful. Special thanks to Pedro and Simon for the help while learning the software package ASPEN, and to Catarina, for lending the entrance card, to be able to work during late hours and weekends.

Finally, huge thank you goes to InnoEnergy for financing the scholarship for this Master Program. Without it, it probably wouldn't have happened.

Abstract (EN)

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

Resumo (PT)

A fileira industrial do Gás Natural Liquefeito (GNL) é um processo com operações unitárias energeticamente intensivas, nomeadamente no processo de regaseificação. Este, é identificado como área potencial para aplicação de metodologias que promovem o aumento eficiência energética.

Os terminais de regaseificação recebem os carregamentos de GNL dos navios. Este é posteriormente regaseificado e distribuído para consumo, recorrendo a um consumo de energia adicional. O objectivo deste trabalho consiste na aplicação de opções de integração de processos para a identificação e avaliação de cenários que reduzem (ou eliminam) o consumo energético despendido nos terminais de regaseificação de GNL. As opções avaliadas consistem na utilização do frio de GNL para aplicações em refrigeração e ainda, integração em ciclos termodinâmicos para geração de energia eléctrica.

Neste trabalho, o Ciclo Orgânico de Rankine (COR), para geração de energia eléctrica é avaliado recorrendo a diferentes fluidos de refrigeração e fontes de calor, sendo depois combinado com processos de Expansão Directa (ED). Para tal, recorreu-se ao software Aspen Plus® v8.8, através do qual se realizaram todas as simulações. Para todas as alternativas estudadas obteve-se um balanço de potência positivo e uma redução na quantidade de água do mar a utilizar,Verificou-se ainda que o balanço melhora com o aumento da temperatura da fonte de calor. O coeficiente de eficiência térmica para o COR varia entre 12% e 21%.

Para a decisão de qual a melhor alternativa técnica do sistema com integração a instalar é recomendada uma análise económica robusta e quais as condições geográficas do local.

Palavras-chave: GNL terminais de GNL, integração, energia, COR, regasificação

Table of Contents

List of Tables

List of Figures

List of Abbreviations used

AAV – ambient air vaporizer

Bcm – Billion cubic meters

BOG – Boil Off Gas

DCF – Discounted Cash Flow

DE - Direct Expansion

HHV – Higher Heating Value

HP – high pressure

IFV – intermediate fluid vaporizer

LNG – Liquefied Natural Gas

LP – low pressure

MTPA – million tons per annum

NCF – Net Cash Flow

NG – Natural Gas

NPV – Net Present Value

ORC – Organic Rankin Cycle

RC – Rankin Cycle

SCV – submerged combustion vaporizer

WF – Working Fluid

Nomenclature

delta h1, delta h2 – Enthalpy lost (LNG) in heat exchangers [kJ/kg]

c1 – Power of compressor [kW]

HHV – Higher calorific value of NG

$\mathrm{MW_a}$ – Molecular Mass of NG

p – Pressure of NG [bar]

p1, p2 …p5 – Power of pumps [kW]

t1, t2 – Power of turbine [kW]

Qev – Heat of evaporation of working fluid (WF)

R – Gas constant

T – Temperature [K]

t – Temperature [^{o}C]

z – Gas compressibility factor

γ_g – gas specific gravity

υ_g – Kynematic viscosity of NG

μ_g – Dynamic viscosity of NG

ρ_g – Density of NG [kg/m^3]

γ_g – Relative gas density

$\eta_{\mathrm{is\ pump}}$ – Isentropic efficiency of pump [kW]

$\dot{W}_{\mathrm{is\ pump}}$ – Isentropic work of pump [kW]

$\dot{W}_{\mathrm{pump}}$ – Real work of pump [kW]

$\dot{V}$ – Volumetric flow [m^3/h]

$\dot{m}$ – Mass flow [t/h]

h^s – Isentropic enthalpy [kJ/kg]

h - Enthalpy [kJ/kg]

$\eta_{\mathrm{is\ turbine}}$ – Isentropic efficiency of turbine [%]

$\dot{W}_{turbine}$ – Real Work of turbine [kW]

$\dot{W}_{is\ turbine}$ – Isentropic work of turbine [kW]

$\eta_{thermal}$ – Thermal coefficient of efficiency [%]

Introduction to thesis work

We live in a world in which finally the energy supply gets all the attention that it deserves. It is not as some time ago, when the cheapest option was the best, and the care for the local and global pollution was almost non-existing. Today, after witnessing all the effects of unconscious use of the vast available fossil fuels resources, the emphasize is put that the future energy supply systems tend to be more energy efficient, with proper processes integration, which should minimize the effect on the local environment and on the global level, related to the global warming due to surplus of GHG emissions.

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

Natural Gas, according to recent reports, is the 3rd biggest provider of primary energy in the world, after crude oil and coal [1]. Unlike the other sources of energy (both fossil and renewable), natural gas is perhaps the single fuel which may be used for all the energy and consumption requirements we have – electricity, heating, cooking, transport, industry production, chemical products etc. According to the forecasts made for the energy mix in the future, the growth trend for natural gas will continue [2]. This is due to the fact of the vast expansion of the Liquefied Natural Gas (LNG) industry, and the high amount of research done in this area to improve processes efficiency and reduce operation costs. With the popularization of LNG, there are many indicators that it can soon overcome high-pressure pipelines international transport of natural gas. As analyzed in many research papers, the utilization of LNG is seen as a perfect option to increase natural gas market competitiveness and to put an end to the attempts of monopoly from some pipeline distributors, which stagnate progress and keeps prices at constant high level [3].

The future of gas supply will be from LNG. Due to this, all the effort should be put, that this industry efficiency is increased to the best possible level, and in the same time to reduce the emissions from the processes to a minimum level. After analyzing the characteristics of LNG and the operations included in the supply chain, it is found that the regasification part can generate significant energy gains, if integrated properly.

The regasification of LNG to condition in which it can be further distributed to consumers, is currently done generally in an energy inefficient way. To heat the LNG (in order to be in gas condition and specified temperature), it is used seawater as a heat source, combustion gases from natural gas, or some other intermediate fluid. All these options are practical and proved for operation, but there is much better practice that can be both practical and more energy efficient. The cold energy of LNG can be utilized in several different industrial processes that require cooling and power generation. In order to have the cooling in industry process implemented, the specific industry has to be very closely located to the LNG terminal. Due to this, the application options are limited. There is higher interest for power generation from LNG cold energy [4]. This can be done by integrating different power cycles with the path of regasification of LNG. The major developments in this area come from Japan, where several power plants are already operating for a long period [4].

In this work, we will evaluate the performance of several different power cycles, combined with regasification of LNG. The most important parameters here will be potential power generation, efficiency of cycles and utilization of LNG cold energy.

Description of work expectation

In order to evaluate the performance of these schemes, we will use the process simulation software ASPEN. It is well established for simulations in the chemical industry. It has high flexibility it is user friendly and has many tools for parameter analysis.

The evaluation of the available options starts from checking the already well-established “combinations”. The systems analyzed start from the most common one, using seawater (only as a further reference for comparison), adding Direct Expansion (DE) cycle, than adding one Organic Rankine Cycle (ORC) to it, and finally implementing ORC and DE together. The evaluations are done on the most important thermodynamic properties at the points of interest, such as: thermal cycle efficiency, differences of enthalpies of natural gas among key points, power generation and seawater requirement.

After analyzing the obtained results from ASPEN, they are to be compared with the results obtained in all the studies on the topic, in order to be verified.

Although we compare several different options, that are not most suitable for direct comparison, we can identify the configurations where they can fit best. Namely, depending on the location where the terminal is placed and the industry nearby, the options for utilization of waste heat, or the requirements for cooling differ.

Contents of the work

After the brief introduction about the thesis work, in **Chapter 1** are defined the most important characteristics of natural gas. This includes physical, chemical properties, phase behavior and other data deemed important for this work. These characteristics are crucial for implementing any gas processing systems, and their proper determination is a must.

Chapter 2 gives information about the rise of the LNG markets and their developments. Also future utilization analysis is provided. This information will help us understand the position of LNG in the energy mix, and the ability to identify possibilities for implementing new technologies. The potential on having new countries to import LNG in terminals is essential for developing new regasification systems.

In **Chapter 3**, the LNG supply chain is displayed. As it can be seen there, the process contains several stages. Every stage is significantly different from the others and has its own unique characteristics.

Chapter 4 is dedicated to the possibilities for regasification of LNG in terminals. First, a terminal and its most important elements are described, and later the regasification part is analyzed. Here are described the most common used options, the new more energy efficient solutions and review of the literature of done research work and new ideas on the topic.

Chapter 5 is like a bridge between **Chapters 4 and 6**. After the literature review, the combinations that are selected for evaluation and the parameters are displayed here. Contains brief description of the software used.

Chapter 6 contains the major part of the work done. Every evaluated scheme is presented here, with the scheme generated from ASPEN, and the obtained results presented.

In **Chapter 7**, there is a discussion for the feasibility, application and economics of the proposed solution.

The work ends with Conclusions and **Future Work Recommendation**. The obtained results and the directions to further improve this concept are discussed.

Due to the vast calculation data needed for justification of results, all the data that is considered crucial for calculations is displayed in **Annex.**

1. Characterization of NG and LNG

This Chapter covers the most important characteristics of Natural Gas (NG), and comparison with LNG, as a special form of NG. Starting from its origins and composition, than going through the most important characteristics, the key parameters of NG are defined. Ending with some insights about its use, and comparison to other fossil fuels, makes the transition from this Chapter to the next.

1.1 The basic – General overview

The most common definition for natural gas used in the literature is that it is a mixture of (mostly) hydrocarbon compounds in gaseous state. In the form that it is discovered, several different types of inorganic impurities are present [5]. According to both geologists and chemists, natural gas is a product of the decomposition of animals and plants. Depending on the origins and locations, its composition may vary significantly. In all the different compositions, methane has the highest percentage. Other present hydrocarbons are ethane, propane, butane and some other. The inorganic impurities present are nitrogen (N_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and there may be traces of other elements. These elements are not desirable for several reasons. They are not combustible, so the heating value of gas will be decreased. They may cause corrosion and other problems on the materials and the equipment used. Due to environmental concerns, the presence and emissions of these elements are often subject to strict regulation.

The accumulations of natural gas at certain specific locations are defined as gas reservoirs. Due to the similar origin as oil, in most of the reservoirs both oil and gas are present, in different ratios. Figure 1, shows general classification of gas reservoirs.

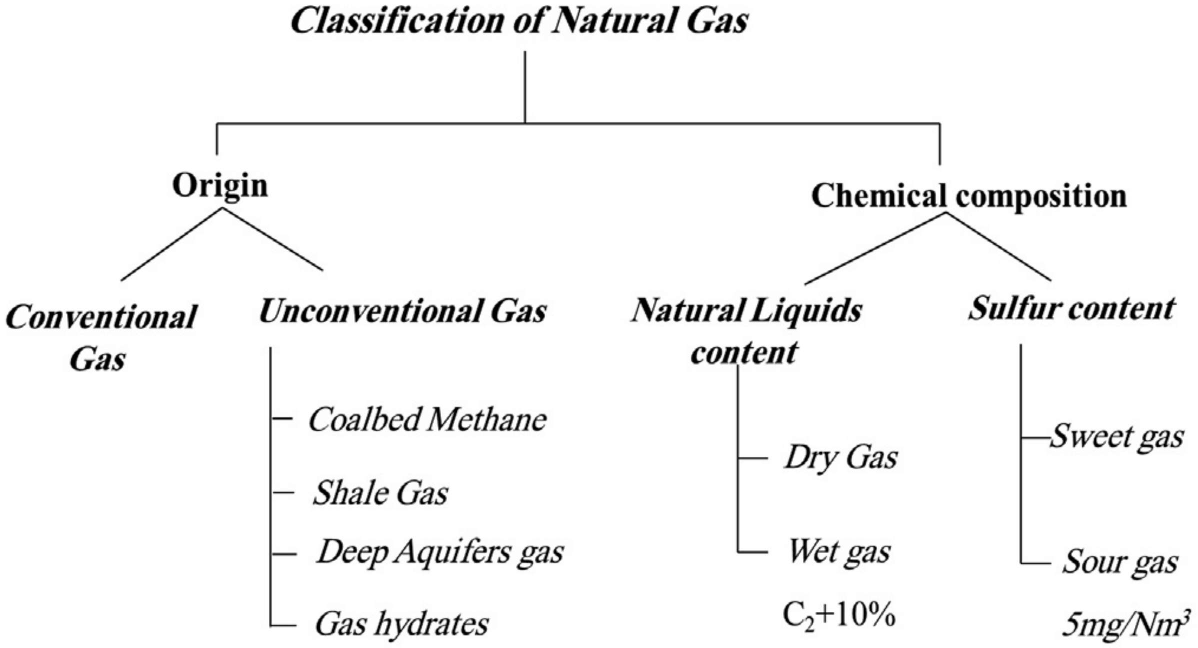


Figure 1: Classification of Natural Gas [6]

The classification is done by two general factors – origin and chemical composition. According to the origin, reservoirs can be classified as conventional and non-conventional.

The conventional gas can be associated or non-associated. Associated is the gas in reservoirs which contain significant amount of crude oil. This gas usually contains less CH_4, and higher percentage of the other present hydrocarbons (ethane, propane etc). The non-associated gas, also known as dry gas, contains minimal amount of oil or not at all. Due to this, in its composition CH_4 is richer compared to the associated gas [6].

The unconventional gas definition depends on the area where it is used. According to IEA, unconventional gas is classified as gas which is technologically more difficult or more expensive to produce than conventional gas [7].

In the industry, it is defined as reservoirs that do not provide economic volumes of natural gas without assistance from massive stimulation treatments, special recovery processes and technologies [7].

Among unconventional gas is classified: coal-bed methane, shale gas, deep aquifers gas and gas hydrates [7]. Here the most interesting one, by far, is the shale gas. It has huge potential and reserves to make significant change in the natural gas industry. However on the other side, it has several environmental concerns, which limit its utilization. Gas hydrates are estimated to have huge potential also, however due to their nature (methane in solid form – ice), their exploitation still needs significant technological development in that sector.

The classification by the chemical composition is done by two criteria. First one is the content of different type of hydrocarbons. If the gas is mostly composed from CH_4 it is referred as dry, while containing higher amounts of other hydrocarbons defines it as wet gas. The second classification done by sulfur content, similar as for crude oil, defines the gas as sweet (low or no sulfur at all) and sour (higher amount of sulfur).

1.2 Composition of natural gas

As displayed before natural gas is a complex mixture of several different components. The share of these components depends on the origin of the gas – the reservoir type. The range of the present components is displayed in Table 1.

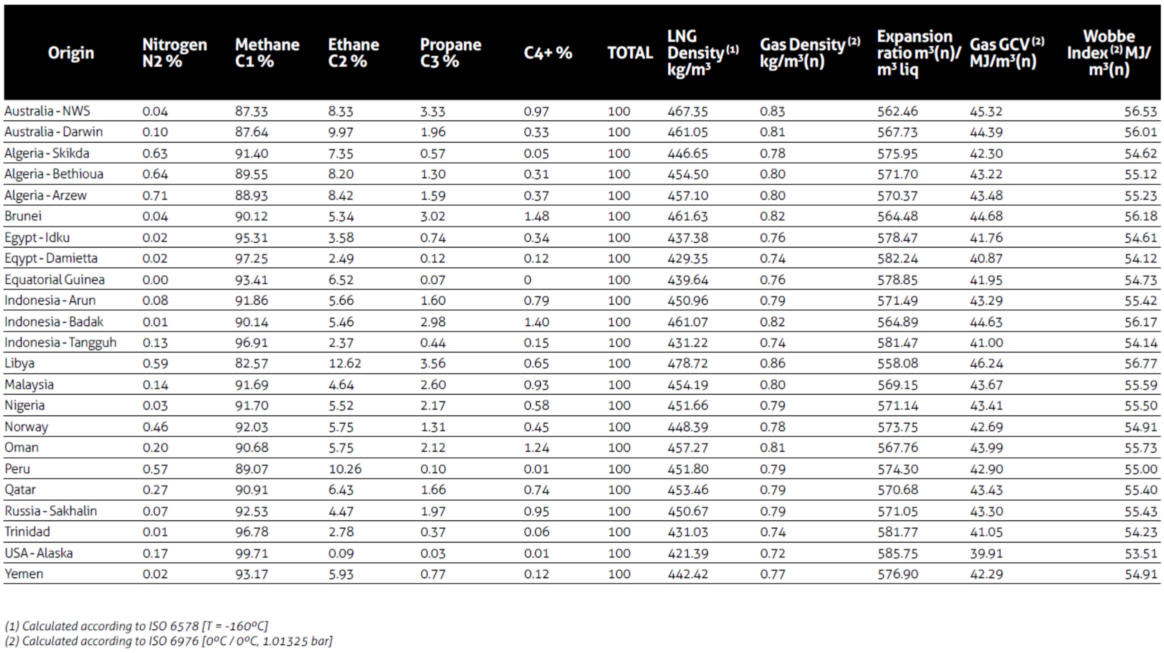
Table 1: Components of Natural Gas [8]

Hydrocarbon	Chemical Formula	Lower Limit %	Higher Limit %
Methane	CH_4	87	99
Ethane	C_2H_6	<1	10
Propane	C_3H_8	>1	5
Butane	C_4H_{10}	>1	>1
Nitrogen	N_2	0.1	1
Other HC	Various	Trace	Trace

This variation of composition will imply additional variation in important gas characteristics, in the stages of its processing. Characteristics such as gas compressibility, density, viscosity, will have very important role in determining gas flow from the reservoirs, calculations for material balance, and design of the processing equipment [9].

On Table 2 are displayed characteristics of natural gas from producing countries around the world, which export LNG.

Table 2: Composition of NG from different countries and characteristics [10]



Origin	Nitrogen N2 %	Methane C1 %	Ethane C2 %	Propane C3 %	C4+ %	TOTAL	LNG Density [(1)] kg/m³	Gas Density [(2)] kg/m³(n)	Expansion ratio m³(n)/ m³ liq	Gas GCV [(2)] MJ/m³(n)	Wobbe Index [(2)] MJ/ m³(n)
Australia - NWS	0.04	87.33	8.33	3.33	0.97	100	467.35	0.83	562.46	45.32	56.53
Australia - Darwin	0.10	87.64	9.97	1.96	0.33	100	461.05	0.81	567.73	44.39	56.01
Algeria - Skikda	0.63	91.40	7.35	0.57	0.05	100	446.65	0.78	575.95	42.30	54.62
Algeria - Bethioua	0.64	89.55	8.20	1.30	0.31	100	454.50	0.80	571.70	43.22	55.12
Algeria - Arzew	0.71	88.93	8.42	1.59	0.37	100	457.10	0.80	570.37	43.48	55.23
Brunei	0.04	90.12	5.34	3.02	1.48	100	461.63	0.82	564.48	44.68	56.18
Egypt - Idku	0.02	95.31	3.58	0.74	0.34	100	437.38	0.76	578.47	41.76	54.61
Eqypt - Damietta	0.02	97.25	2.49	0.12	0.12	100	429.35	0.74	582.24	40.87	54.12
Equatorial Guinea	0.00	93.41	6.52	0.07	0	100	439.64	0.76	578.85	41.95	54.73
Indonesia - Arun	0.08	91.86	5.66	1.60	0.79	100	450.96	0.79	571.49	43.29	55.42
Indonesia - Badak	0.01	90.14	5.46	2.98	1.40	100	461.07	0.82	564.89	44.63	56.17
Indonesia - Tangguh	0.13	96.91	2.37	0.44	0.15	100	431.22	0.74	581.47	41.00	54.14
Libya	0.59	82.57	12.62	3.56	0.65	100	478.72	0.86	558.08	46.24	56.77
Malaysia	0.14	91.69	4.64	2.60	0.93	100	454.19	0.80	569.15	43.67	55.59
Nigeria	0.03	91.70	5.52	2.17	0.58	100	451.66	0.79	571.14	43.41	55.50
Norway	0.46	92.03	5.75	1.31	0.45	100	448.39	0.78	573.75	42.69	54.91
Oman	0.20	90.68	5.75	2.12	1.24	100	457.27	0.81	567.76	43.99	55.73
Peru	0.57	89.07	10.26	0.10	0.01	100	451.80	0.79	574.30	42.90	55.00
Qatar	0.27	90.91	6.43	1.66	0.74	100	453.46	0.79	570.68	43.43	55.40
Russia - Sakhalin	0.07	92.53	4.47	1.97	0.95	100	450.67	0.79	571.05	43.30	55.43
Trinidad	0.01	96.78	2.78	0.37	0.06	100	431.03	0.74	581.77	41.05	54.23
USA - Alaska	0.17	99.71	0.09	0.03	0.01	100	421.39	0.72	585.75	39.91	53.51
Yemen	0.02	93.17	5.93	0.77	0.12	100	442.42	0.77	576.90	42.29	54.91

(1) Calculated according to ISO 6578 [T = -160ºC]
(2) Calculated according to ISO 6976 [0ºC / 0ºC, 1.01325 bar]

As It can be seen the gas coming from different parts of the world have different composition in start, which later yields different gas characteristics, such as density and expansion ratio.

1.3 Natural gas characteristics

Among the most important characteristics of natural gas are: gas-specific gravity, pseudocritical properties, viscosity, compressibility (deviation) factor, gas density, gas compressibility, heating value and Wobbe index. Accurate calculation of these parameters is crucial for optimal construction of the natural gas systems.

Natural gas is a complex mixture of several different types of components. In order to apply the developed models for calculating its properties, it is needed to know its composition. When new field/reservoir for gas is developed, sample of the gas is taken to laboratory. Using chromatography, a detailed composition of the gas is obtained, most often expressed in molls.

Gas-specific gravity (γ_g) is the ratio between the molecular weight (MW) of NG and air. Taking the composition of air approximated to 21% O_2 and 79% N_2, its molecular weight is 28.97 [g/mol]. The formula to calculate γ_g is:

$$\gamma_g = \frac{MW_a}{28.97} \tag{1}$$

The molecular weight of NG is calculated according to its composition, using the mixing rule. This ratio will always be lower than unity. Most often it is in the range of 0.6-0.75.

Viscosity is defined as a measure for the resistance to flow of the fluid. It is characterized for both liquids and gases, and it describes how “difficult” it is to move the fluid. Liquids have higher viscosities compared to gases. There are two measures for viscosity: dynamic and kinematic. In NG industry dynamic viscosity is used most often.

The relation between dynamic and kinematic viscosity is with the density of the fluid:

$$\upsilon_g = \frac{\mu_g}{\rho_g} \tag{2}$$

Where:

$$\upsilon_g - Kynematic\ viscosity\ of\ NG$$

$$\mu_g\ Dynamic\ viscosity\ of\ NG$$

$$\rho_g - Density\ of\ NG$$

Similar as for the composition, for new gas fields, measurement is preferred to define the viscosity of the gas. To measure viscosity, viscometer or rheometer is utilized.

In the literature there are charts and correlations developed in order to estimate gas viscosity.

Gas compressibility factor is also known as deviation factor, or z factor. It gives an overview how much the real gas deviates from the behavior of ideal gas at given temperature and pressure. It can be defined from the ratio of volumes of real and ideal gas:

$$z = \frac{V_{real}}{V_{ideal}} \tag{3}$$

Gases are compressible fluids. Due to this, their **density** will vary with temperature and pressure. Starting from the equation for ideal gas, density can be expressed as:

$$\rho = \frac{m}{V} = \frac{MW_a p}{zRT} \tag{4}$$

Where:

$$MW_a -\ molecular\ mass\ of\ NG$$

$$p - pressure\ of\ NG$$

$$z - gas\ compressibility\ factor$$

$$R - gas\ constant$$

$$T - temperature\ [K]$$

After all the processing and transport operations, the final utilization of natural gas is as a fuel. Due to that, one of the key characteristics is its heating value – the heat that it releases in combustion. As it is displayed in Table 2, depending on the composition the heating value can vary. There are two types of heating value defined, and they should be differentiated in order to avoid confusion about the value and later in analyzing processes efficiency.

Gross (Higher, HHV) heating value is the total energy transferred as heat in an ideal combustion reaction at a standard temperature and pressure in which all water formed appears as liquid [a1].

Net heating value (Lower) is the total energy transferred as heat in an ideal combustion reaction at a standard temperature and pressure in which all water formed appears as vapor [a1].

As it was displayed in Table 2, the heating value and density of NG vary, depending on NG origin. However, most of the devices that burn and use the exhaust gases coming from NG combustion (burners, boilers, gas turbines etc.), are designed to provide best efficiency in operation for a pre-defined operating parameters. In order to deal with the different NG composition and characteristics, a practical indicator for NG is **Wobbe index**. It is defined as an indicator of interchangeability of NG.

Wobbe index (Wb) is defined as characterization for gas mixtures, based on the released heat during combustion. It is frequently used to determine the limits of certain components in the gas composition. It can be calculated from:

$$Wb = \frac{HHV}{\sqrt{\gamma_g}} \tag{5}$$

Where:

$$HHV - Higher\ calorific\ value\ of\ NG$$

$$\gamma_g - Relative\ gas\ density$$

On Figure 2 is displayed the variation of Wobbe index due to different composition and heating value for NG coming from different regions.

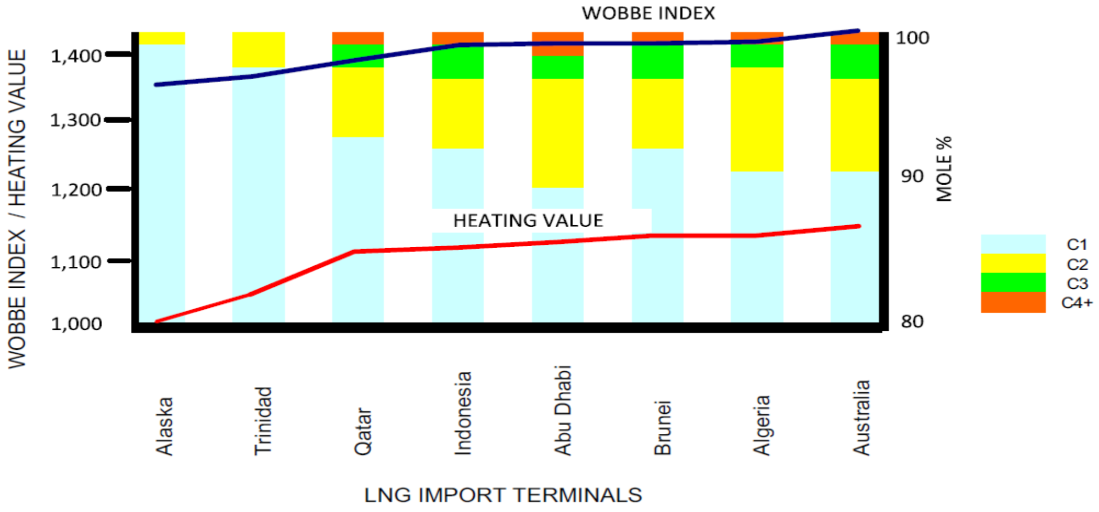


Figure 2: Wobbe Index variation [11]

1.4 Equations of state – EOS

The simplest developed correlation to describe behavior of gases is the equation for ideal gas behavior.

The concept of ideal gas is used as a starting point in describing the behavior of real gases. As an approximation is stated that in ideal gas the volume of molecules and the forces between the molecules are so small that they have no effect on the behavior of the gas. The mathematical equation for ideal gas is:

$$PV = nRT \tag{6}$$

While dealing with gas behavior with low pressures (not higher than 1atm), the ideal gas equation can be implemented to obtain gas behavior. The expected error from this approach is around 2-3%. However when calculations for higher pressures are needed, utilizing the ideal gas equation can provoke mistake of several hundred percent, which is very far from being acceptable. Due to this, another approach is required.

The Law of Corresponding States is proposed by van der Waals in 1873. It expresses a generalization that equilibrium properties which depend on intermolecular forces are related to the critical properties in universal way [a7]. This Law gives the most important basis for further work on correlations and estimation methods. The basic equation for this law is:

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT \tag{7}$$

Where:

$$a, b - constants$$

An ideal estimating method for properties would contain [12]:

- Provide reliable physical and thermodynamic properties for pure substances and mixtures at any given temperature, pressure and composition
- Indicate the phase – solid, liquid or gas
- Requires minimum input data
- Least-error
- Indicate probable error
- Minimize computation time

Based on van der Waals work and the Law he proposed, several different equations of state have been developed. Among the most popular and practical to utilize in the petroleum industry are Peng-Robinson EOS and Soave Redlich Kwong, commonly known as SRK. Peng-Robinson EOS is the most frequently used method for natural gas engineering. It has been developed at the University of Alberta, Edmonton, Canada, especially for natural gas systems [13].

After modifying van der Waals equation, the general form of Peng-Robinson EOS is [13]:

$$\left(P + \frac{\alpha a}{\check{\upsilon}^2 + 2b\tilde{\upsilon} - b^2}\right)(\tilde{\upsilon} - b) = RT \tag{8}$$

Where:

$$\alpha, a, b - functions\ of\ the\ critical\ properties$$

This equation is used in many of the simulation software, including ASPEN Plus, which will be utilized in this work.

1.5 Liquefied natural gas – LNG characteristics

Liquefied natural gas, widely known by the abbreviation LNG, is natural gas in liquid phase. In order to obtain LNG, natural gas need to be cooled (liquefaction process) to temperatures of around -162 ^{o}C, for atmospheric pressure. For natural gas, the critical parameters, pressure and temperature are around 46 bar and -82 ^{o}C, respectively [14]. These values can vary depending on the exact composition, having in mind that natural gas is a mixture of several gases.

The main component of natural gas is methane. Its concentration varies, but in all the cases it's the major part. Due to it, very often, as approximation natural gas is considered as a pure substance – methane, to make it easier for solving certain problems. Other components present in natural gas, are other paraffinic hydrocarbons such as ethane, propane, butane. Nitrogen can be present in very small amount (less than 1%). Before being liquefied, the gas has to be clean from oxygen, carbon dioxide, sulfur compounds, mercury and water.

The evaluation of LNG starts by assessing its chemical and physical characteristics [a4]. These characteristics will depend on the composition of LNG, which will be a result from the characteristics of the reservoir (origin of natural gas) and the liquefaction process used. LNG is characterized as a colorless, odorless and noncorrosive liquid [15].

It is essential to have good understanding about the pros and cons from LNG. Not only the engineers which are developing the systems, but also the local communities which should be the one utilizing the gas in the last phase. The Asian countries Japan and South Korea, has taken this to the highest level by creating museums in which children can see the behavior of LNG [8]. As companies which have strongly contributed to the development of all types of systems for processing of LNG, Osaka Gas Company and Tokyo Gas Company are the leading ones in this sector. They have opened Gas Science Museums – the first one was opened in the year 1982 and it is estimated that every year 50,000 children have the opportunity to visit this museums which demonstrate LNG properties [8].

In order to be liquefied, natural gas has to be cooled to temperatures of -162 ^{o}C. This makes it a cryogenic liquid, which demands special equipment for handling. As cryogenic liquids are defined those that are handled at -100 ^{o}C or lower [8].

When LNG gets in contact with ambient air or water, it starts to boil. This is because the environment is at much higher temperature than the boiling temperature of LNG (-162 ^{o}C). This phase change at room temperature is well illustrated at Figure 3.

Figure 3: LNG at room temperature [8]

For safe handling of LNG processes, it is essential to know its behavior, in cases of unintentional or intentional release into atmosphere. On Figure 4 is displayed training simulation for personnel working with LNG. When sufficient amount of LNG is released at atmospheric conditions, it vaporizes. These vapors are cold and they will condense the moisture from air, creating a vapor cloud in the process.

Figure 4: Controlled release of LNG for the purpose of staff training [8]

1.6 Natural Gas and LNG comparison

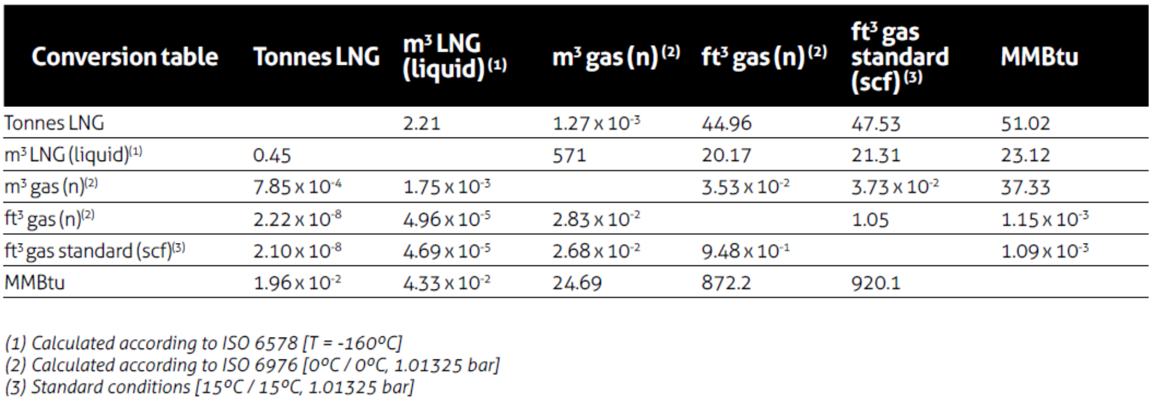
Before being liquefied, the gas is compressed, in order to facilitate further transport. Due to this compression, the volume ratio between LNG and NG is 1/600 – 1m^3 of LNG contains 600m^3 of NG.

The relation between the quantities of NG and LNG are very essential. In addition, we need to have in mind that there are three major types of unit systems used in the world: Metric, Imperial and US customary units. Often the trade and some research data are operated in systems which contain fundamental differences, and due to it, the conversion of units is very important, and the tables summarizing the key conversions are very practical. The relation between the quantities of LNG and NG are displayed in Table 3. Detailed conversion tables for the most used units are available at NG Conversion Pocketbook [16].

After vaporization (regasification) of LNG to natural gas, it is combusted, to generate heat. The characteristics of this fuel are very low particle emissions, lower carbon dioxide emissions compared to other fossil fuels, low level of nitrogen oxides and almost no sulfur oxides. Due to these characteristic, natural gas has the reputation of clean fuel.

The density of LNG is in the range of 430-470 kg/m^3 [15]. If it's spilled in water (during transport for example), it floats on the surface, and vaporizes.

Table 3: Key conversions between LNG and NG [10]



Conversion table	Tonnes LNG	m^3 LNG (liquid) (1)	m^3 gas (n) (2)	ft^3 gas (n) (2)	ft^3 gas standard (scf) (3)	MMBtu
Tonnes LNG		2.21	1.27×10^{-3}	44.96	47.53	51.02
m^3 LNG (liquid)(1)	0.45		571	20.17	21.31	23.12
m^3 gas (n)(2)	7.85×10^{-4}	1.75×10^{-3}		3.53×10^{-2}	3.73×10^{-2}	37.33
ft^3 gas (n)(2)	2.22×10^{-8}	4.96×10^{-5}	2.83×10^{-2}		1.05	1.15×10^{-3}
ft^3 gas standard (scf)(3)	2.10×10^{-8}	4.69×10^{-5}	2.68×10^{-2}	9.48×10^{-1}		1.09×10^{-3}
MMBtu	1.96×10^{-2}	4.33×10^{-2}	24.69	872.2	920.1	

(1) Calculated according to ISO 6578 [T = -160°C]
(2) Calculated according to ISO 6976 [0°C / 0°C, 1.01325 bar]
(3) Standard conditions [15°C / 15°C, 1.01325 bar]

Having in mind the huge temperature difference between LNG and the surrounding environment, it is essential to provide suitable insulation in all the processes in the supply chain. If kept under constant pressure LNG will not have significant temperature change. This phenomenon is known as auto-refrigeration. If the Boil Off Gas (BOG) is extracted from the tanks in a controlled process, the auto-refrigeration will keep the major part of the content in the desired temperature [8]. The exiting BOG is used in several different purposes, depending whether on ship or at LNG tanks in ports.

In the highly competitive oil and gas industry, in order to obtain sufficiently good performance at low temperatures, it is essential to have accurate description of phase behavior of the hydrocarbon mixtures used in the processes.

1.7 Comparison to other fuels and utilization

NG is a fossil fuel, same as oil and coal. Its origin and composition were analyzed earlier. Due to its carbon contents, after combustion there are CO_2 emissions. However, due to the fact that the C/H ratio in this fuel is much smaller compared to oil and coal, and to the ease of combustion, the emissions of CO_2 are significantly lower. In addition, due to the treatment before use (cleaning), NG is almost sulfur free and also has less NO_x emissions than oil and coal. Comparison is provided in Table 4.

Table 4: Comparison of CO_2 emissions of fossil fuels [17]

Fuel type	NG	Diesel	Hard Coal
Emissions kgCO_2 / kwh	0.2	0.27	0.34
Emissions kgCO_2 / GJ	56.1	74.1	94.6

.

2. LNG Market

After discovering of natural gas, there has been constant effort to be able to liquefy it, in order to facilitate transport. After several related discoveries, natural gas is liquefied in US. According to reports, the first liquefaction of natural gas was performed in US in 1918 [18].

After this the commercialization of projects started. In 1959 the first LNG ship from Louisiana US sailed to United Kingdom. Later UK started importing gas from Algeria also, making this country the first major exporter of LNG. The exports were made from the national company Sonatrach [18].

Today's biggest consumer Japan, started importing from the year 1969. The imports were coming from Alaska, US. In the coming two decades, Japan invests heavily in LNG terminals, and since then is by far the biggest importer of LNG. Due to the major supply with gas, in that period gas turbines were developed as an environmentally better option compared to steam turbines in coal power plants. [18]. On Figure 5 is presented a World Map with the first LNG terminals

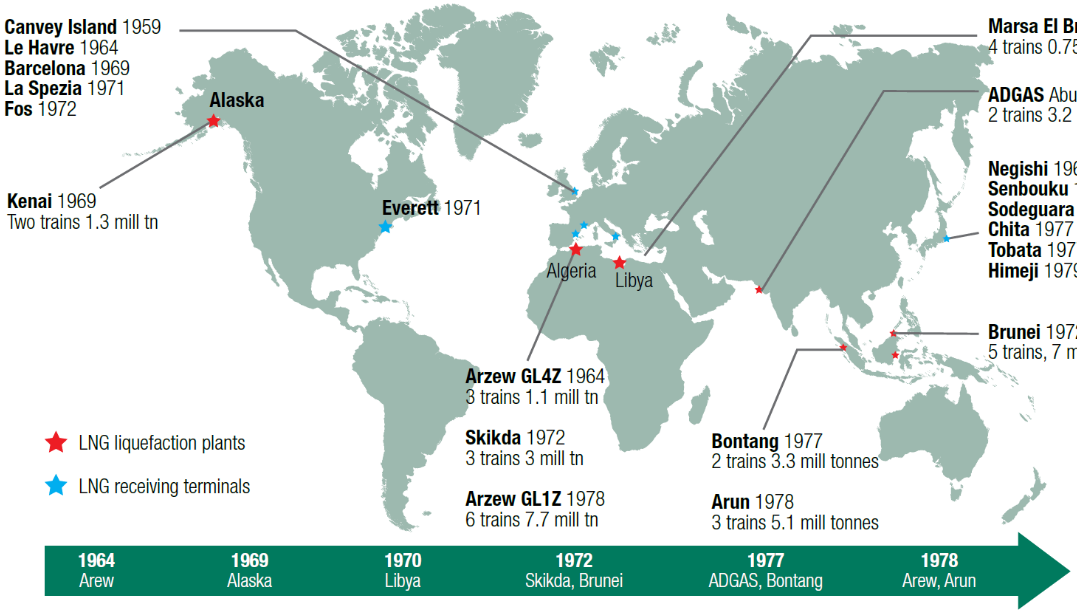


Figure 5: First LNG terminals in the world [19]

Natural gas has important role in many countries around the globe to achieve economic and energy demand goals. This implies to both producing (exporting) countries and to the ones that import it. For a period longer than 40 years (since the start of LNG trade until now), the safety record has been very positive for LNG industry.

The natural gas market is restricted by distance between the producing country (exporter) and the consuming (importer). Since the first major projects on gas trade were by pipelines, as a proven and cheaper option, the trade connections are between countries in close regions such as: Europe-Russia, Middle East – Asia and US-Canada.

After its slow start, the LNG industry takes off in continuous progress. After analyzing saved records for LNG trade throughout the years, the increase is obvious. Figure 6 displays the share of LNG in the natural gas utilization.

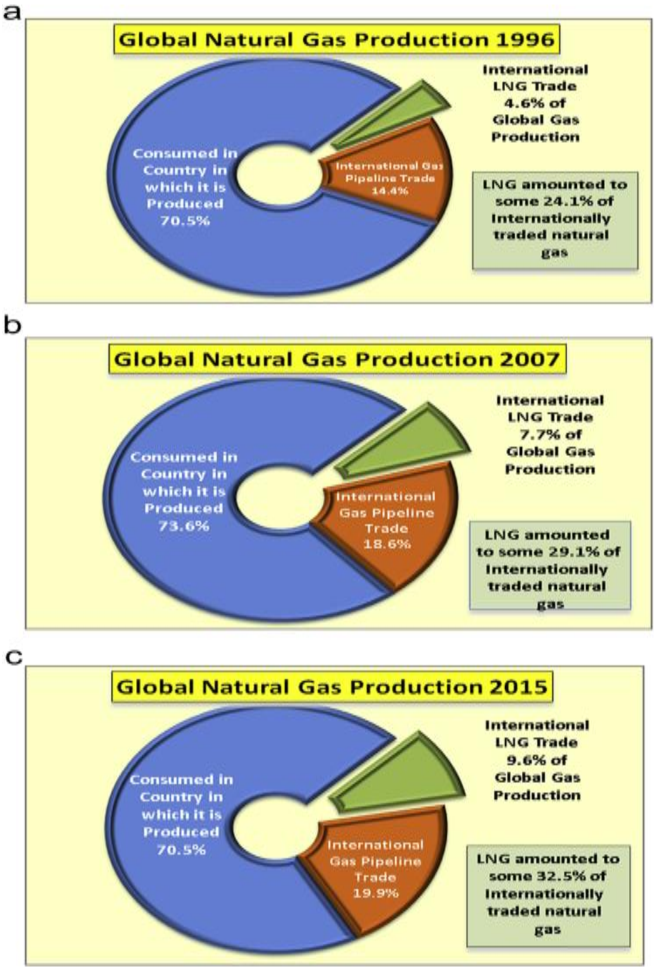
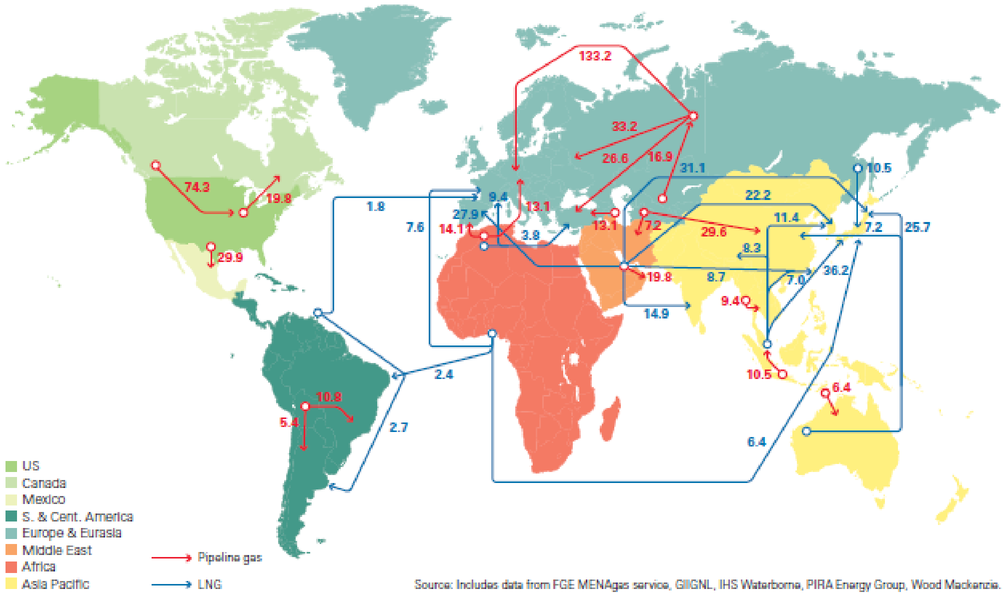


Figure 6: LNG share in years 1996, 2007 and 2015 [3]

In the BP Review for 2016 [1], is displayed the current situation of the natural gas industry, the participation of LNG and key trends.

The trade routes are established primarily based on the distance between countries, the amount of the gas demand per country, the long or short term contracts, and ultimately relations between countries.

As displayed in the USA analysis document [18], the trade can roughly be divided into two big regions: Atlantic and Asia/Pacific basin. It is an interesting fact that the total consumption in the Atlantic region is much higher than that of Asia/Pacific, but the second region has much higher imports and is responsible for the development of the LNG international trade and the constant grow. All the trade flows of NG (both by pipeline and LNG) are presented in Figure 7.

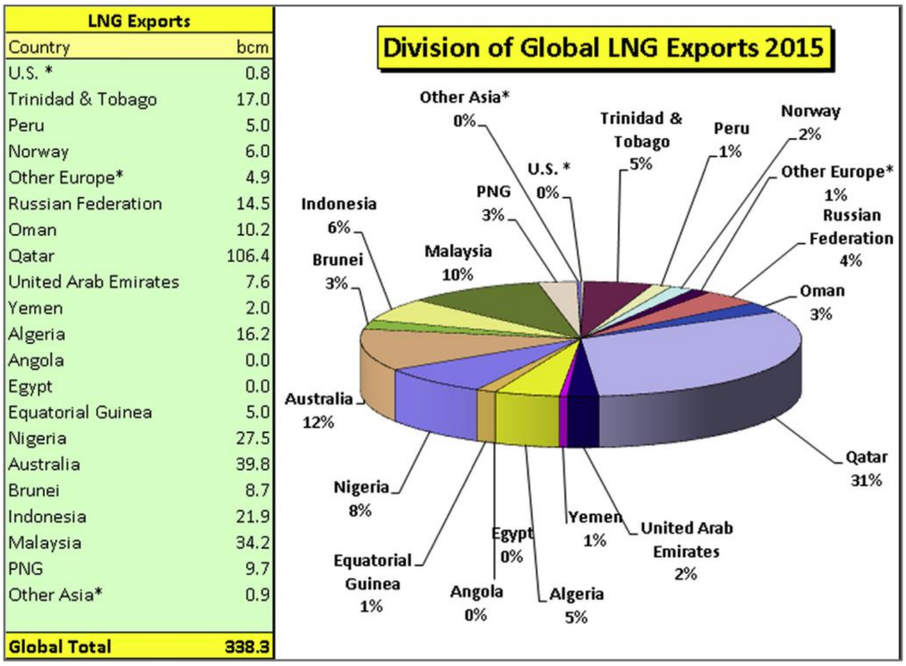


Source: Includes data from FGE MENAgas service, GIIGNL, IHS Waterborne, PIRA Energy Group, Wood Mackenzie.

Figure 7: NG trade flows in the World [1]

As an exemption, it can be noted that in some periods there are shipments between locations that are not connected on the map. This is due to the fact that the consumption varies, the market flexibility and supply grows, and the importers have several available options now.

The exporting countries are well established in this market. They have certain market share, and have sufficient resources to invest in technology improvement and capacity increase. On Figure 8, are shown the top exporting countries, by amount of LNG, and as a percentage of the total trade.



LNG Exports

Country	bcm
U.S. *	0.8
Trinidad & Tobago	17.0
Peru	5.0
Norway	6.0
Other Europe*	4.9
Russian Federation	14.5
Oman	10.2
Qatar	106.4
United Arab Emirates	7.6
Yemen	2.0
Algeria	16.2
Angola	0.0
Egypt	0.0
Equatorial Guinea	5.0
Nigeria	27.5
Australia	39.8
Brunei	8.7
Indonesia	21.9
Malaysia	34.2
PNG	9.7
Other Asia*	0.9
Global Total	**338.3**

Figure 8: Major LNG exporters for year 2015 [3]

2.1 The LNG market structure today

LNG market is strongly developed at the moment. In addition in all scenarios, it is predicted constant grow in the near future, and combining these two facts, LNG is regarded as one of the most interesting markets.

The most important facts about LNG industry for the year 2016 are displayed in Table 5.

Table 5: Key facts for LNG in year 2016 [10]

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

It is notable that there are two times more countries that import LNG compared to exporters. The number of exporters is relatively stable, due to the fact, that the countries that have potential to export LNG have already developed suitable infrastructure for that. On the other side of the chain, due to the many benefits and decreasing prices, the number of importers is constantly increasing. In 2016 countries four new countries appeared as LNG importers, and 11 new regasification terminals started operating. Even countries which have high capacity installations for pipeline transport started building LNG terminals, in order to diversify their supply. Among the most important on this list are: UK, Netherlands, Poland, and others.

As obvious consequence from the ratio of the importing and exporting countries, the difference between the regasification and liquefaction capacity is also significantly different. There is more than double capacity for regasification than liquefaction. The reason behind this is that the total capacity of the regasification terminals is not entirely utilized. Some of them serve as a backup, for peak-shaving periods, or in periods with unexpected high demand of gas.

There is increase of 7.5% in the imported quantity compared to year 2015 [10]. It is expected the growing trend to continue in the future, partially due to the increase of natural gas demand and partially due to choosing LNG instead of pipeline imports.

As one of the trademarks of the LNG market, is the huge part the Asian market plays in it. Japan and South Korea have high consumption of LNG for a long time. When we consider also the increasing consumption in China, and the expected grow in India, it is obvious that this region will keep its major share of LNG imports. In 2016, this part was 73% of the total share [10].

As other characteristic on the other side of the market, the exporters, there are several countries which hold important share of the exports. Qatar is the biggest exporter, with 30% from the total quantity [10]. Also this is the country which invests most in developing new technologies to increase the size of the liquefaction trains (plants). After Qatar, next on the high exporters list are Malaysia and

Australia. Malaysia is among the first countries that became major exporters of LNG, and Australia has recently increased its capacity.

The trade relations, contracts between countries and the directions of trade are displayed on Figure 9.

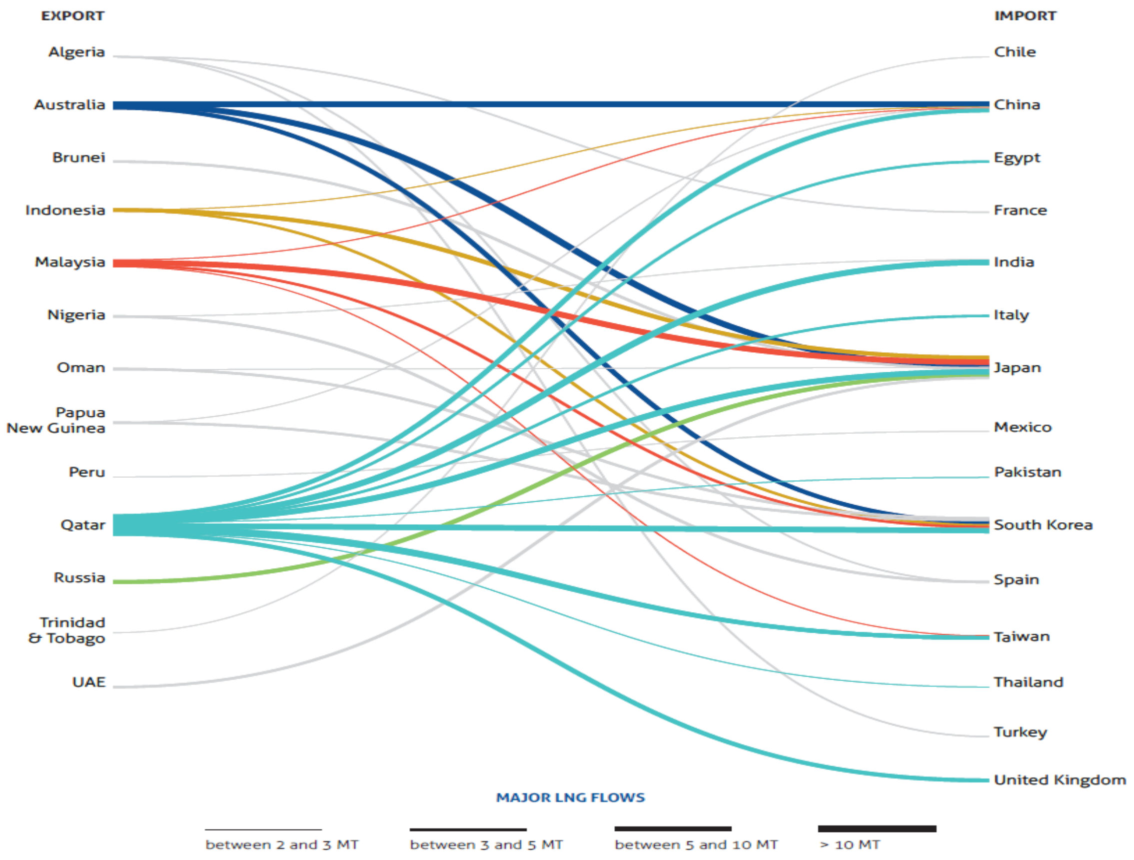


Figure 9: Trade flows for LNG [10]

In 2016 there has been increase in both liquefaction and regasification terminals. The liquefaction capacity is increased for 36 Million Tons Per Annum (MTPA), while the regasification capacity is increased by 32 MTPA. Under construction are additional 86 MTPA of regasification capacity, and 108 MTPA of liquefaction capacity.

Having in mind the projects under construction, on both sides exporting and importing, the growth of the market is ensured.

2.2 The future of the LNG market

In the outlook of BP, for the energy consumption up to 2035 [2], LNG is identified as one of the key factors. Significant growth in the sector is expected. In the first few years, the growth in exporting capacity is expected to come from US (due to their shale gas boom) and Australia, which has several big projects in final stage of construction.

According to the Outlook, the growth in LNG trade will be seven times higher than that by pipeline trade, which should result in 2035, LNG holds almost a half of the total trade of gas. At the moment, it has a share of 32%. The huge interest in LNG comes from the fact that unlike pipeline transport, LNG carriers can be redirected to preferred locations. When demand and supply varies in some regions, the cargoes can be redirected according to the needs. This should help to have much better integrated gas market in the world.

2.3 Spot and Short term contracts

As one more interesting feature of the LNG markets are the spot and short-term contracts. Spot contract is defined as contract for buying/selling a commodity for immediate settlement (payment and delivery) within few working days. This comes useful in the LNG sector due to price and demand variation. As a short term contracts are defined those below four years of duration. In 2016, 74.6 million tons of LNG has been traded under spot and short term contracts, which is 28% from the total share [10]. After the growth in the previous years, the last 2-3 years there is stabilization of the quantities and share this type of trades cover. Due to that, since they cover almost 1/3 of the total trade, they are important factors in the drive for increase in the coming period, and the factors affecting them should be carefully considered [20].

2.4 LNG in Portugal

In Portugal, there is one regasification terminal, located in the port of Sines. This terminal is in the complex with the oil refinery.

This terminal has been constructed in 2004, and it is used for import of LNG through ship carriers and for trucks loading, for distribution along the country. It is owned and operated by REN Atlantico.

It has a storage capacity of three tanks with a total capacity of 390000 m^3. For regasification, there are seven vaporizers, and the nominal capacity is 7.6 Billion cubic meters (Bcm) per year [10] .

The majority of the supply comes from Nigeria, through long term contracts through the Portuguese company Galp Energia [10].

3. LNG Supply Chain

From the phase of exploration up to the final distribution of natural gas to final consumers, there are several phases. The whole process is displayed on Figure 10 below. Due to the many stages involved in the process, the capital investments are very high for making new terminals.

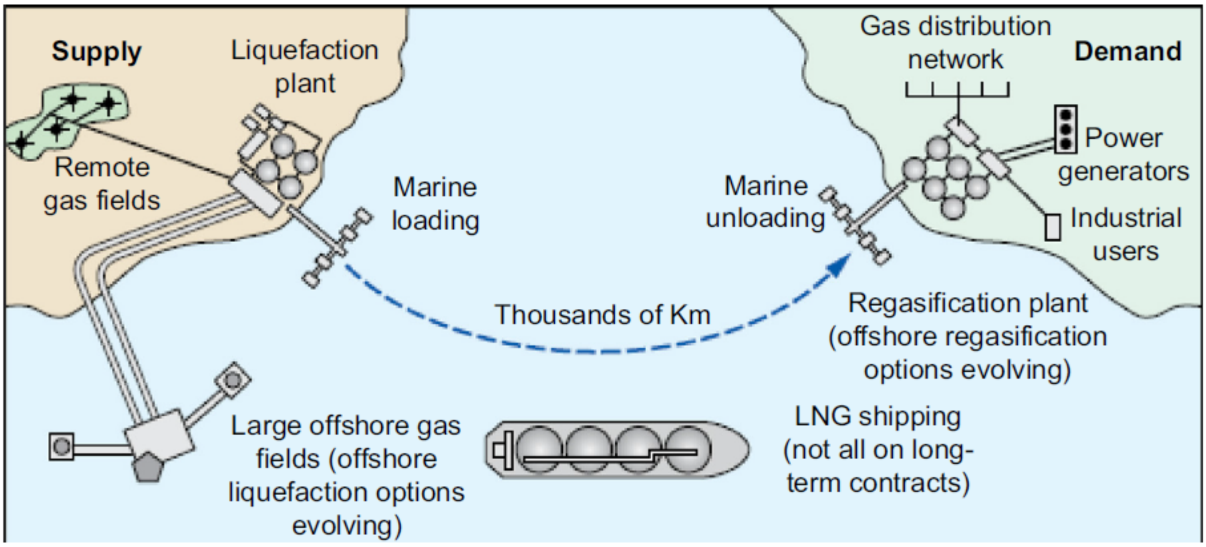


Figure 10: LNG supply chain [11]

The process starts with phase one usually defined as production and treatment. This part is defined in the petroleum industry as upstream. Briefly, the path of LNG starts at gas fields, which can be on and offshore. The obtained gas from the field is treated, depending on further process requirements and on the original composition. After removing the impurities from the gas in the treatment process, the next stage is liquefaction. Here, natural gas is compressed (approximately to 600/1 ratio), and then cooled to a point at which it is in liquid phase. From the liquefaction terminal, LNG is loaded onto specially designed ships for transport through thousands of kilometers. The ship is unloaded at receiving terminal, where LNG is regasified to conditions specified from the consumers.

3.1 Production and treatment

As a production of natural gas can be defined the gas brought on the surface from the onshore or offshore wells. If the gas is treated on site, then the production and treatment processes are considered together.

However should the treatment station be located remotely from the field, the gas obtained from the well need to be compressed to pressure high enough to reach treatment station.

The production process is currently under extensive technological research in order to be able to exploit unconventional gas resources. The technology for conventional gas is well developed and proven in practice, but the conventional gas is running out and due to it the unconventional sources are gaining popularity.

The main difference of the gas sources is from the location and depth in which gas is located. Due to that different fracturing should be utilized to enable gas to reach the collection points on the surface. Figure 11 displays different techniques implemented to deal with different reservoirs.

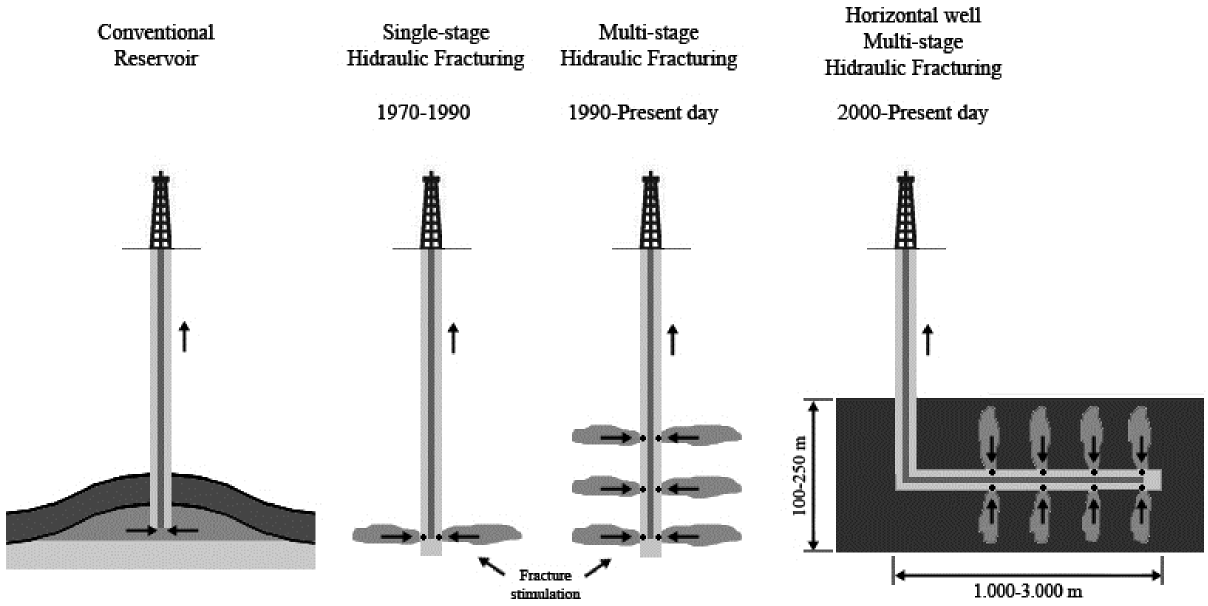


Figure 11: Technology for fracturing [5]

Depending on the intended use (local use, pipeline transport, LNG or other) the treatment process can vary. However, for all the treatment process there are several characteristics in common, such as:

- Separate the liquids from natural gas such as crude oil, hydro-carbons condensates, water and if any solids are present
- To remove recoverable hydro-carbons vapors
- Water vapor present and impurities may be treated on-field or further in liquefaction plant.

It is very common to couple the treatment plant with the liquefaction one.

3.2 Liquefaction

The next process is the liquefaction. In this part the gas is first compressed at high pressures, in order to significantly reduce volume, and later cooled to approximately -162 ^{o}C in order to obtain liquid phase. This process is ongoing in so called liquefaction train. Briefly, the liquefaction process is displayed on Figure 12. When arriving at the liquefaction stage, the gas is already cleaned from impurities, so at this stage, depending on the original composition, some hydrocarbons can be separated. Usually propane and butane are separated to obtain LPG.

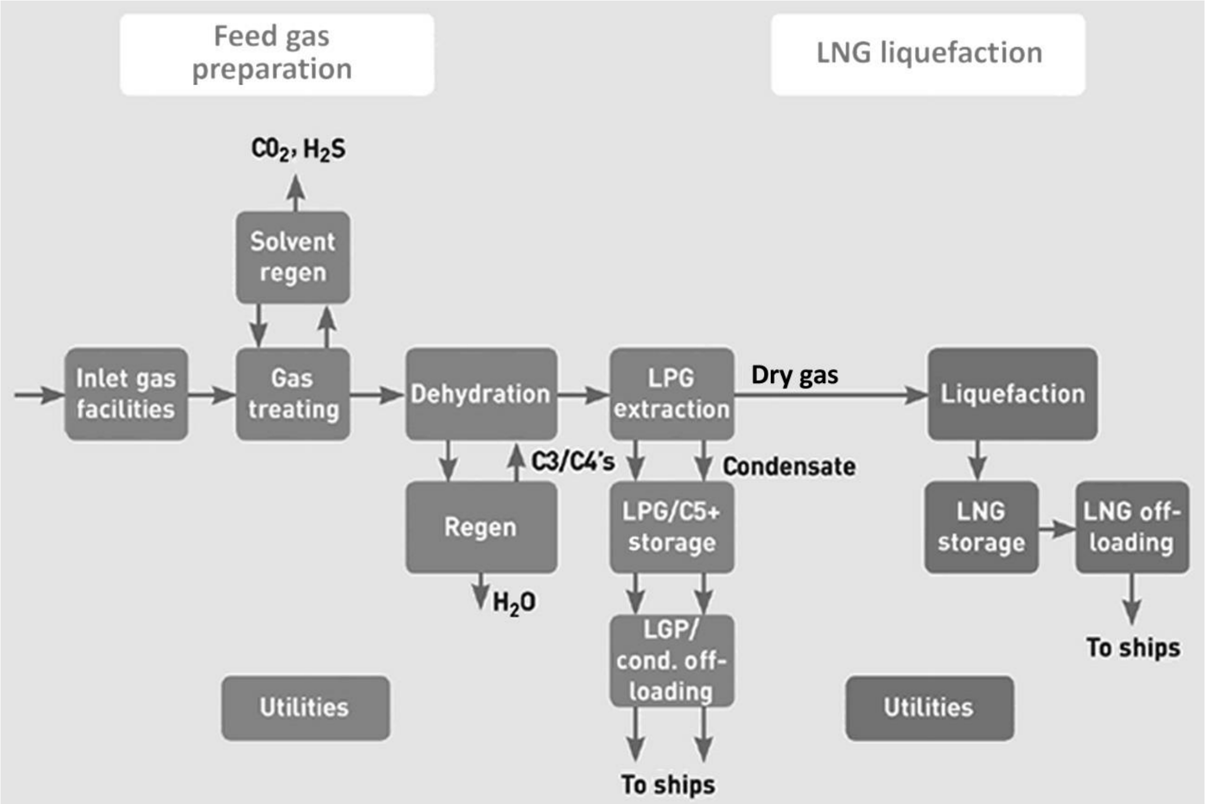


Figure 12: Pretreatment and liquefaction of NG [5]

The liquefaction part is considered as the most expensive part of the chain, both in terms of capital investment and in operational expenses.

The plant, as displayed in Figure 12, consists of two major parts. The first one is pre-treatment and the second is liquefaction. During pre-treatment acidic gases such as CO_2 and H_2S, water, mercury, and other impurities that may solidify at the cooling temperature of LNG, are removed. In the liquefaction part, latent and sensible heat from natural gas is removed.

The whole process of turning gas into LNG, storing it and ultimately loading at the LNG carrier requires a lot of pumping applications [22]. Improving economy of scales by designing bigger liquefaction units (trains), decreases the price per ton of LNG, and helps in making the industry more attractive [22]. Depending on the source gas (associated or non-associated), the plant produces LNG and LPG.

The main units present at liquefaction plant are [11]:

- Feed gas compressor, when the pressure is not enough
- CO_2 removal, by a wash process
- H_20 removal by an adsorber
- Natural gas liquefaction
- LNG storage
- LNG loading stations
- LNG metering stations

A block diagram with the units listed above is displayed in Figure 13.

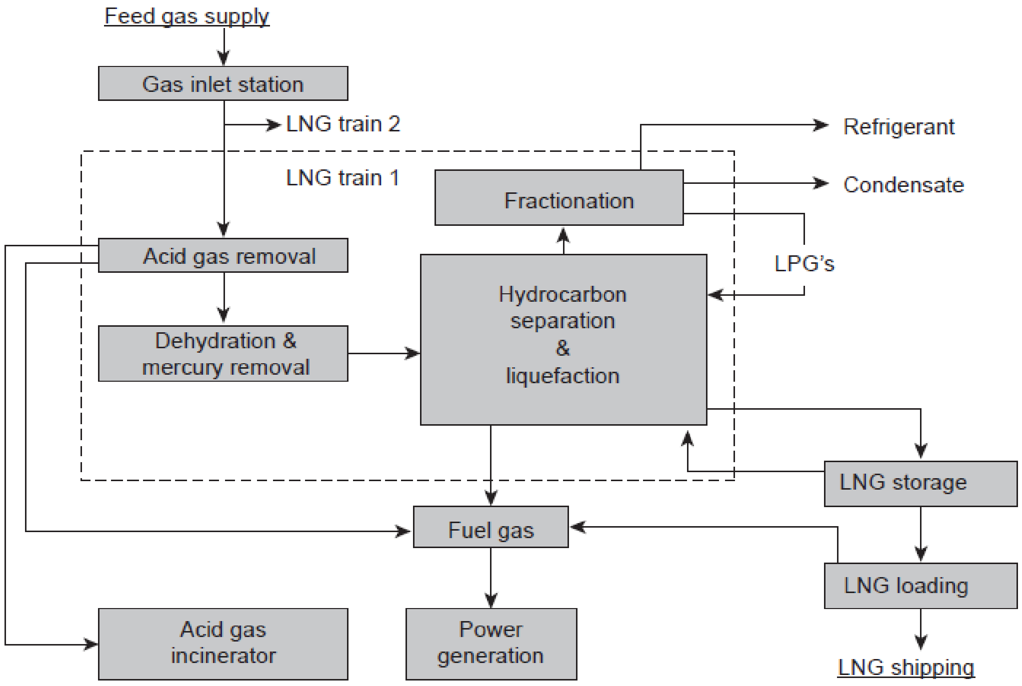


Figure 13: Block diagram with units in liquefaction plant [11]

As the liquefaction part is the most important in the chain, there are many different processes that might be implemented [5]. There are 3 main groups, which have further sub-divisions. The main groups are: cascade process, mixed refrigerant liquefaction process and expander/turbine based process.

The further sub-divisions of these processes are displayed in Figure 14.

Except from the configuration, the liquefaction plants are classified according to their use. By this classification, there are: base-load, peak-shaving and small-scale plants.

Base-load plants are mega-projects. They are directly linked to a gas field. Their capacity is higher than 3 MTPA of LNG. The major part of the world production of LNG comes from base-load plants.

Peak-shaving plants are used to balance the gas demand. They can operate in both functions – to both liquefy gas, and to later vaporize LNG. In periods of low gas demand, surplus gas is liquefied and stored. In periods of high demand, the stored LNG is regasified and supplied in the network.

Small-scale plants produce LNG in small quantities to supply LNG trucks and small carriers. Typically the yearly production from this type of plants is lower than 0.5 MTPA.

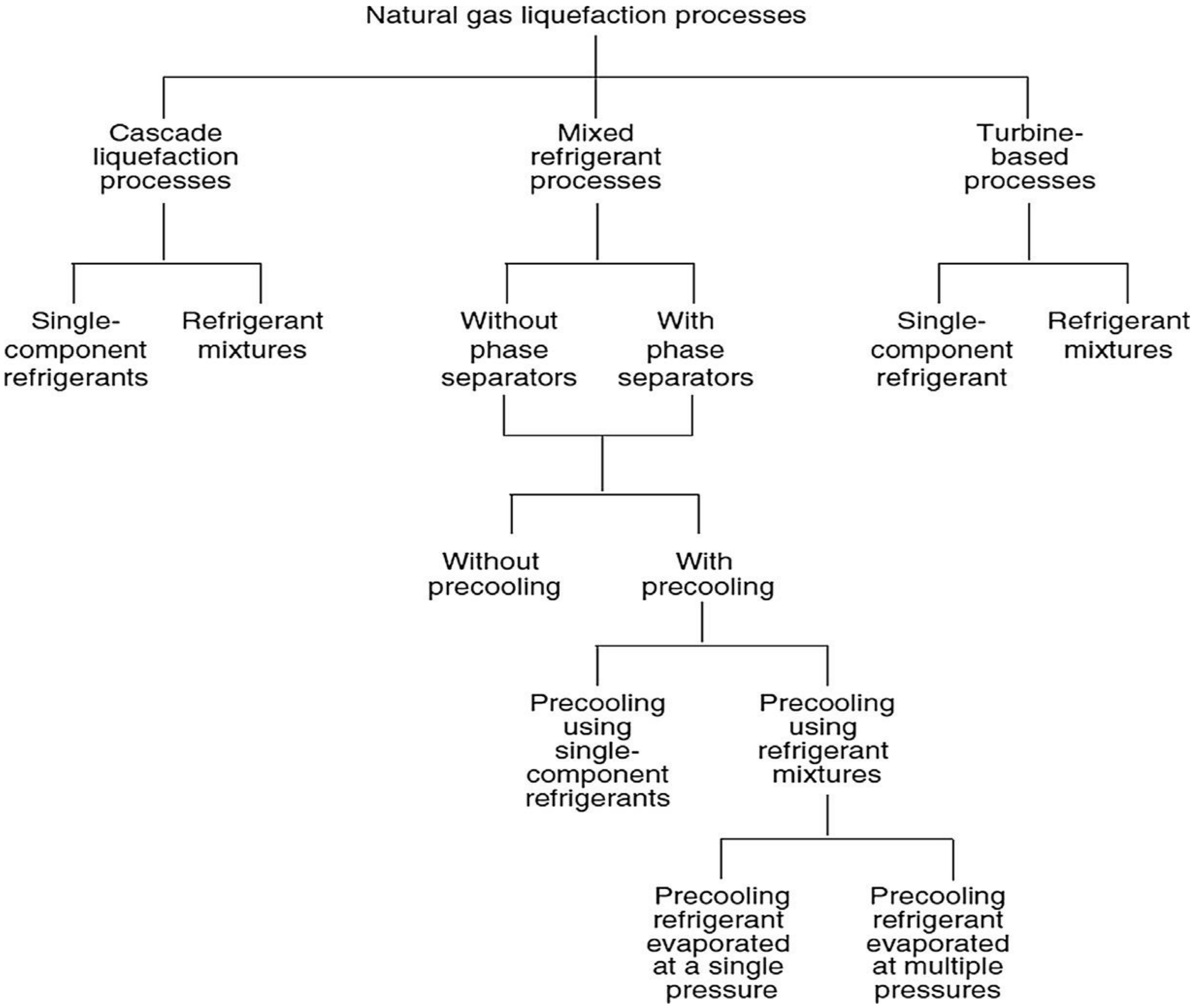


Figure 14: Classification of liquefaction processes [11]

3.3 FPSO

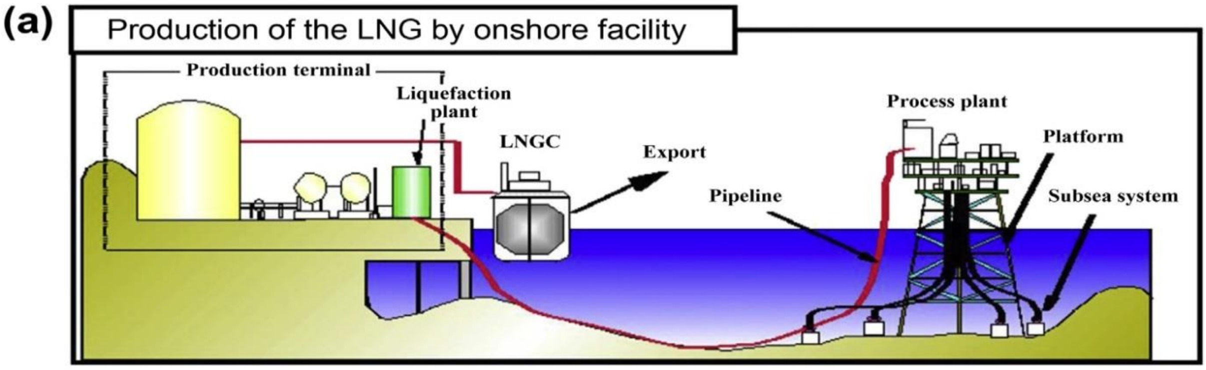
The majority of the new discoveries of oil and gas fields lay in deep off-shore basins. The conventional approach is to connect these fields by pipelines to an onshore plant, to utilize the gas. In order to improve competitiveness and decrease operating costs, “floating plants” are being designed. FPSO stands for floating, production, storage and offloading of LNG. FPSO is an improvised floating vessel, which has some advantages compared to the conventional onshore plants. When FPSO is utilized, there is no need for long underwater pipelines, onshore terminal (which occupies significant amount of land), and can be deployed to other location when the gas field is exhausted. The schemes for conventional plant and FPSO are displayed in Figure 15.

3.4 Maritime transport

Third stage is the maritime transport. For this purpose are utilized big ship vessels. Same as the development at the other stages of the LNG supply chain, here high flexibility is required.

Although the only function of these vessels is to accept the LNG cargo at the liquefaction terminal and deliver it to the regasification one that can be performed in different ways [7]:

(a) Production of the LNG by onshore facility



(b) Production of the LNG by LNG FPSO

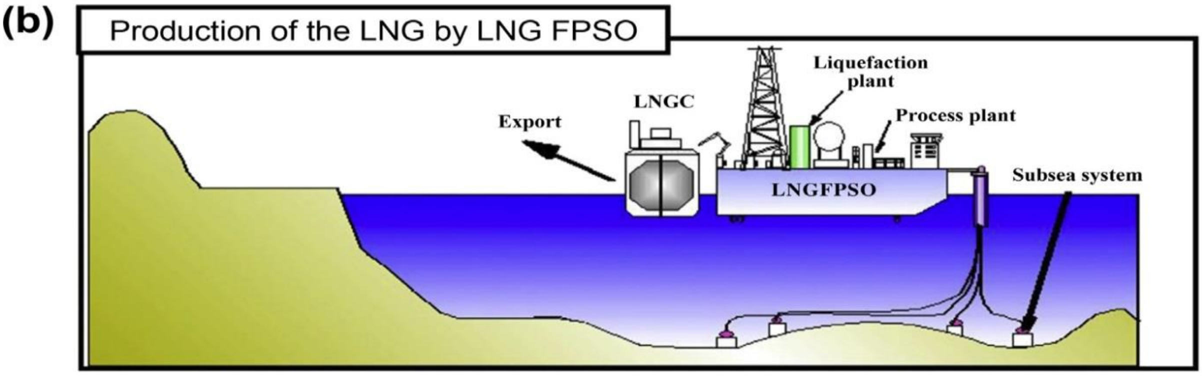


Figure 15: Production of LNG - on and offshore [11]

- Shore to vessel – most common transfer, from plant to vessel
- Truck to vessel – rarely used, but its technically feasible, to load the ship carrier from previously filled trucks
- Vessel to Vessel – probably one of the most important, due to the high interest in construction of floating production and regasification units (FPSO and FSRU)

The LNG carriers due to the special cargo they carry have several strict requirements, both for safety and environmental concerns. The carriers design is adjusted to the needs. Since the industry went through several different phases in its development, the design and certain characteristics of these carriers changed over time.

The most important characteristics of the carriers are [7]:

- Ship capacity (mostly expressed in m^3)
- Types of tanks used
- Engines used for the ship
- Systems to deal with BOG

After arriving in ports, the ship is unloaded in to storage reservoirs. The final phase is regasification of LNG. In heat exchangers, popularly called vaporizers for this purpose, LNG is released at conditions specified by the regulations/consumers demand. Since the evaluation of these terminals is the key focus in this work, they are elaborated in details in the following chapters.

4. Regasification of LNG

The receiving terminal is the place where the LNG carrier delivers the cargo. This is the last location of the LNG supply chain. Here LNG is accepted from the carrier, stored, and regasified, according to the demand. After this terminal, natural gas is supplied to the consumers through distribution pipelines. The major terminals are located in coastal area, in order to be able to accept the arriving ships. Due to the difficulties associated with finding suitable locations, close to densely populated areas, the offshore regasification terminals are emerging. Although there are still difficulties with implementing LNG off-shore regasification, there is constant improvement in this technology.

4.1 LNG Regasification Terminals

Regasification terminals can be divided in two big groups: on and offshore. The first ones are also perceived as conventional or classical. They have been used since the beginning of the LNG industry. They are considered to be well-developed and optimized due to the high number of constructed terminals for vide variety of capacities. There is huge documentation available on every stage of these terminals: research part, construction, capacity optimization, operation and other important aspects.

The second type of terminals, offshore, comes as an innovative approach in the LNG industry. Over the years with the increasing concerns for environmental impact and increasing strict regulations on operation of the conventional terminals, offshore terminals came as a way to deal with those problems. Although there are several completed projects and more under construction, these terminals are still considered under development, with significant improvements possible.

4.1.1 Terminals function and target

Although the difference between on and offshore terminals is significant in many parts, the function they need to perform is almost identical. The terminals need to [26]:

- Receive LNG from the special ship carriers
- Store LNG in suitable tanks
- Regasify LNG and prepare it for further distribution
- Adjust output of NG according to national grid demand
- Meet NG characteristics required (most important Wobbe index and heating value)
- Adapt to daily and seasonal fluctuations in demand
- Fill LNG trucks (if such installation is present)
- Odorize output NG (depending on configuration of network)

4.1.2 Offshore terminals

An offshore terminal receives LNG from the delivery vessels, regasifies it, and delivers it to consumers onshore through subsea pipeline. There are two main concepts for offshore terminals: Gravity Based Structure (GBS) and Floating Storage and Regasification Unit (FSRU). Which one will be utilized depends on several conditions related to the location.

GBS are fixed by the sea floor by concrete structure. This structure contains storage tanks and regasification equipment. The first terminal of this type was constructed near Rovigo, Italy [11].

FSRU is a LNG ship, very similar to the carriers and FPSO. Actually both FSRU and FPSO can be made from previous carrier, which is modified according to new demands.

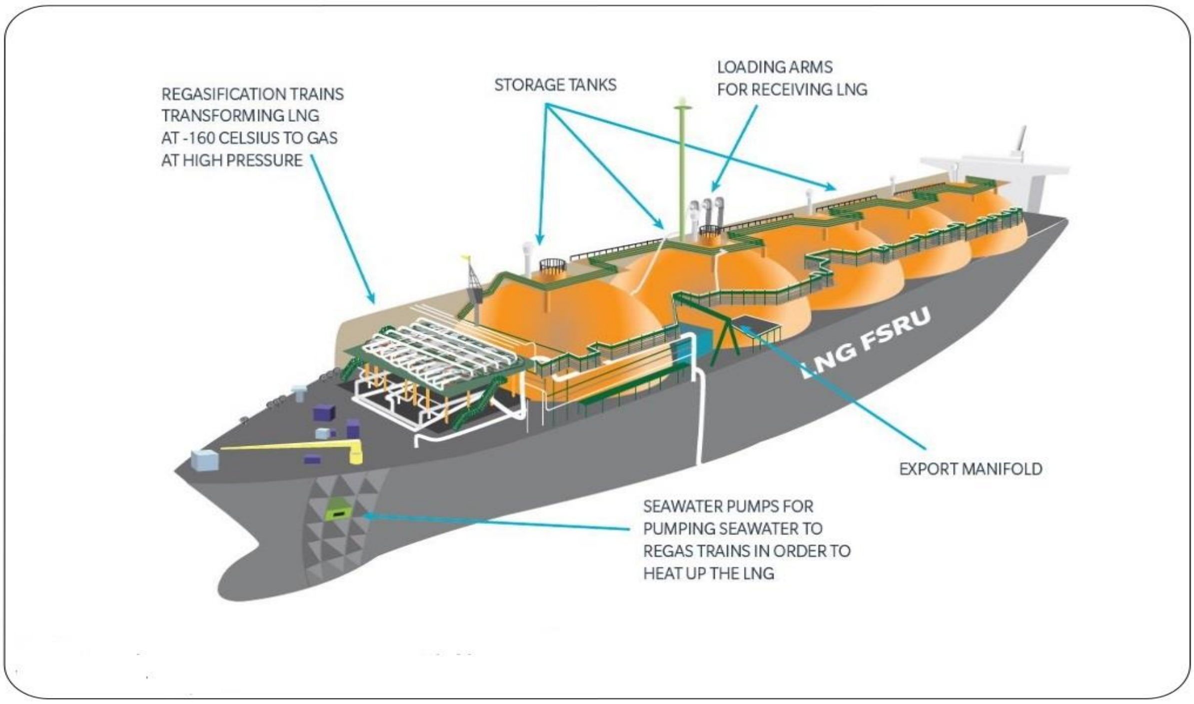


Figure 16: FSRU installation [21]

GBS takes more time to be built and is more expensive compared to FSRU. As an advantage for GBS is that its capacity can be increased, while FSRU is limited to the ship size.

The equipment used in identical to onshore terminals, just due to the limited space, there is a need for new solutions which have less area requirement.

After the first unit is constructed in 1977 [10], their popularity is growing, and the installed capacity increase. The main data about constructed units and capacity is displayed in Table 6.

Table 6: Offshore terminals capacity [10]

Number of operating units (year 2016)	24 units
Total capacity	3.6 million m3
Units under construction	9
Expected additional capacity	1.5 million m3

4.1.3 Onshore terminals

General scheme of an onshore receiving terminal is displayed in Figure 17. LNG is unloaded from the ships by pumping it to the unloading arms on the Jetty, and finally delivered to the tanks.

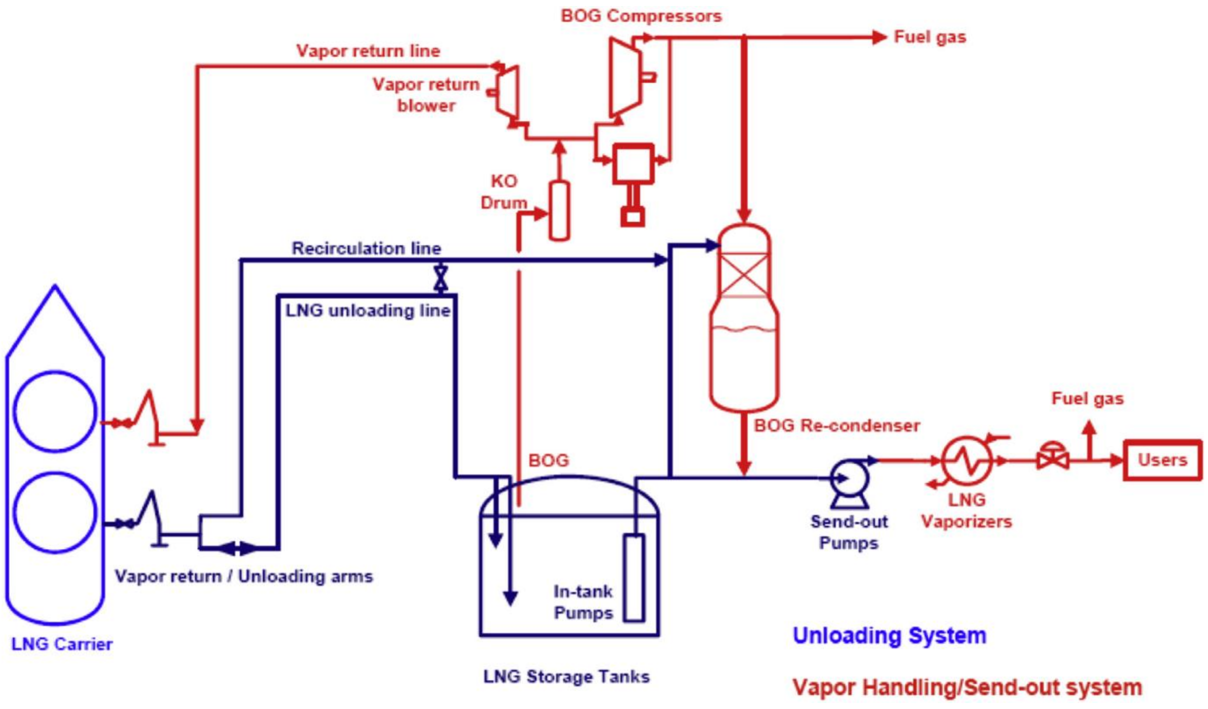


Figure 17: LNG Regasification Terminal [11]

After arrival in port, the carrier moors at the unloading quay. An average ship of 145,000 m^3 capacity needs approximately 12 hours to fully unload at a terminal with unloading speed of 12,000 m^3/h [11]. Before and after unloading there are several other activities at the ship, such as turning basins, berthing, preparation for unloading and departure. Due to this, ships usually stay at port for 24 hours.

The Jetty is equipped with 3 unloading arms for LNG, one vapor return arm and one hydraulic arm. During ship unloading, vapor is returned back to the ship to replace the unloaded volume and to avoid vacuum conditions.

The onshore terminals capacity is displayed in Table 7.

Table 7: Onshore (conventional) terminals capacity [10]

Total capacity (year 2016)	830 MTPA
Expected additional capacity	86 MTPA

4.1.4 Satellite Terminals

In the last period these terminals have growing popularity. They are used as back-up, peak-shaving or from other logistics need (for off-grid consumers). Their capacity is small, and generally they are land based and supplied by LNG trucks.

4.1.5 Terminals Design Operation Construction

Most of the terminals are considered major scale projects, which may have strong influence on the region where they are constructed. Due to that, in terminal constructions many factors need to be addressed. Among the key can be listed:

- Land availability (on or offshore facility)
- Expected LNG volume at the moment and future expansions (terminal size)
- LNG supply options (location and composition of LNG)
- Connection to near distribution network
- Regulations in place

As indicated in Chapter 2, the growth of the LNG market provides opportunity for new terminals construction. The new terminals can be divided in two major groups – on and offshore. Figure 18 presents the share of both type of terminals and the upcoming projects.

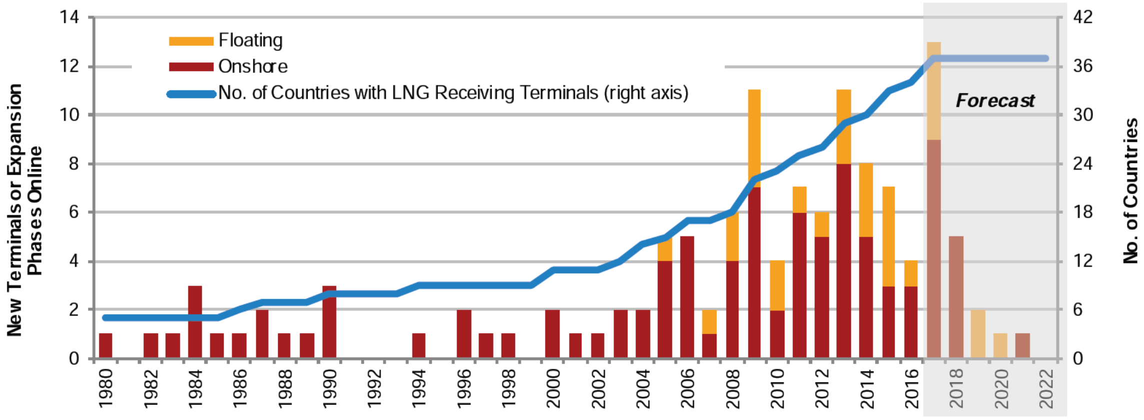


Figure 18: Share of on and offshore terminals [22]

4.2 Equipment used

In order to perform all required functions, one terminal is equipped with several different types of devices. Most of the terminals are huge projects, containing a lot of units and devices. However, the most important ones are: tanks for cryogenic storage, pumps, BOG equipment and vaporizers.

4.2.1 LNG Storage tanks

The storage is at close to atmospheric pressure, at insulated tanks that can hold LNG below boiling point. These tanks are double-walled and well insulated, in order to have proper operation. This is in order to reduce to minimum heat gain and reduce volumes lost due to boil-off gas. The boil-off rate is around 0.05% of the volume of the tank per day [11].

The capacity of the tanks is similar to the ones of the carriers, in order to enable unloading of the carrier in a single tank. The majority of the existing tanks are with capacity of 160,000 m^3. The new constructed tanks have capacity of 200,000 m^3 and higher, in order to match the size of the new LNG carriers. The size of tanks is determined after the site locations are taken into consideration.

There are two main types of storage tanks – in ground and above ground tanks.

4.2.1.1 In ground tanks

In ground tanks consist of stainless steel membrane, which is supported by polyurethane foam insulation. In addition there is reinforced concrete caisson. The roof is constructed from carbon steel, and has glass wool for insulation.

Typical configuration of an in ground tank is shown in Figure 19.

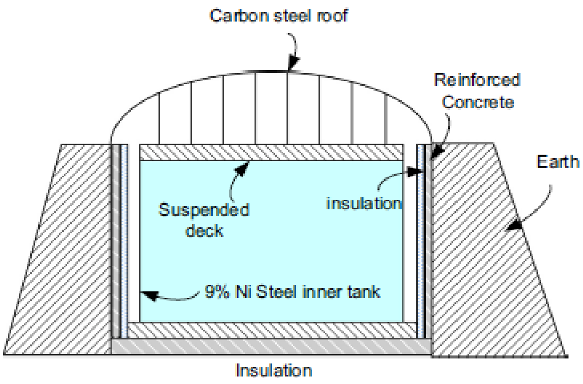


Figure 19: In ground storage tank [11]

These types of tanks are employed at locations sensitive to earthquakes, such as Japan, Korea and Taiwan. In addition their safety is higher, due to the fact that they are in the ground. These tanks can be positioned close to each other, so there is also saving in land area.

For the price of their benefits, mostly in safety, they are more expensive and take longer period to build compared to the above ground tanks.

4.2.1.2 Above ground tanks

These tanks have two layers of containment. First containment is by the inner tank, which keeps the LNG. As a second containment can be used dykes and berms or build a second tank around the first one.

There are three main types of tanks which are used [11]:

- Single containment
- Double containment
- Full containment tank

Self-supporting inner cylinder is the basis for single containment tank. This cylinder is made from steel which contains 9% nickel. Outer tank, made of carbon steel, surrounds the inner tank. As second containment here, is used bund wall or dyke, external to the primary tank. This type of tank is considered as old technology and is cheaper than the other options, but it is prone to hazards, and rarely considered for new projects. However, in some exemptions when the terminal is located at a place with available land area and is far from urban areas, this type of tank can provide cheap solution, which still satisfies all the regulation and safety criteria. Figure 20 shows the single containment tank appearance and scheme.

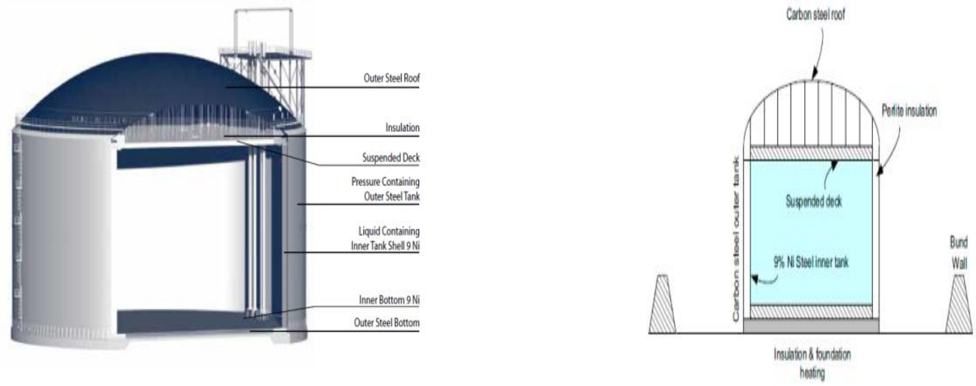


Figure 20: Single containment above ground storage tank [11] [24]

Double containment tank is similar to the single containment tank. The difference is that here, concrete constructed walls are used as secondary containment, and they are close to the primary tank. This tank is more expensive, but requires less space, and it is regarded as safer option. Figure 21 shows the double containment tank appearance and scheme.

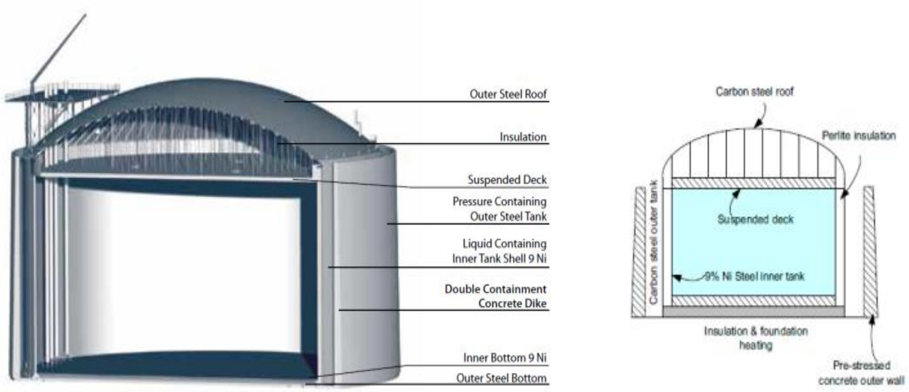


Figure 21: Double containment above ground storage tank [11] [24]

Full containment tank is regarded as the most secure option, and most of the new projects use this type of tanks. Figure 22 shows the full containment tank appearance and scheme.

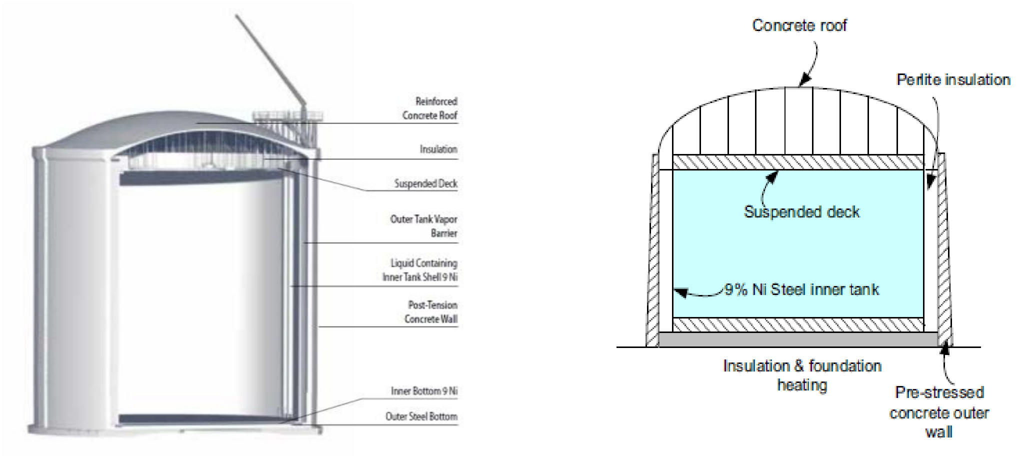


Figure 22: Full containment above ground storage tank [11] [24]

4.2.1.3 Tanks filling process, operation, stratification and rollover

The construction of LNG tanks is based on the safety and the requirements imposed from the regulations on the building site. However, even with the best available option for storage (full containment), other aspects have to be carefully evaluated in order to allow optimal operation.

The most important issue related to LNG storage tanks is LNG stratification and tank rollover.

Stratification is defined as the phenomenon of forming different cells among the stored LNG, which is caused by LNG with different densities [23]. The stratification in the tank can be controlled and used to regulate the amount of BOG that is released.

Rollover is undesired phenomenon. It is defined as rapid release of LNG vapor caused by the stratification. Rollover is classified as a hazard for the operating terminal, and the efforts are put to be avoided. When rollover occurs, the amount of BOG released is much higher than during normal operation, it can get up to 30 times [25]. Since this is much more than the BOG system can handle, most of it is released through the safety relieve valves and vents on the roof of the tank. This LNG is release in the atmosphere, which is double loss – unused fuel and methane emission (which is strong GHG) and there is the danger of explosion.

These two phenomena are well evaluated, and the parameters that affect them. Due to that, there is good practice of dealing with them, leaving just separate incident cases. Constant monitoring is the best way to avoid undesired effects. As most important parameters are defined [23]:

- Vertical profile of temperature and density in LNG tank
- BOG sendout rate
- Rates of filling, recirculation and sendout LNG
- Composition of LNG
- Tank pressure

Filling in the bottom of tanks and using jet nozzles is another good practice. If different LNG composition is accepted, then it has to be stored at different tanks. Low nitrogen content (<1%), would additionally decrease the risk of rollover. The "laying" period of LNG in tanks shouldn't be long, in order to avoid weathering.

Lastly, there are several different LNG rollover simulation models used in the industry. By supplying the operators on site with these models, they can adjust the operation of the terminals to avoid undesired effects.

4.2.2 LNG pumps

The unloading of the LNG carriers into the storage tanks is performed with LNG arms. Arm is formed from a riser pipe, inboard and outboard arm. Additional systems and devices are installed on the arms, to secure proper operation and safety during it. Their capacity can vary, generally it is in the range between 4000 and 6000 m^3/h. Depending on the capacity of the carrier and the storage capacity of the terminals, there are two or three arms for unload of LNG, one vapor return and one spare arm.

LNG is pumped to higher pressure prior to vaporizing, because it is much cheaper (less electricity used to drive pumps than compressors) to pressurize it while it is still in liquid phase, than when it is vaporized.

To pump LNG from the tanks, submerged LNG pumps are used. Pumps are used to pump LNG to low and high pressure. The low pressure (LP) pump discharges LNG at pressures around 8-10 barg.

The high pressures (HP) pumps take LNG from the BOG recondenser at pressures around 8 barg, and then pumps LNG to sendout pressure requirements which are in the region between 80 and 120 barg. In some exceptional cases the distribution pressure can be lower (such as in Japan [4]).

The HP pump takes (suck) the LNG coming from the LP pump and the BOG recondenser, unless there is different technical solution to deal with BOG. The specified operating pressures, according to [11], are in the range between 80-120 barg. However, taking into consideration the vast diversity of LNG applied projects there are many special constructions which are operating out of this range. Same as for the LP pump, the pump curve needs to be analyzed to specify an optimal working regime.

Among the companies which are referenced as best for providing solutions for LNG pumping are: Ebara, Atlas Copco, Nikisso, Hitachi, Shinko and others.

4.2.3 BOG recondenser

Although high attention is put in tanks containment and insulation, there is no such thing as perfect insulation. Due to this incoming heat goes in the tank, which causes some volume of LNG to start to vaporize in the form of BOG. Due to the strict environmental norms, flaring this BOG is forbidden. There are several technical solutions to deal with it. It can be used as a fuel gas for some of the processes requiring power or heat, or it can be reliquefied. The implemented solution will depend on the terminal and ship configuration.

In the phase of ship unloading, BOG emissions increase and can vary significantly. At terminals, there is additional compressor, to be used just during the carrier unloading. If in some case, even the capacity of the two compressors is not enough, the remaining BOG is flared or vented. The variation of the amount of BOG is significant, and mostly dependent on carrier unloading time and gas sendout from the terminal [25].

Three most common approach to deal with BOG are to mix it with the sendout LNG, to reliquify it and return to tanks or to compress it to sendout pressure. It is estimated that it is 30-60% more energy efficient to mix it with the sendout LNG compared to direct compression to distribution pressure [25].

The first option is much more common in practice. A scheme of this process is displayed in Figure 23.

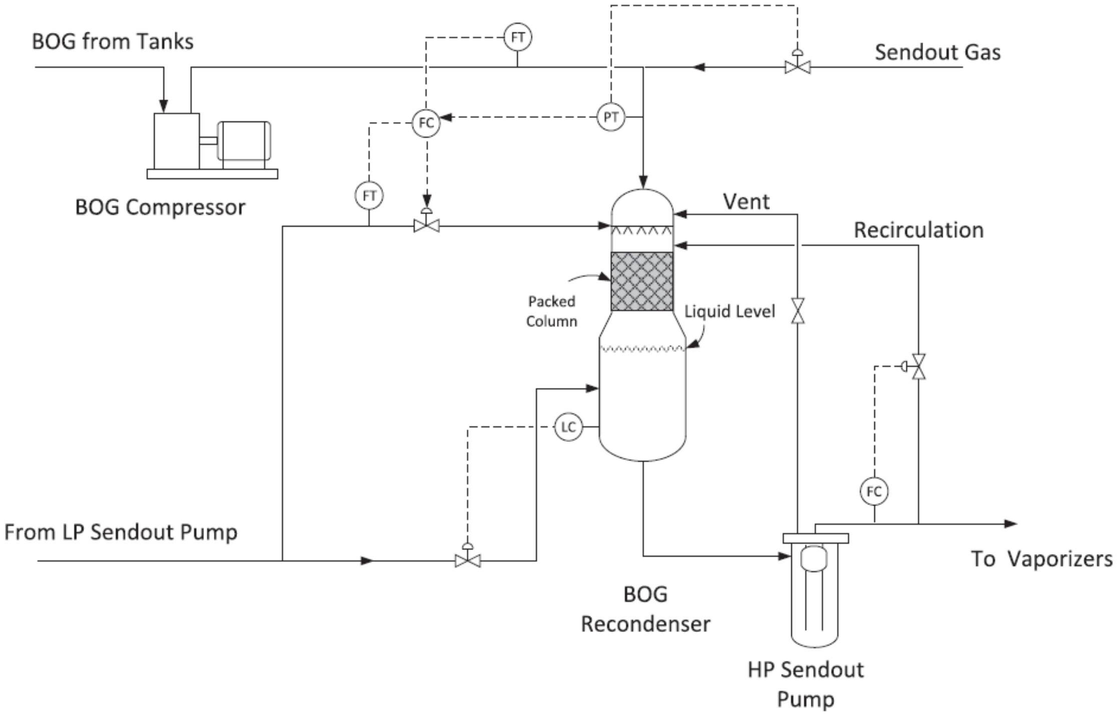


Figure 23: BOG treatment system scheme [11]

4.2.4 Additional equipment and components

In addition to the most important components, there are several other which are also very important for proper function of the terminals. They will be described briefly in this work.

Pipes used in the LNG terminals are usually made from austenitic steel [26]. In order to minimize the heat transfer with the surrounding, a proper insulation is a must. Polyurethane and foam glass are used as insulation materials [26].

For monitoring and control purpose, there is equipment in dispatch room and components for local operation. The monitoring process is used to control the work of all the key elements in the terminal (tanks, pumps, BOG equipment etc) described above.

The safety of the terminal is primary concern. The LNG industry has great record of safety in operation, listing only few separate accidents in its history. All the effort put in planning the key elements contributes to the safety factor.

Nevertheless, all LNG terminals contain the required ventilation space, fire-fighting equipment and according to standards, they are respectively distanced from close cities, and have their equipment properly positioned.

4.3 Vaporizers part

There are several important parameters that have to be considered prior to selection the type of vaporizer. Site location, environment, regulations and proper operation are some among them. As in every other project, the costs and the Net Present Value (NPV) of the project are very important.

For the most common, base load regasification terminals, there are two major types of vaporizers commonly used. Open rack vaporizers (ORV) account for the majority of vaporizers used (70%), and Submerged Combustion Vaporizers (SCV) contribute with 20% of the total share. There are several other designs which are less frequently implemented: Ambient Air Vaporizers (AAV), Shell and Tube Exchange Vaporizers (STV) and Intermediate Fluid Vaporizers (IFV).

4.3.1 ORV - Open rack vaporizers

The source heat used here is seawater. In the heat exchanger the water at around ambient temperature is the hot stream and LNG at cryogenic temperature is the cold stream.

Most often aluminum alloys tubes with fines are used in the heat-exchangers. This material provides good mechanical characteristics to deal with low temperature and high pressure of LNG. The part of the surface that comes into contact with seawater is using coating as a protection against corrosion.

Due to their simple construction, they are very popular for use. Maintenance is also simple. Their construction is displayed in Figure 24, containing the most important elements.

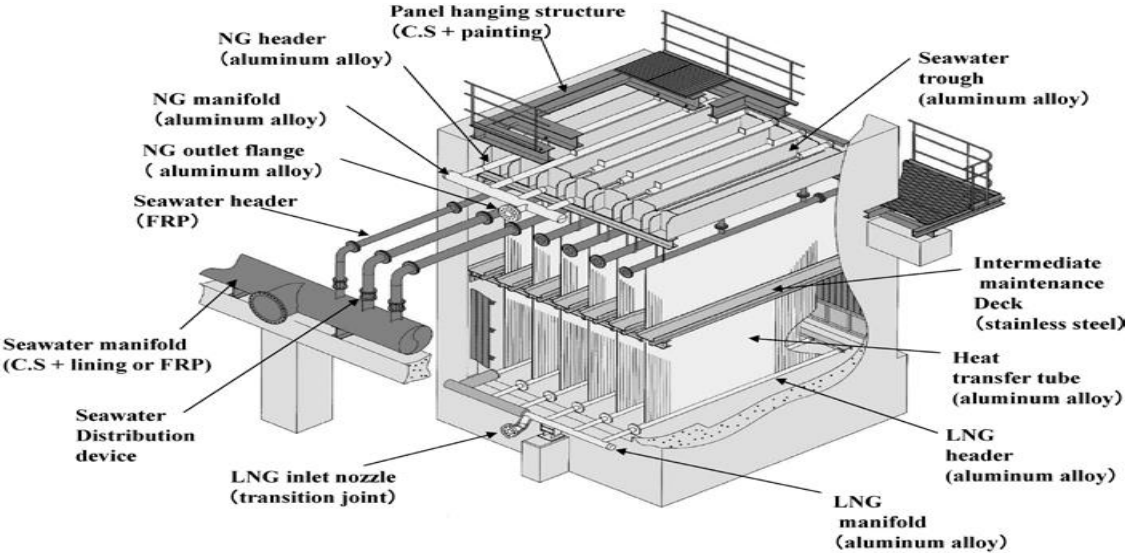


Figure 24: ORV main elements [27]

They are flexible in operation. The flows of water and LNG can be adjusted according to the needs, and the utilization of the available panels can vary. They are very reliable, and safe for operation. If there is leakage of LNG, they can be turned off instantaneously.

Low amount of chorine has to be added to seawater to prevent marine growth in the equipment. The discharge water also needs to have very low level of chlorine into it.

In order to determine whether this type of vaporizer is suitable to use at terminal, several factors need to be evaluated:

- Seawater characteristics (contents of: heavy metal ions, sand and suspended solids,
- Environment considerations
- Marine life destruction effect
- If temperature of seawater drops low (below 5 ^{o}C) back-up vaporizer should be present

4.3.2 SCV – Submerged combustion vaporizers

This type of vaporizer may use up to 1.5% of LNG as a fuel in the process of vaporization. Due to this the operational costs are significant. SCV unit is displayed in Figure 25.

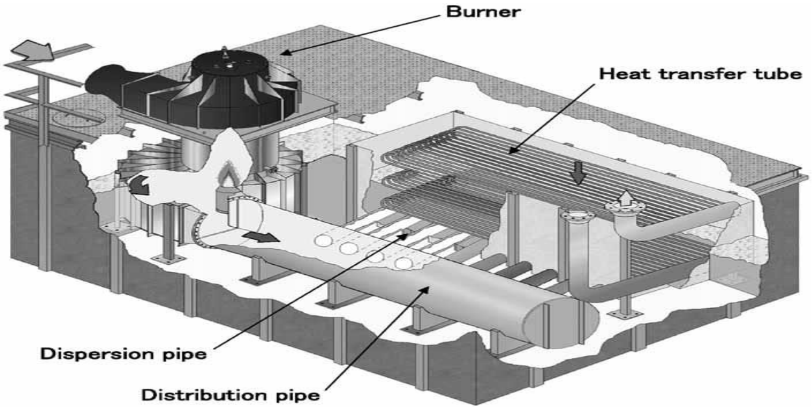


Figure 25: SCV main elements [27]

Underwater burner burns fuel-gas to generate heat for the vaporization of LNG. Both the burner and the heat transfer elements are submerged in the water. The water is heated from the hot exhaust gases from the burner. Due to the high heat source, the dimensions of this vaporizer are smaller compared to other options for the same capacity. Even in a case of lack of supply of fuel-gas for the burner, the vaporizer continues to perform properly for some time, thanks to the heat capacity of the heated water. Since there is no need for water intake and discharge, this process is simpler and has less construction expenses. The regulations for the level of emissions have to be respected, which may be a reason to use low NOx burners.

4.3.3 Intermediate fluid vaporizer – IFV

Closed loop is used here with ethylene glycol or propylene glycol as a potential working fluid. Figure 26 shows scheme of IFV.

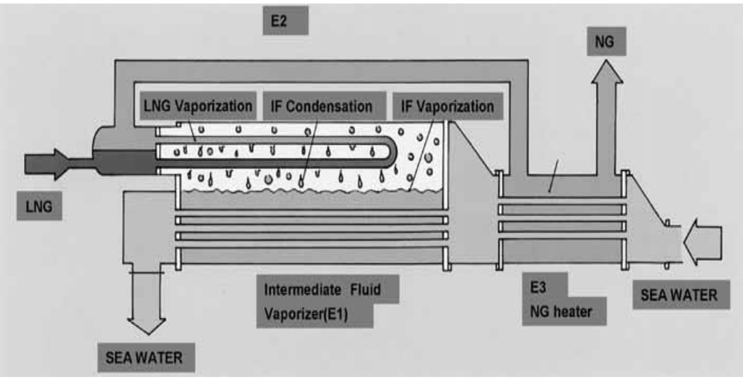


Figure 26: IFV scheme [27]

In the IFV, there is a heat source, which transfers the heat to a heating medium, which later vaporizes the LNG. As a heat source can be used seawater, waste heat or ambient air heat. As a heating medium usually is used propane, butane, ethylene glycol, propylene glycol or some other fluid.

This vaporizer comes as a modified version of the original ORV. Mostly used for locations with lower temperature of the seawater, this vaporizer relies on the intermediate fluid, which is heated by seawater, and later heats the LNG. Titanium alloy is used for the tubes where heat-transfer occurs, to deal with low temperatures [28].

The IFV are a popular solution for FSRU terminals.

4.3.4 AAV systems – Ambient Air Vaporizer

They utilize the heat from the ambient air, instead of seawater or combustion gases. Due to this they are considered the most environmental friendly among the vaporizers used for LNG. On the other side they require more heaters due to lower heat transfer compared to other options, and will also require more space on the terminal location.

The AAV can operate at direct air/LNG heat transfer or through intermediate fluid. It can operate on natural and forced draft.

Air is forced through fans in the heat transfer area, where air gets cooled and LNG is vaporized. Before discharge, air is colder than on the intake, and there are water droplets and possible ice formation, which require defrost. From the mixing of the cold discharge air and the warmer outside air, there is possible fog formation. In Figure 27 is displayed AAV.

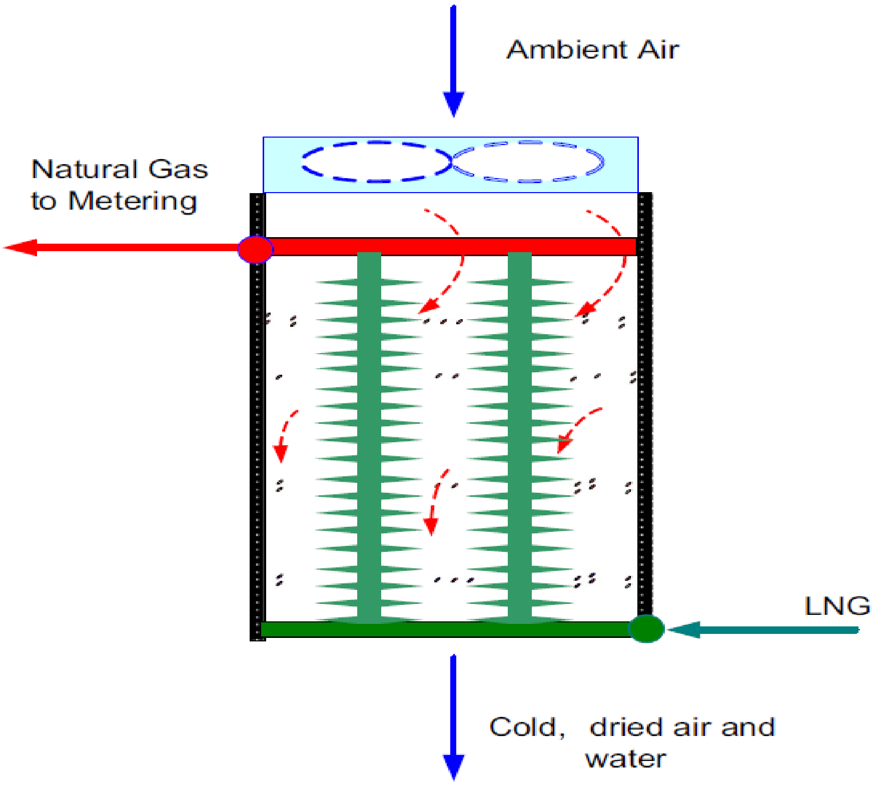


Figure 27: AAV scheme [28]

These systems are best employed in the tropical areas, where the air temperature is high throughout the whole year. In regions with lower air temperatures, there should be a back-up option from some of the other vaporizers.

4.3.5 General considerations

As previously indicated, most of the terminals are currently running on ORV and SCV systems. This is due to the fact that these systems are most reliable, with proven history of operation, and the fact that in the period of their construction, the energy efficiency issues were not priority.

In many terminals, there is a combination of the previously described systems. They are used depending on the gas requirements and the ambient conditions, in order to achieve most economical and reliable operation.

Today, due to the high energy use concerns, there is drive to design new types of vaporizers, which will have better energy efficiency. Improved vaporizers can help decrease energy use, while proper process integration and utilization of the cold energy in the LNG can minimize the energy requirement for vaporization and facilitate some other process. The utilization of the cold energy of LNG is displayed below.

Table 8: Comparison of different types of vaporizers [28]

Vaporizer	CAPEX	OPEX	Size	Environmental Impact
ORV	Medium	Low	Medium	Marine life destruction concerns
SCV	Low	High	Small	Exhaust gases emission
IFV	Medium	Medium	Medium	Marine life destruction concerns
AAV	High	Low	High	Except dense fog generation, no other effects

From Table 8, and the previous description can be concluded that there is no straight-forward answer for a best vaporizer. Selection of vaporizer will depend on site location, climate, project size and other important conditions.

4.4 Utilization of cold energy – Literature review

The final stage (regasification) is the process where some of the LNG energy can be recuperated. Due to the high potential available, the utilization of LNG cold energy has been subject to extensive research work and high number of projects has been implemented. However, in order to make practical use of this energy, there are several constraints that need to be dealt with.

First of all, there has to be a need for cooling application very close to the terminal. A feasible distance is considered up to 2-3 km [29]. In addition the process cooling energy needs to adapt to the LNG sendout, because that is the primary function of the terminal. As an additional constraint coms the fact that, most of the large terminals are situated in ports far from urban areas, so in order to make use of the cold energy, some specific industry has to be located nearby.

There are two major groups of solutions for cold energy utilization: cooling applications and combination with power cycles. In both areas there is vast research work and implemented projects. However, recently, due to the growing concerns about the energy supply and environmental impacts, the power generation option is more attractive for both research and implementation.

The available cold energy of LNG can vary. In different reports, authors suggest numbers in the range of 700-800 kJ/kg [4]. It will depend on the assumption for LNG composition, the tanks condition and the sendout condition. Since in this work, for simulation will be used ASPEN software, the available cold energy of LNG will be calculated based on the values gained from the software.

4.4.1 Cooling Applications

Since LNG terminals are built all over the world, in different countries and different temperature regions, there has been very high number of ideas how to utilize the cold energy available in LNG. Potential uses for LNG cold are:

- Industrial cooling [30]
- Air components separation [31] [32] [33]
- Agro-food industry [34] [35] [36]
- Space air-conditioning in commercial sector (hypermarkets) [36]
- Seawater desalination [37] [40]
- Cold storage with Phase Change Materials (PCM’s) [38]
- District cooling with using absorption cycle [39]
- BOG liquefaction system [40]
- Liquefaction of CO2 [30]
- Dry Ice Production [30]
- Pumped thermal energy storage [41]

Depending on the surrounding capacities, some of these options may be implemented.

4.4.2. Power Generation

This is the most attractive area for LNG cold utilization. This trend started in Japan, with the first plants developed by the Tokyo and Osaka Gas Companies, and currently being topic of wide research. In most of the applications in power cycles, the cold of LNG is used to cool the condenser. However, except for that there are few other proposed combinations.

The power cycles which are analyzed for utilizing the cold energy of LNG are the following:

- Organic Rankine Cycle (ORC)
- Brayton cycle
- Kalina Cycle
- Combined cycle with gas turbine (CCGT)
- Cooling of intake air for CCGT [42] [43] [44]
- Micro cogeneration systems MCHP for small terminals [45]
- Novel cycles [46] [47] [48]
- Combination of several cycles or modifications to the previously mentioned [49] [50]

The above named cycles contain vast research data, which is confirmed by generating close results from several different, independent researchers. Due to the growing attractiveness of process integration and combination of cycles, in the evaluated literature, were found few novel concepts, which need to go the path of the previous cycles – to be performed in several works, to validate their performances. Some of the interesting new concepts come in the form of:

- Biomass utilization coupled with LNG regasification [50]
- CO2 capture integration [48]
- Integration of small scale LNG regasification [45]
- Utilizing Geothermal Power [52]
- Utilizing solar energy [53] [54]
- Hybrid energy system, based on compressed air energy storage (CAES) [55]
- Pumped thermal energy storage PTES [56]

In the reviewed literature, these cycles were found, which means, it is not excluded that other combinations are possible for power generation using LNG cold energy.

4.4.3 ORC

Rankine cycle (RC) is used to describe performance of thermal cycle which includes steam turbine for power generation. This cycle is implemented in all thermal power plants: coal, nuclear and some based on oil or natural gas.

Organic Rankine cycle (ORC) is a modification of the original cycle. Although the cycle and processes remain exactly the same, the difference is in the choice of the working fluid. This cycle utilizes organic, high molecular mass, and the most important feature – boiling temperature much lower compared to water. This modified cycle has been mostly used for low temperature heat sources utilization such as combustion of biomass, industrial waste heat, geothermal energy and solar sources.

The ORC has been among the most popular topics of research, related to thermal cycle power generation. Its versatility of utilization various fluids and having several possibilities for low grade waste heat, gives very high number of possible combinations and processes implementation.

ORC have been popular due to its many benefits: adaptability to different heat sources, proven technology with great maturity, less complexity and maintenance, low investment and maintenance cost and well known market suppliers [51]. The efficiency can be increased by using regenerators.

Among the environmental benefits from utilizing ORC are utilization of heat which otherwise would have been wasted, improved efficiency and process integration, and reduced emissions of CO, CO2, NOx and other pollutants.

4.4.3.1 Principle of work – scheme

On Figure is presented a scheme of ORC cycle. The four main components for this cycle are evaporator, turbine, condenser and pump. Although this is the general and most common configuration, certain modifications are possible, while trying to make the most out of the system.

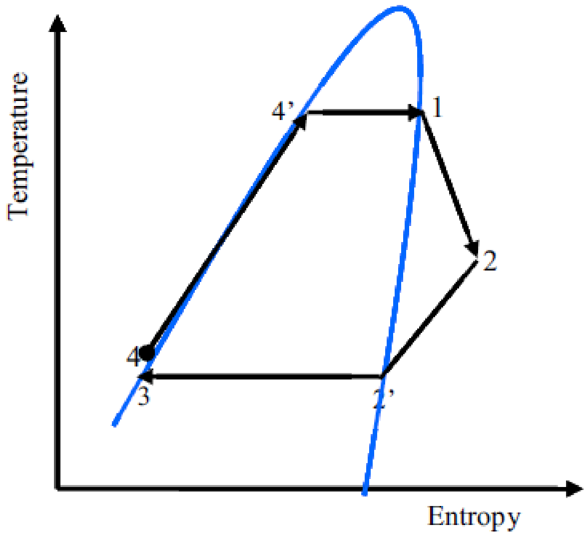


Figure 28: T-s Diagram of ORC [51]

The working fluid leaves the condenser as saturated liquid. In the pump it is pressurized to the desired pressure. The next step is to evaporate the liquid in the evaporator to a vapor state. In the end, vapor with desired pressure and temperature is exhausted in the turbine, in order to get electricity generation. The exhausted steam goes to the condenser and then the cycle repeats.

The isentropic efficiency of the pump is defined with:

$$\eta_{is\ pump} = \frac{\dot{W}_{is\ pump}}{\dot{W}_{pump}} \tag{9}$$

The work performed from pump is:

$$\dot{W}_{is\ pump} = \dot{m} \cdot (h_4^s - h_3) = \frac{\dot{m} \cdot (P_4 - P_3)}{\rho} = \dot{V} \cdot (P_4 - P_3) \tag{10}$$

The real work of the pump is:

$$\dot{W}_{pump} = \frac{\dot{W}_{is\ pump}}{\eta_{is\ pump}} = \frac{\dot{m} \cdot (h_4^s - h_3)}{\eta_{ispump}} = \frac{\dot{V} \cdot (P_4 - P_3)}{\eta_{is\ pump}} = \dot{m} \cdot (h_4 - h_3) \tag{11}$$

Isentropic efficiency of the turbine is:

$$\eta_{is\ turbine} = \frac{\dot{W}_{turbine}}{\dot{W}_{is\ turbine}} \tag{12}$$

The isentropic work of turbine:

$$\dot{W}_{is\ turbine} = \dot{m} \cdot (h_2^s - h_1) = P_1 \cdot \dot{V}_1 \cdot \frac{k}{1-k} \cdot \left[\left({}^{P_2}\!/_{P_1}\right)^{\frac{k-1}{k}} - 1\right] \tag{13}$$

The work of turbine is:

$$\begin{aligned} \dot{W}_{turbine} &= \eta_{is\ turbine} \cdot \dot{W}_{is\ turbine} = \\ &= \eta_{is\ turbine} \cdot (h_2^s - h_1) = \eta_{is\ turbine} \cdot P_1 \cdot \dot{V}_1 \cdot \frac{k}{1-k} \cdot \left[\left({}^{P_2}\!/_{P_1}\right)^{\frac{k-1}{k}} - 1\right] \end{aligned} \tag{14}$$

The heat of evaporation and condensation of the Working Fluid (WF) are:

$$\dot{Q}_{evaporation} = \dot{m} \cdot (h_1 - h_4) \tag{14}$$

$$\dot{Q}_{condensation} = \dot{m} \cdot (h_3 - h_2) \tag{15}$$

The thermal efficiency of the ORC, based on First Law of Thermodynamics is:

$$\eta_{thermal} = \frac{\dot{W}_{output} - \dot{W}_{input}}{\dot{Q}_{evaporation}} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_{evaporation}} \tag{16}$$

As for the conventional RC, the approach for improvement is similar. Higher temperature heat source, higher operating pressure of WF and lower pressure and temperature in the condensing part are recommended [57]

Although this scheme and cycle are quite simple, the complexity arises when it needs to be combined with other processes. When combining it with other processes the heat source (evaporator) is limited, and this also limits the pressure to which it should be pumped. This will be discussed in details in the part of combining with LNG and waste heat sources.

4.4.3.2 Working fluid selection

Due to the growing popularity and interest, there has been plentiful of research for most suitable working fluids for ORC, since there are many different possible options.

For every waste heat, a most suitable fluid has to be defined. Among the most important parameters of the working fluid are: toxicity, chemical stability, boiling temperature, flash point, specific heat, latent heat and thermal conductivity[58]. There are three general groups of fluid classification: wet, dry and isentropic.

Main obstacle for rapid development of ORC is actually the fluids used. A lot of them have been phased-out due to environmental impact, and it is very probable that in the near future the list of phased-out fluids will grow larger. Comprehensive review of the suitable working fluids and their most important characteristics is given in [58].

4.4.3.3 Heat source and integration

As it was already mentioned that ORC has huge flexibility, it means that the different combinations will have different boundary conditions (heat source and heat sink especially) and different performance criteria may be utilized.

Figure 29 displays this in the best way.

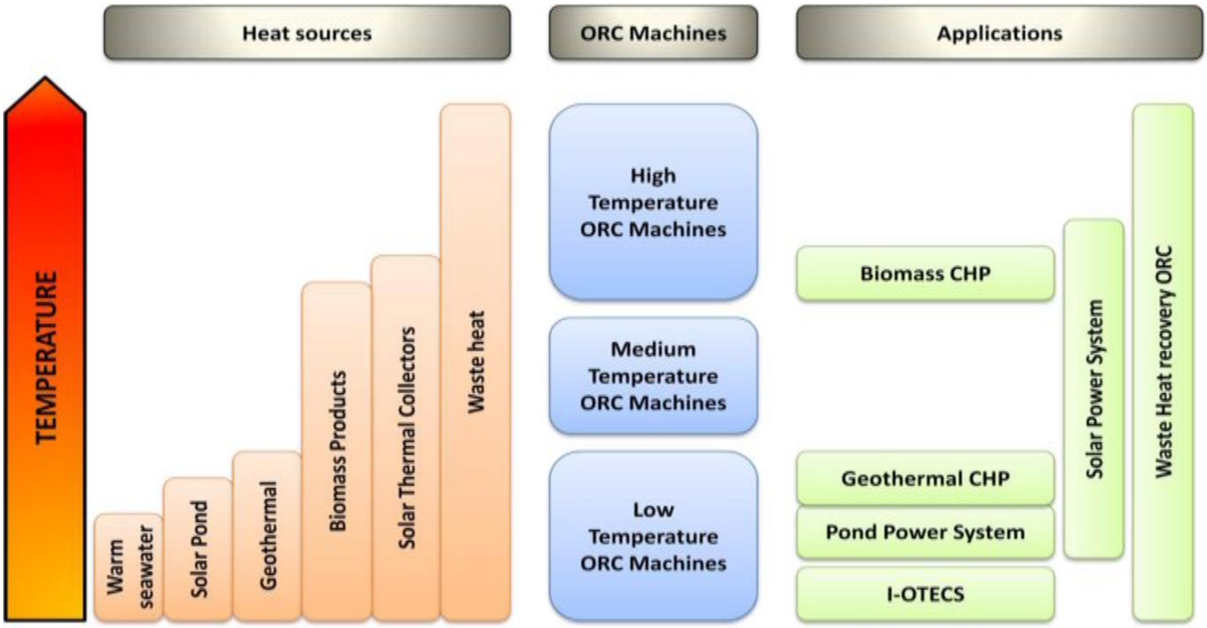


Figure 29: Heat sources for ORC and application [51]

The heat source temperature will define the needed machinery, and will show which application is the best for that case. ORC installations are considered as a small power units going from a kW to few MW [59]. It is notable that LNG is not listed on this figure. The reason is that the capacity and number of plants implemented to integrate with LNG is much smaller compared to the other applications listed here. In addition, the main purpose of integrating ORC and LNG terminal is to make use of the cold energy of LNG.

This will mean that the heat sink (condenser part) will be at temperature much lower than the one at “conventional” ORC’s. Due to that, the evaluation of the effectiveness of this combination will be based on other criteria.

4.4.4 ORC coupled with LNG

The cold energy of LNG is used to cool the condenser in this application. This comes as a practical way, to reduce (or even eliminate) the energy spent for seawater pumps to vaporize LNG and in the same time to supply cooling to the condenser of the ORC.

This cycle comes as a starting basis for most of the work done on LNG coupling. Namely, it has been implemented in many power plants, there is data for its performance, and it’s a subject to intensive research with several different modifications evaluations.

The proposed modifications are:

- Several ORC cascade cycles
- Utilizing low grade waste heat
- Different heat sources for the evaporator
- Utilizing mixed working fluids (zeotropic mixtures)

Due to this, there are significant performance indicators available, especially for the thermodynamics efficiencies of the proposed cycles.

Refuse incineration gases as heat source for an ORC with ammonia-water working fluid is presented in [60]. Cascade of cycles including ORC is evaluated in [61]. Ammonia-water mixture as a working fluid is evaluated also in [62]. The difference here is that there is separating unit for ammonia. This scheme is optimized in [63]. Energy and exergy analysis of ORC scheme utilizing low grade heat are displayed in [64] and [65].

New cascade system is proposed in [66]. Cascade combination of various number of ORC is proposed in [67]. A cascade ORC with binary and tertiary mixtures is evaluated in [68]. Two stage ORC is examined in [69], while optimization of a cascade ORC is done in [70] and [71]. Optimization of ORC based on superstructure approach is presented in [72] Thermo-economic and thermodynamic analysis of ORC coupled with LNG is presented in [52] and [73] respectively.

Among the mixed working fluids, by far the most popular for research is the mixture between ammonia and water. This combination shows great thermo-dynamical merits to couple with LNG regasification process. A pinch-point analysis is performed in [74]. Also, some of the novel cycles proposed for LNG cold utilization, use ammonia-water mixture as working fluid. The optimization of this process is evaluated in [75], using genetic algorithams.

Direct expansion cycles are often combined with ORC. The possible DE configurations with other cycles are presented in [76] while [77] presents a combination of 3ORC and DE cycle.

A comprehensive review on the majority of the work done on this thematic is provided in [review articles] [78] [4] [79].

4.4.5 Implemented projects

Japan as the highest importer of LNG in the world, is among the countries which have contributed most to the development of technology for this industry. As in the other parts of the supply chain, in the regasification and process integration there are technical solutions from Japanese companies. As pioneers in this area are considered Tokyo and Osaka Gas companies, which have developed the first projects, and have the most developed projects in total. In the table below is presented a list of developed projects.

Table 9: List of power plants that utilize LNG cold energy [4]

Company	Terminal	Start of work	Type cycle	Power (kw)	LNG flow	p NG
Osaka Gas	Senboku	1979	RC	1450	60	30
Toho Gas	Chita Kydo	1981	RC	1000	40	14
Osaka Gas	Senboku	1982	RC+DE	6000	150	17
Kyushu	Kitakyusyu	1982	RC+DE	9400	150	9

	LNG					
Chubu Power	Chita LNG	1984	RC+DE	2*7200	150	9
Touhoku Power	Niigata	1984	DE	5600	175	9
Tokyo Gas	Negishi	1985	RC	4000	100	24
Tokyo Power	Higasi Ougishima	1986	DE	3300	100	8
Osaka Gas	Himeji	1987	RC	2500	120	40
Chubu Power	Yokkaichi	1989	DE+RC	7000	150	9
Tokyo Power	Higasi Ougishima	1991	DE	8800	170	4
Osaka Gas	Himeji	2000	DE	1500	80	15
Osaka Gas	Senboku	2004/2010	Cooling of intake air	1100 MW	-	-

Except for the projects in Japan, Spain is the first country in Europe that has power plants to utilize the cold energy of LNG. Gas company Enagas constructed the power plant in their Huelva LNG terminal. It is a power plant operating on ORC, utilizing seawater as a heat source. The installed capacity of this plant is 4.5 MW [4]. Its operation started in April 2013. The same company has one more project, to develop a power plant at Barcelona terminal. This plant should operate on DE and the capacity is 5.5 MW [4].

4.4.5.1 Osaka Gas Company projects

Osaka Gas company is importing LNG in Japan since 1972 until today. With their vast experience in the field they have developed numerous projects in cold LNG energy utilization.

In their Himeji terminal they have installed an ORC power generation unit. As working fluid is used propane, as heat source seawater is used and the installed capacity is 2500 kW. A scheme of this system is presented on Figure 30.

The company is known for their efforts to make a 100% utilization of the LNG energy in terminal. In their terminals Senboku 1 and 2, they have put a lot of effort into using the cold energy for several different purposes.

As it was noted earlier, it is a must that the terminal is placed in industrial complex in order to make several processes integration. The Senboku case is a great example for that, having an oil refinery and other chemical plants close to it.

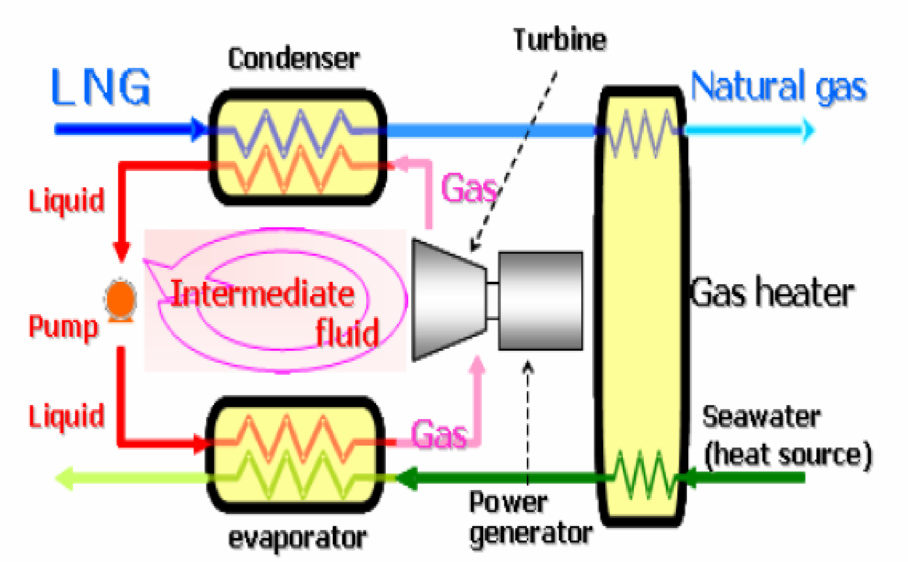


Figure 30: Scheme of ORC with LNG cold energy integration [30]

The applied process integration in this terminal is displayed in Figure 31.

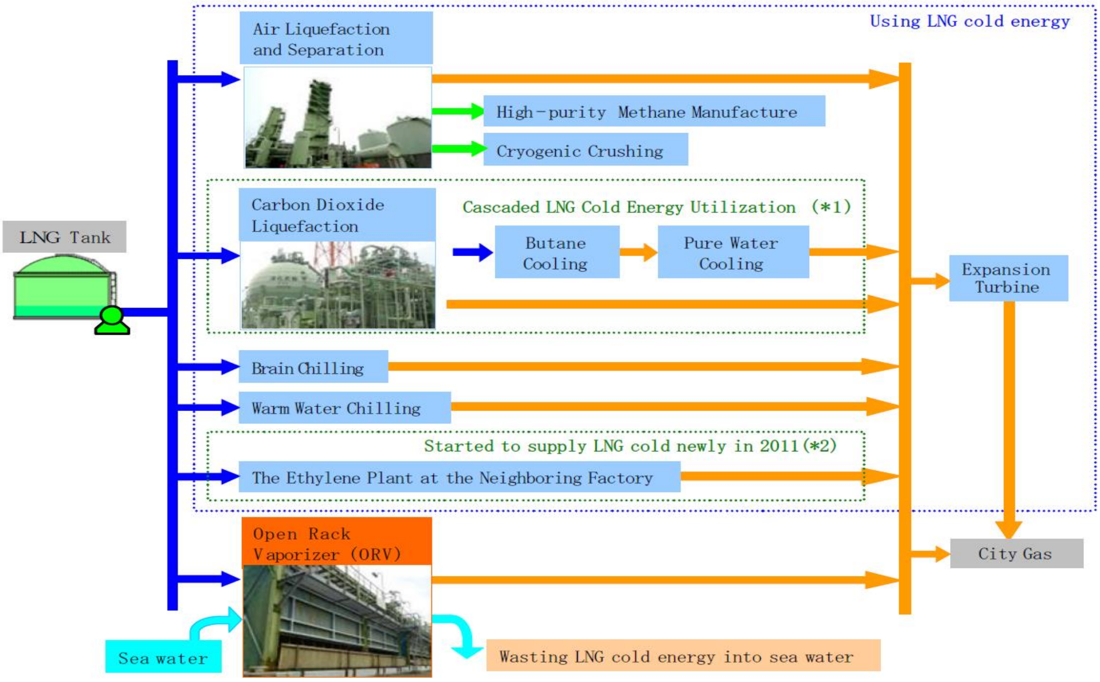


Figure 31: Utilization of cold energy at Senboku terminal [30]

It is noted that some part of LNG is regasified using seawater. In order to deal with this and to improve the overall efficiency of the cold energy use a new scheme is under research and development. This scheme is presented in Figure 32.

The new scheme is adjusted to the available industries nearby. A proper integration of the processes can be done only when the use patterns of all included industries match, which is not an easy task.

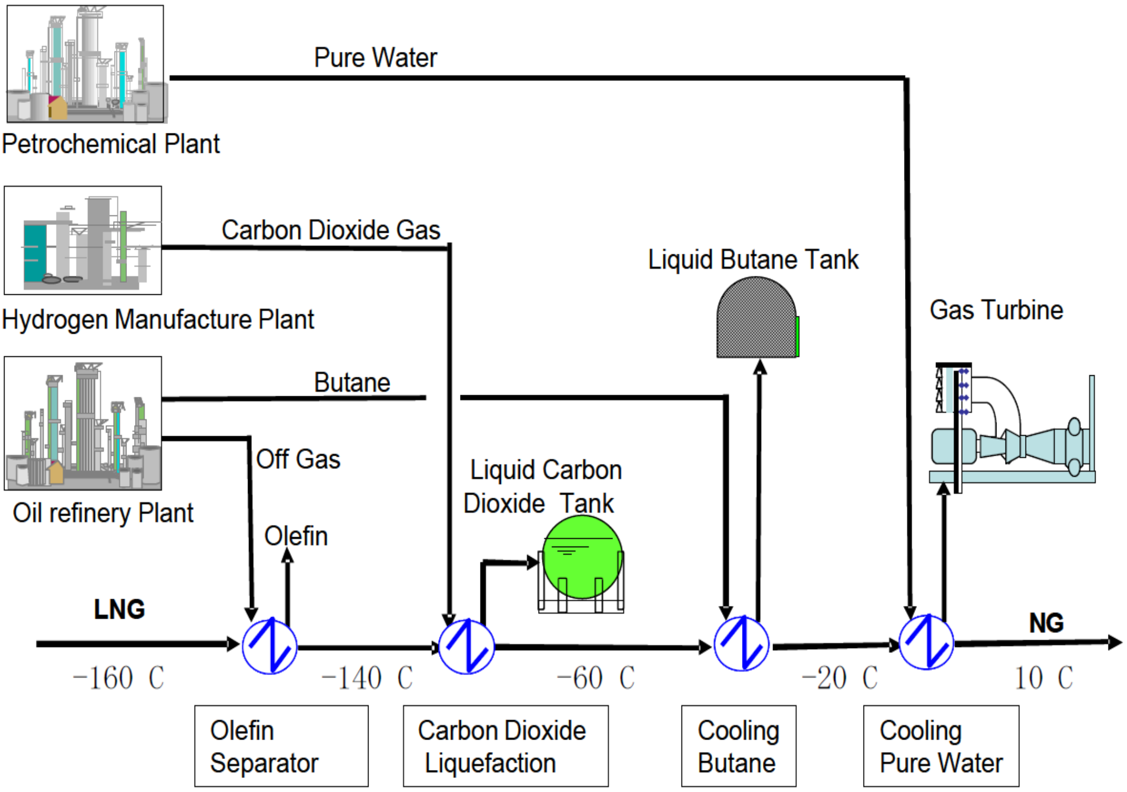


Figure 32: Research scheme to improve cold energy utilization at Senboku terminal [30]

The effect of fluctuation of LNG demand is displayed in Figure 33. This is a very important parameter for any application of the LNG cold energy. Terminals with flat profile of sendout gas will be prime contenders for process integration.

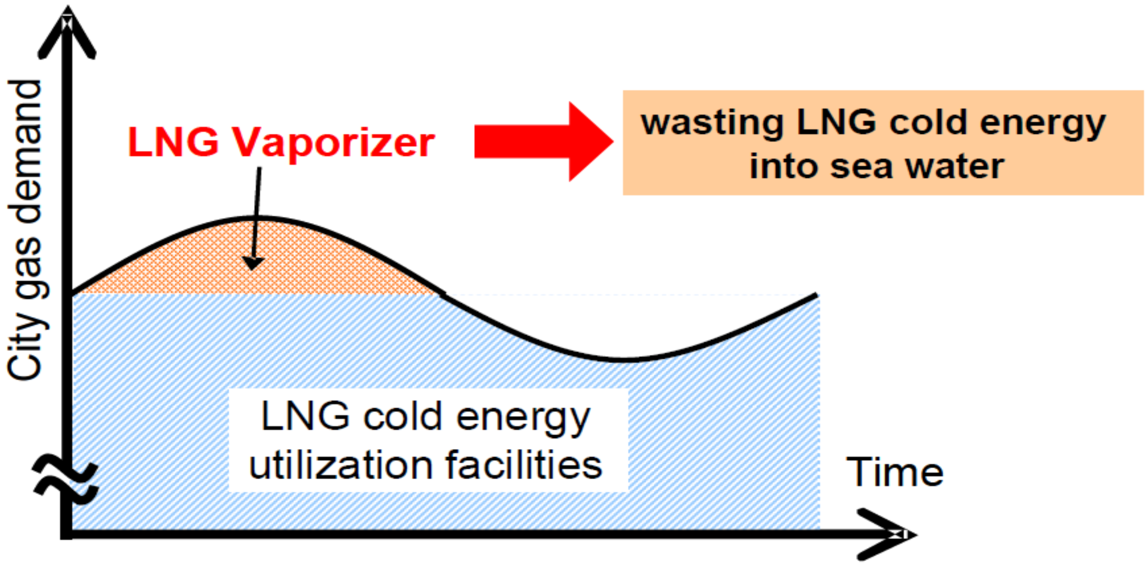


Figure 33: LNG cold energy availability based on gas demand [30]

5. Simulations description

The main purpose of this work is to identify possible cycles to integrate the LNG regasification, in order to make use of the available cold energy. After the literature review and the analysis of available and implemented options, ORC is chosen as a cycle to integrate with LNG regasification.

In order to obtain accurate results, the starting data and assumptions are very important. This Chapter explains which cases are chosen to be evaluated and on which criteria. It also includes an overview of the software used, in this case ASPEN Plus.

5.1 ASPEN Software characteristics

ASPEN is market leading chemical modeling and simulation software, preferred in the industry. It contains extensive database of units, specialized work environments and robust software. Some of its most important features are:

- Optimize process capacity and operating conditions
- High model accuracy with very accurate physical properties of substances
- Identify energy saving opportunities
- Reduce GHG emissions in processes
- Economic evaluations

The name of the software comes as an acronym from Advanced System for Process Engineering. It is based on simulation of flow sheet. In latest versions (as the one used in this work V. 8.8) the software is known as Aspen Plus.

It is used for Process flow diagrams (PFD), material and energy balances, and the basic process design. It is continually upgraded, to improve performance and functionality,

ASPEN is a process simulation software package which is very often utilized in the processing industry. Once a process design is specified and thermodynamics models are selected, ASPEN uses mathematical models to predict the performance of the process. After obtaining initial results, and analyzing them, this process can be done in an iterative way to improve performance. Namely, the key points of the scheme/circuit are identified, and detailed analysis is implemented for them, in order to obtain optimal desired parameters. Quite often optimization of one important parameter is done on the expense of other one, so it is important to analyze these relations, and establish suitable trade-offs. All the concepts and ideas named here, will be presented in details further in this report. Although for these work we analyze combinations of several often used components such as pumps, compressors and heat exchangers, ASPEN is very powerful tool and can be utilized for much more complex units and processes. It can be implemented for multiple-column separation systems, chemical reactors, and even electrolyte solutions.

With its great power, comes the danger of not proper use. ASPEN is robust and very powerful software, but it is meant to be used by students, engineers and researchers, which are already familiar with the theoretical details about the process designs they want to implement. During the work several types of “hidden” errors have been noticed, which are not shown from the program, and unless noticed during the results review, may lead to unacceptable mistakes in projects.

The software doesn’t design the process flowsheet. The user has available vast choice of components and blocks, and he can align them according to his preferences/needs. The design specification is accepted by the software, and the processing is done based on the input parameters entered by the user. Due to this, the user has to be familiar with the process, and have some insight about the size and units entered as input. In order to confirm the reliability of the entered data used here, the simulations part comes as last in order. First is the description of the processes used, than supported by research done in the field with published articles used as a benchmark, and finally implementing the simulations and discussing the possible options for improvement.

5.2 Assumptions prior to simulation

The simulations are performed in an idealized system, neglecting several factors. Although this will give results which later need adjustment in order to suit operating systems, this approach is accepted in work reviewed on this topic [4]

The simplifications and constraints used here are [4]:

- 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 (CH_4)
- The heat exchangers used are counter current, and the temperature difference between the hot and cold stream can’t be lower than 5 ^oC
- Due to environmental regulations, the difference in the seawater intake and discharge can’t be lower than 5 ^oC

These conditions have to be respected in order to obtain relevant final results.

5.3 Simulations run and indicators used

The simulations start with the basic scheme of classical ORV regasification. This is the best indicator of how much energy is wasted in conventional terminals. The first integration is simulated with direct expansion cycle (DE). Than the most popular combination is evaluated – ORC. ORC will be analyzed with different working fluids and different heat sources. As a last combination is a scheme with both ORC and DE, to show the benefit from both cycles working together.

For all the schemes same indicators are used. These are operational parameters and they are used to evaluate the key parameters for the energy balances and their influence on the net balance. The four parameters that will be used to evaluate the schemes are:

- Net power balance
- Waste of LNG cold energy/enthalpy
- Seawater requirement
- Thermal efficiency of cycle

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:

$$P_{net} = \sum Pt + \sum Plng + \sum Psw + P_{c.bog} + P_{p.wf} \tag{17}$$

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:

$$\Delta h = h_{in} - h_{out} \tag{18}$$

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:

$$m_w = m_{w1} + m_{w2} \tag{19}$$

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:

$$\eta_{th} = \frac{W_t - W_p}{Q_{ev}} \tag{20}$$

6. ASPEN Work

This Chapter contains the simulation work and the analysis of the obtained results.

6.1 Seawater regasification

Here is displayed the basic scheme for seawater regasification. The scheme generated in ASPEN is displayed in Figure 34.

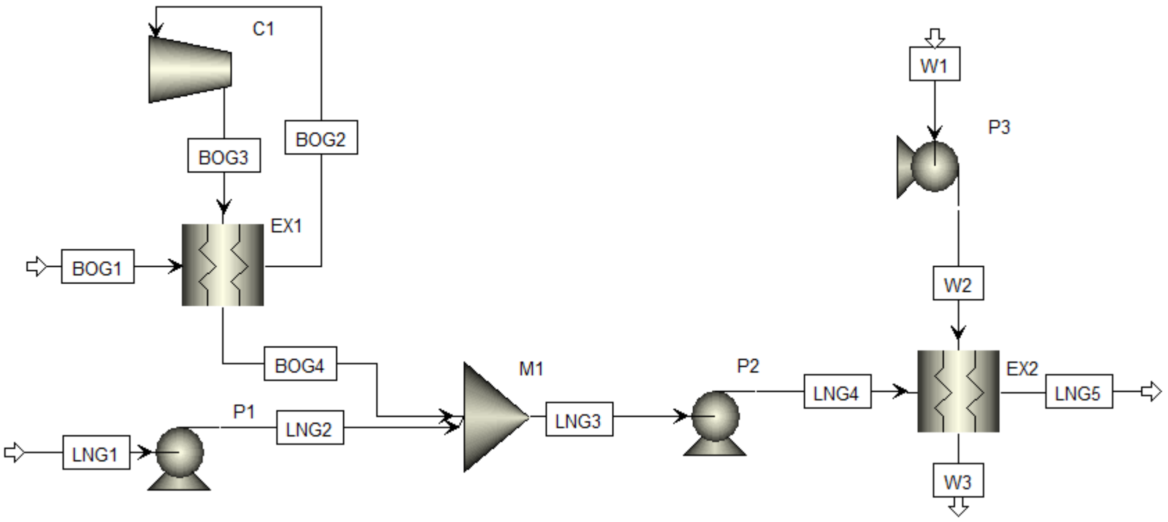


Figure 34: Seawater regasification scheme from ASPEN Plus

The Input parameters for the simulation are displayed in Table 10.

Table 10: Input data for case 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 ^oC p=1.2 bars	m=3.65 t/h
Incoming LNG stream	LNG1	Temperature, Pressure and mass flow	T=-162 ^oC 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 ^oC	4950 t/h
Seawater Pump	P3	Discharge Pressure	1.5 bar	
ORV	EX2	Gas stream Temperature	10 ^oC	

The starting pressure of both LNG and BOG streams is defined as an operating pressure in the storage tanks. LNG is sucked by the LP pump, while BOG goes to the compressor. Then both are compressed at same pressure (8 bar), which is also the operating pressure for the BOG recondenser. From the recondenser, the stream goes to the HP pump for LNG.

Here LNG is pumped to high pressure due to the economics of high pressure regasification compared to regasification at low pressure and later compressing in gas phase.

In the ORV (EX2 on the scheme on Figure 34), LNG is regasified to the required condition using seawater as heat source. In this heat exchanger is also important to avoid temperature drop of water of 5 °C, due to environmental regulations.

After running the simulation for the specified entry parameters the results obtained are displayed in Table 11.

Table 11: Results for case 1

Description	Pnet (MW)	Seawater (t/h)	Enthalpy lost (kJ/kg)
Seawater regasification	1.23	4950	736.71

These results just confirm the previous discussion about this scheme. The net power balance is negative due to the expenses from LNG and seawater pumps and the BOG compressor. There is a need of large amount of seawater to vaporize LNG in the heat exchanger. Since no process integration is implemented most of the available enthalpy is wasted in the heat exchanger.

The results for all the streams on this scheme are displayed in Annex.

The sensitivity analysis is run on the pressure after pump P2, and on intake water temperature in stream W1.

The result from the pressure variation is displayed in Figure 35.

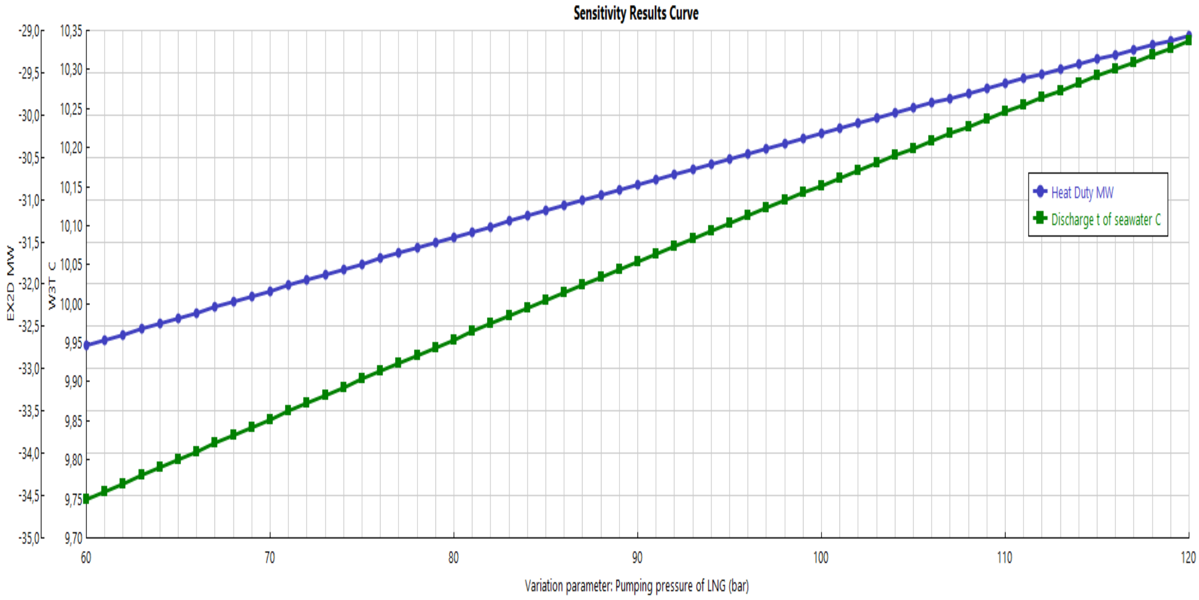


Figure 35: Sensitivity results for LNG pressure change

The variation of the pressure from 60 to 100 bar shows its effect on the heat exchanger and the discharge temperature of the water. With increase of pressure, the heat duty in the exchanger is decreased, which also results in slightly higher discharge temperature of the water from the vaporizer. However, this comes at cost of pumping LNG to higher pressure than the one of the distribution, which will result in higher electricity consumption from the pump P2, and higher expenses in the investment part due to the fact that all the equipment should be constructed to operate under higher pressure.

The effect on the temperature change is displayed in Figure 36.

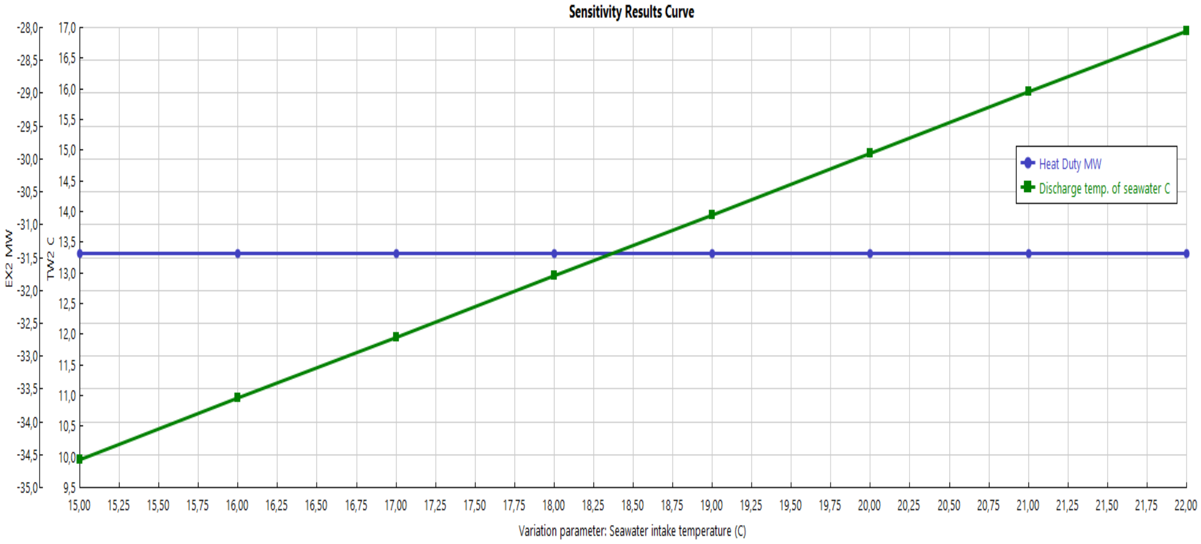


Figure 36: Sensitivity results for intake water temperature change

Higher water temperature won’t have any effect on the heat duty of the exchanger, and the temperature difference between intake and discharge of water will be in the region around 5 °C.

6.2 Direct Expansion Integration

This comes as the most simple process integration scheme. One turbine (expander) is added, to make use of the mechanical energy contained in LNG. This scheme is shown in Figure 37.

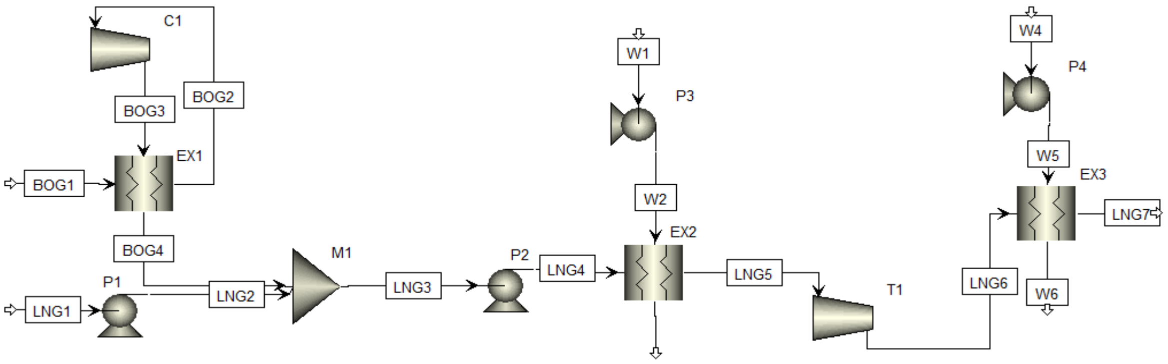


Figure 37: Scheme for Direct Expansion (DE)

The entry data is identical to Scheme 1 (Table 10). The addition of new parameters and change of some of the existing ones is displayed in Table 12.

Table 12: Additional input data for case 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

Running the simulation, and evaluating the pre-defined parameters Table 13 is obtained. In order to showcase the usefulness of the DE cycle, this scheme is run for several different pressures. The values are from certain use of sendout gas low pressure distribution Japan, CCGT plant, local distribution and high-pressure distribution

Table 13: Table of results for Case 2, for 4 different sendout pressures

Description	**P sendout**	**Pnet (MW)**	**Seawater (t/h)**	**Enthalpy lost (kJ/kg)**
National grid	80 bar	0.06	5170	764.27
Japan case (9bar)	9 bar	-6.03	6750	959.89
CCGT	25 bar	-3.56	6200	918.05
Local Distribution	30 bar	-3.07	6100	900.17

After running the scheme for four different sendout pressures, the obtained results show us where the utilization of DE cycle is most beneficial. When having very low distribution pressure, such as in Japan (due to seismic instability), the power generated is at the highest. The local distribution and CCGT plant are in the middle with positive net balance, but around one half compared to the Japan case. In the case of national grid distribution at high pressure (80 bar), the results are not so good. Despite the power generation, the net balance is still negative.

The sensitivity on the discharge pressure on the whole range between 80 and 9 bars is displayed in Figure 38.

Since the higher pumping pressure is generally limited due to technical specifications of equipment (here we use 120 bar), the application of DE cycle will depend on the distribution pressure. Low pressure will provide enough pressure difference to generate enough power to have positive net balance.

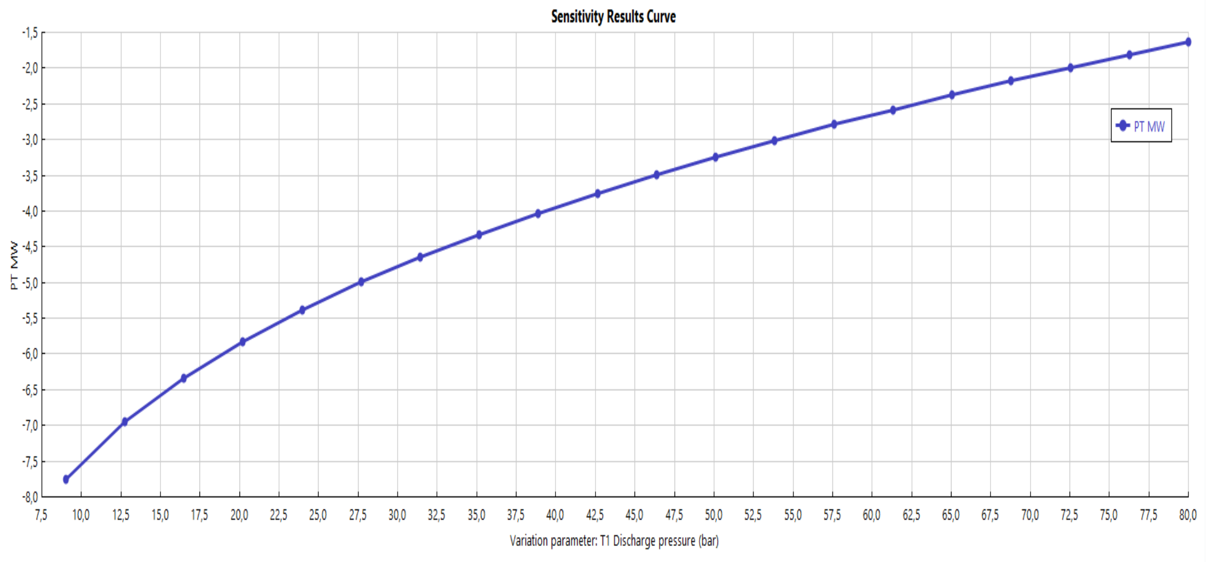


Figure 38: Discharge pressure effect on power generation in turbine

6.3 ORC analysis

The ORC with its flexibility in terms of working fluids and heat sources provides great opportunity for various analysis. Here will be evaluated three types of heat source: seawater, exhaust steam (water) from steam turbine and hot exhaust gases. Along with them, several combinations of working fluids will be tested, in order to analyze their characteristics and suitability for this process.

The scheme for this process is displayed in Figure 39.

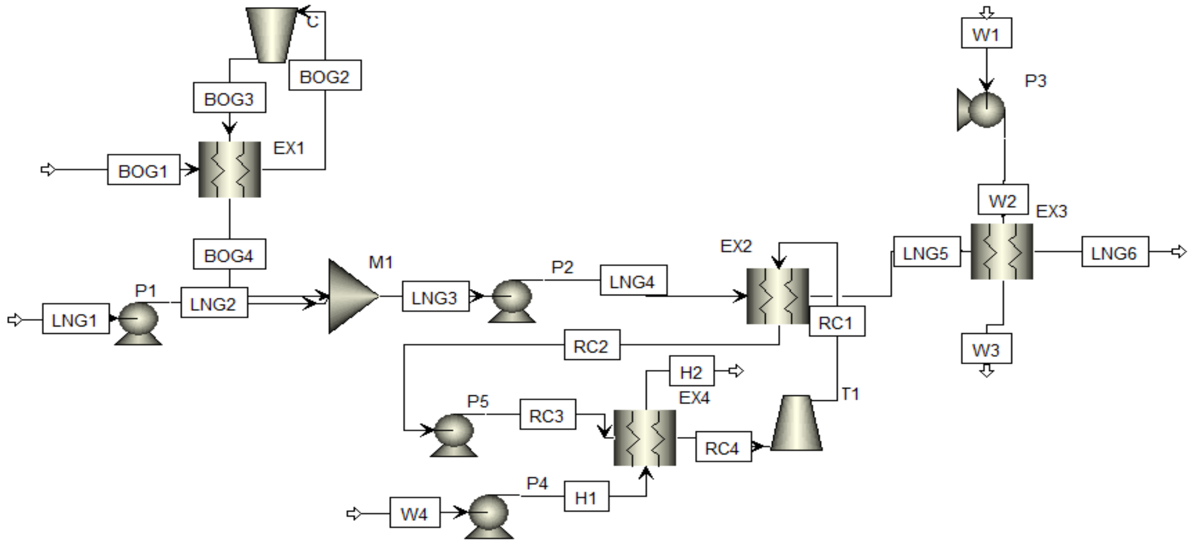


Figure 39: ORC Scheme with seawater as heat source

Boiling points of the working fluids will depend on the heat source temperature. Due to that three different heat sources will be evaluated. For working fluid will be evaluated propane, ammonia and mixture of ammonia-water. They are chosen because most of the research work is done on them and some of the implemented projects also.

6.3.1. ORC with Seawater

This is unconventional ORC system. Generally ORC is adapted to make use of some waste heat and in this case the source is only 15 ^{o}C. This constraint significantly reduces the choice of working fluid. For this heat source and to utilize LNG cold energy, propane and ammonia will be evaluated. The mixture of ammonia-water can't run with these parameters because the boiling temperature of the mixture is higher than the temperature of seawater. The parameters for the units used in the ORC are displayed in Table 14.

Table 14: Input data for ORC 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

After running the simulation, the results obtained are displayed in Table 15.

Table 15: Results for ORC with seawater as heat source

Description	Pnet (MW)	Seawater (t/h)	Enthalpy lost (kJ/kg)	Thermal efficiency (%)
Seawater ORC propane	-2.52	5650	198.00	14.06
Seawater ORC ammonia	-2.21	5650	156.44	12.24

The results from the two working fluids are quite close. The propane cycle has higher power generation and higher coefficient of efficiency (first law), while with the ammonia cycle there is less enthalpy loss from LNG wasted in the vaporizer.

Since this simulation indicates the most important technical aspects of these cycles to be close, the choice which one to use further may be more on the economical and operational side. Propane is considered as safer fluid than ammonia, and most of the implemented projects until now use propane.

Most of the operating parameters are pre-defined either technically or by regulations, so here is little place for variation. The variations possible for this scheme are the working fluid and the heat source. In the next analysis, the heat source used will be exhaust steam from steam power plant.

6.3.2. ORC with exhaust steam

One more option for a heat source can be exhausted steam from a steam power plant. In order to use as much as possible from the steam energy, it is released at very low (vacuum) pressure and temperature. In order to have proper process integration, the exhaust steam is condensed in the heat exchanger where the working fluid is vaporized (EX4 on the scheme).

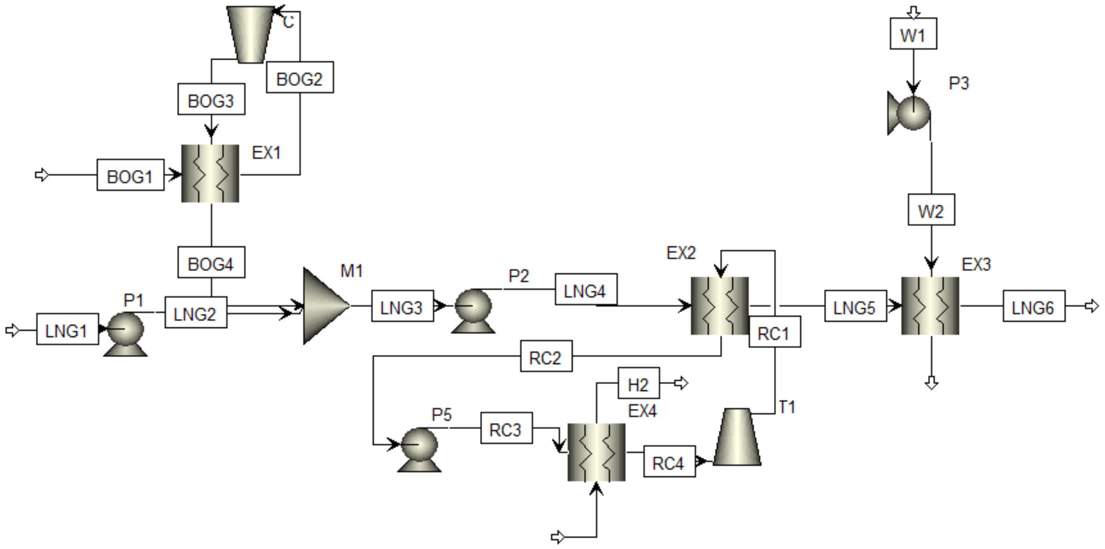


Figure 40: ORC with exhaust steam as heat source

Figure 40 shows this scheme

Although the parameters of exhaust steam can vary significantly, depending on type of turbine and plant, in general steam is exhausted at very low pressure and temperature, in order to utilize most of its potential. For this simulation, exhaust steam with the following parameters is used [81]:

Table 16: Exhaust steam parameters

Parameter	Quality (vapor fraction)	Pressure	Temperature
Value	0.9	0.05 bar	36 ^{o}C

For Input in ASPEN two parameters are required. Here we entered the quality and pressure, and the temperature was generated from the software. Comparing again to the used reference, this value for temperature is in the range of acceptable temperature of exhaust steam (30-40 ^{o}C).

This heat source has temperature more than twice times higher compared to the first case. This increases the available working pressure of the working fluid, and due to that, increases the power output from the turbine. The only difference to the ORC with seawater is the pumping pressure of the WF. They are displayed in Table 17.

Table 17: Input data for ORC with exhaust steam

Unit/Stream	Propane as Working Fluid	Ammonia as Working Fluid
P5 – pump for WF	P=11 bar	P=11 bar
RC2 – WF specification	m = 201 t/h	m = 72 t/h
H1 – heat source (steam)	m = 42 t/h	m = 45 t/h

Compared to the previous one, only the pump for seawater used as heat source (P4) in the ORC is eliminated. The results obtained after running this simulation, are displayed in Table 18.

Table 18: Results for ORC with exhaust steam

Description	Pnet (MW)	Seawater (t/h)	Enthalpy lost (kJ/kg)	Thermal efficiency (%)
Steam ORC propane	-3.82	1350	195.47	17.78
Steam ORC ammonia	-3.75	1100	160.90	16.70

Once again both fluids show similar performance, and propane showing higher power output and efficiency of the thermal cycle.

It is notable that the mass flows of WF and heat source differ for propane and ammonia. The final result is obtained with the goal to have the total incoming exhaust steam condense, and make double gain from this process integration. The WF of the ORC transfers heat to LNG in the process of condensation (block EX2 on Figure 40) and evaporates by “accepting” heat from the exhaust steam, which is entirely condensed (block EX4 on Figure 40).

The most relevant parameters for all streams are available in Annex.

6.3.3 ORC with exhaust gases as heat source

Exhaust gases with temperature of 200 ^{o}C are chosen as heat source for this simulation. The gases contain CO_2 and N_2 in mass ratio 0.51/0.49. As working fluids are used propane, ammonia and ammonia-water mixture (mass ration 0.6/0.4).

Since the exhaust gases are afterwards released in the atmosphere, there are no particular requirements related to them. It is assumed that they are coming after the filtering systems. Their characteristics used are displayed in Table 19.

Table 19: Parameters of exhaust gases

Parameter	Quality (vapor fraction)	Pressure	Temperature
Value	1	1	200 ^{o}C

The only condition is that they don't start to condense in the heat exchanger, in order to avoid problems with corrosion (Vapor fraction has to be 1 on outlet).

With the high temperature heat source, the working pressure can go significantly higher. However since in the reviewed articles [4], all the work is done for pressures in the region of 20 bar, this will be the highest pressure used. The change of parameters compared to previous ORC cases is:

Table 20: Input data for ORC with exhaust gases as heat source

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	m = 2000 t/h	m = 2000 t/h	m = 2000 t/h

The obtained results from this simulation are presented in Table 21. This table gives very interesting results, which can be used as guidance for further analysis.

Table 21: Results for ORC with exhaust gases

Description	Pnet (MW)	Seawater (t/h)	Enthalpy lost (kJ/kg)	Thermal efficiency (%)
Gases ORC propane	-4.95	1350	201.06	21.13
Gases ORC ammonia	-5.03	1050	155.48	19.99
Gases ORC mixture	-5.63	0	0.00	17.37

Propane and ammonia were evaluated in all three heat sources. The increase of power output and thermal efficiency are obvious with heat source temperature increase. The seawater need is significantly decreased compared to the first case because seawater is no longer needed as heat source. The power output is increased due to the higher entry pressure in the turbine.

The lost/unused enthalpy from LNG is also decreased. This is a great indicator that this solution makes multiple uses.

The last case (ammonia-water) comes as a total opposite to the first one (seawater regasification). The ORC cycle with ammonia-water mixture has the best performance indicators. It has best net power balance, no seawater requirement and no waste of LNG enthalpy. All the cold energy of LNG is used in the condenser for ammonia-water and because of that the need to have additional seawater vaporizer is eliminated.

However, it is notable that this system was only tested with the last heat source (hot gases). With low temperature heat source, this system can't run due to the high boiling temperature of ammonia-water mixture [76]. The system without seawater regasifier is presented in Figure 41.

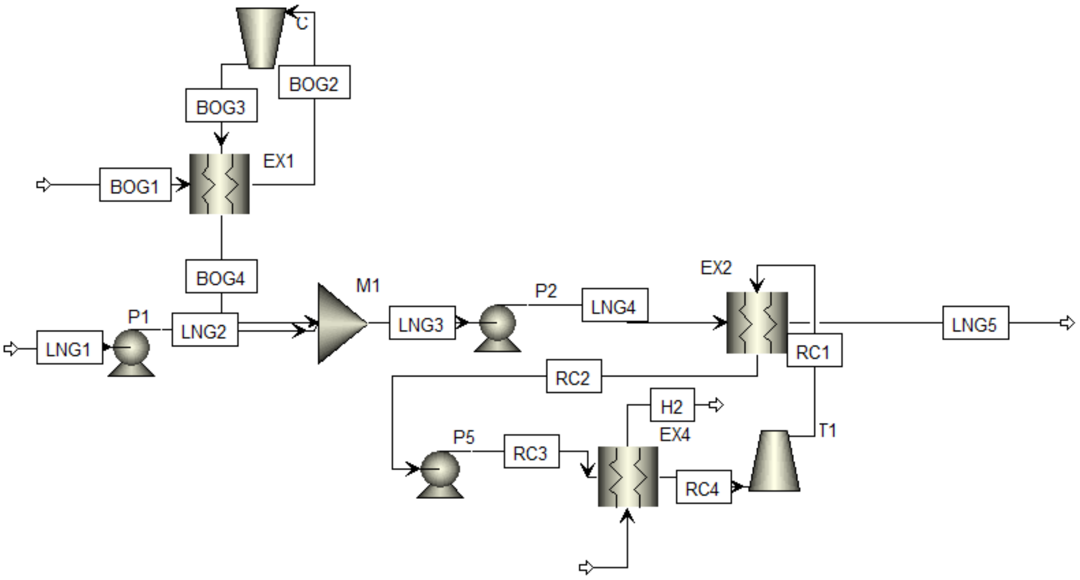


Figure 41: Scheme of ORC without seawater regasifier

6.3.4 Cycles and heat sources comparison

Since many combinations for ORC were evaluated, now we run an additional parameter analysis to see which factors have influence.

The effort put into finding a higher source heat source is for the purpose of obtaining higher pressure of WF in ORC. The effect of increased pressure on the most important parameters is evaluated through sensitivity analysis, for the 3 working fluids.

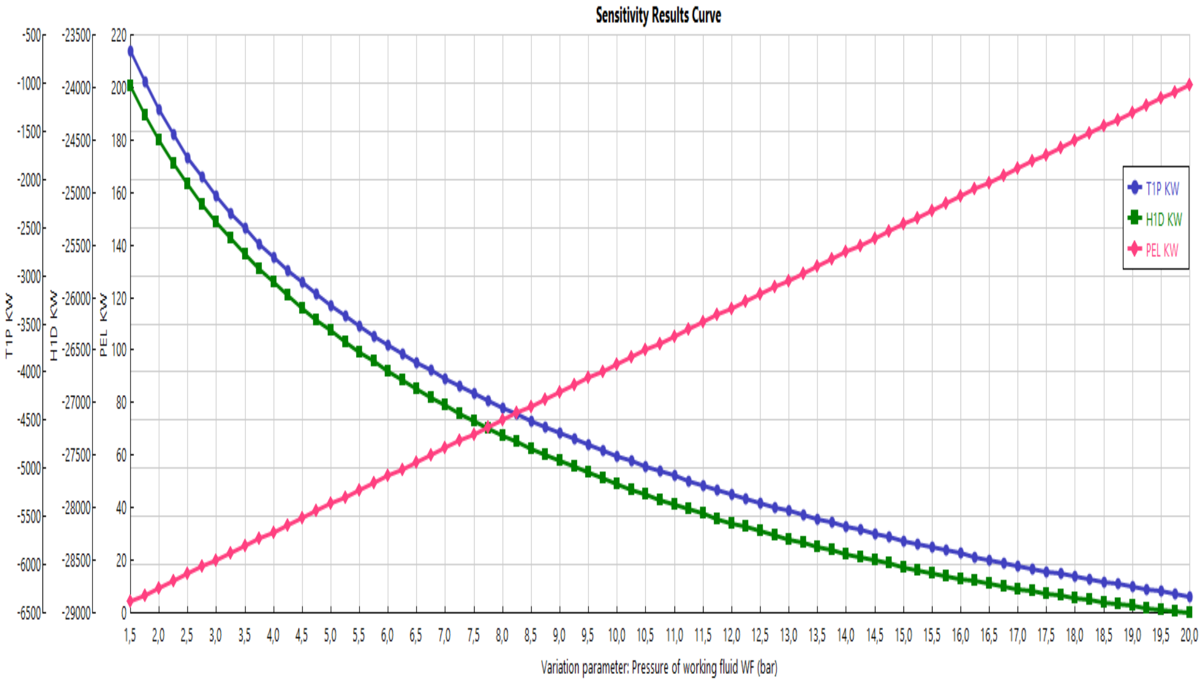


Figure 42: Sensitivity analysis for Gases ORC Propane

This analysis shows the influence of working pressure of WF on the power generation in turbine, heat needed for evaporation of WF in the heat exchanger and the power consumption of the pump for WF.

Figures 42, 43 and 44 display the sensitivity analysis for propane, ammonia and NH3-H2O mixture, respectively.

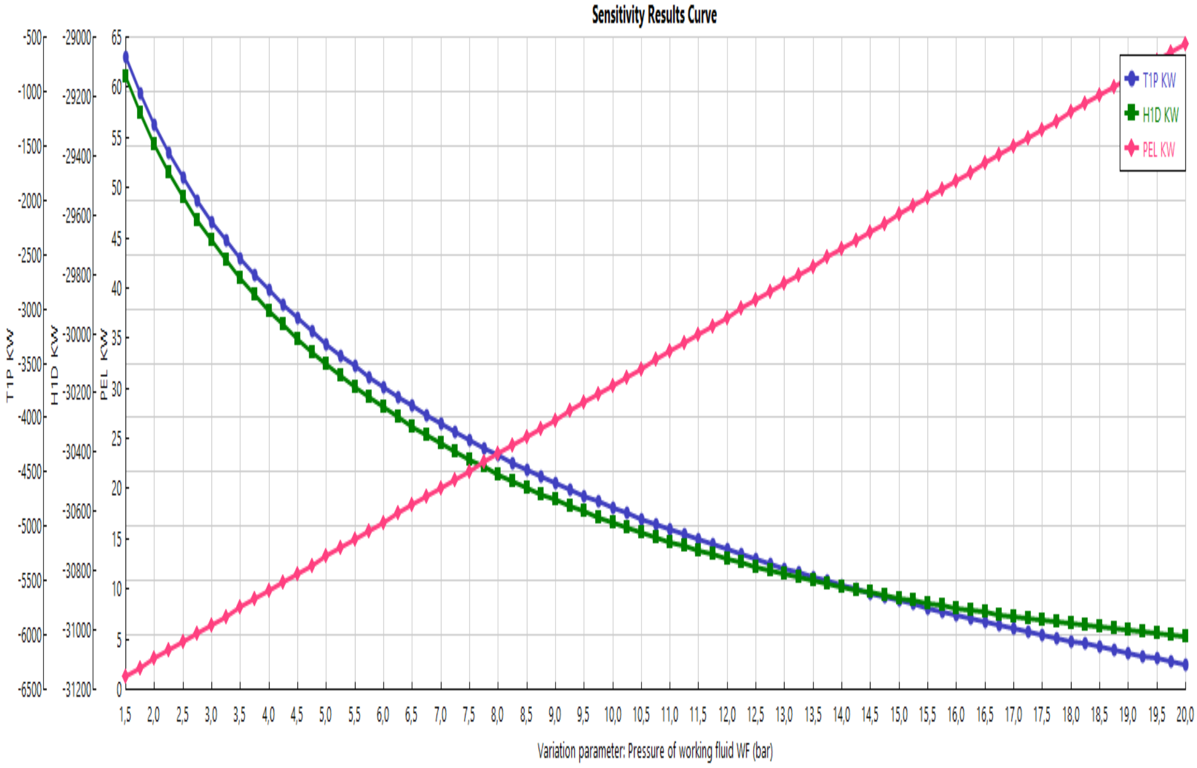


Figure 43: Sensitivity analysis for Gases ORC Ammonia

The similar (almost identical) form of the curves for all 3 options, prove the influence of operating pressure on the other parameters.

Higher pressure means higher electricity consumption in the pump, higher power generation in the turbine and higher heat needed for evaporation of the WF.

These three parameters define the coefficient of efficiency of the cycle, based on First Thermodynamics Law.

$$\eta_{th} = \frac{W_t - W_p}{Q_{ev}} \tag{21}$$

The variation of this coefficient in the range of the operating pressure is obtained after replacing the obtained values from the sensitivity analysis results in the previous equation.

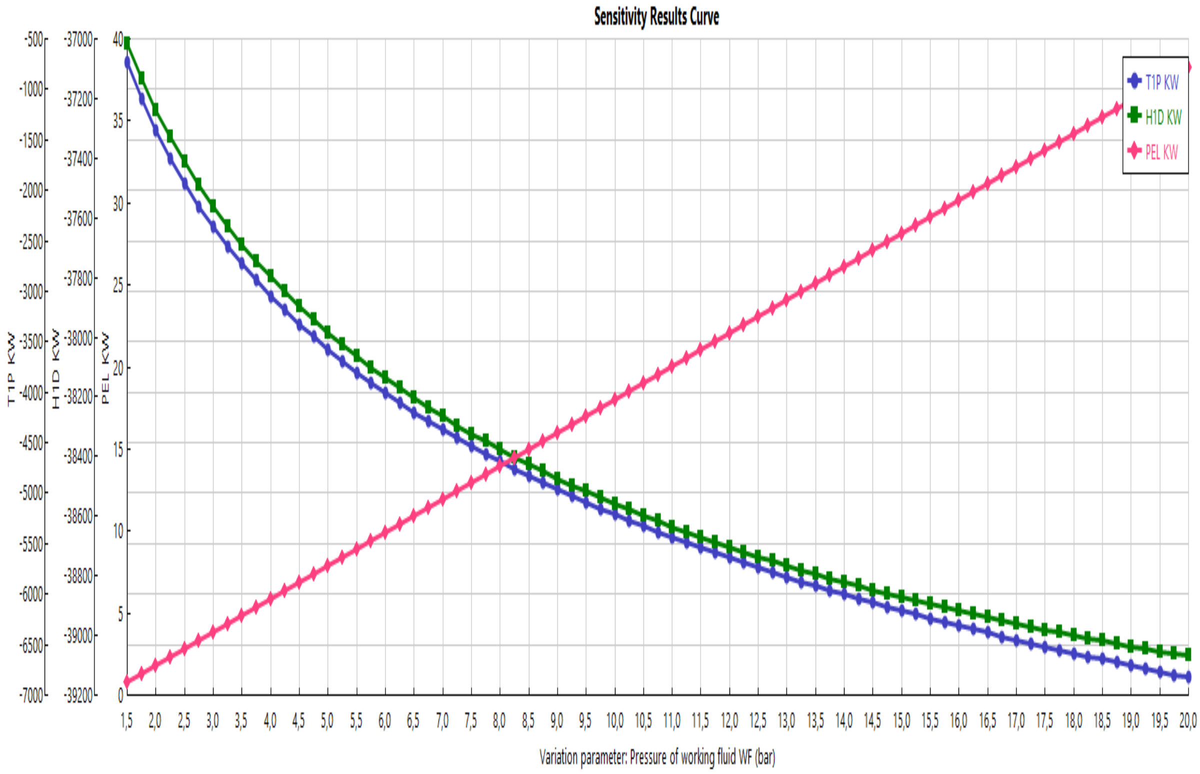


Figure 44: Sensitivity analysis for Gases ORC NH3-H2O

The results from the sensitivity analysis, added into equation (21), give the thermal efficiency coefficient. It is displayed in Figure 45.

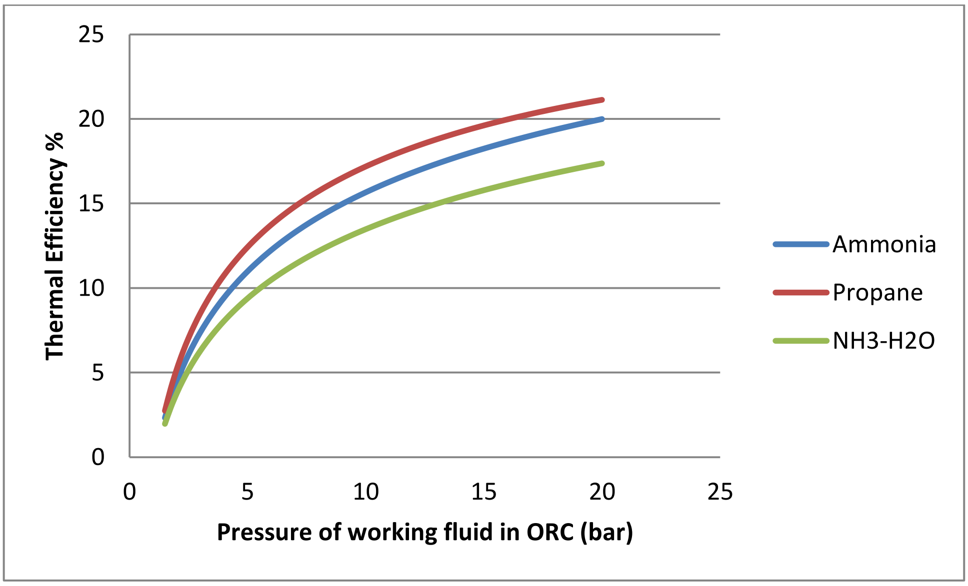


Figure 45: Variation of η_{th} with working pressure for 3 working fluids

After the pressure, the mass flow of the WF is also very important parameter for the behavior of the system. The analysis of the influence of mass flow of WF on the temperature of LNG leaving the exchanger (block EX2 on scheme), on the power consumption of the pump for WF and the power generation in the turbine is displayed.

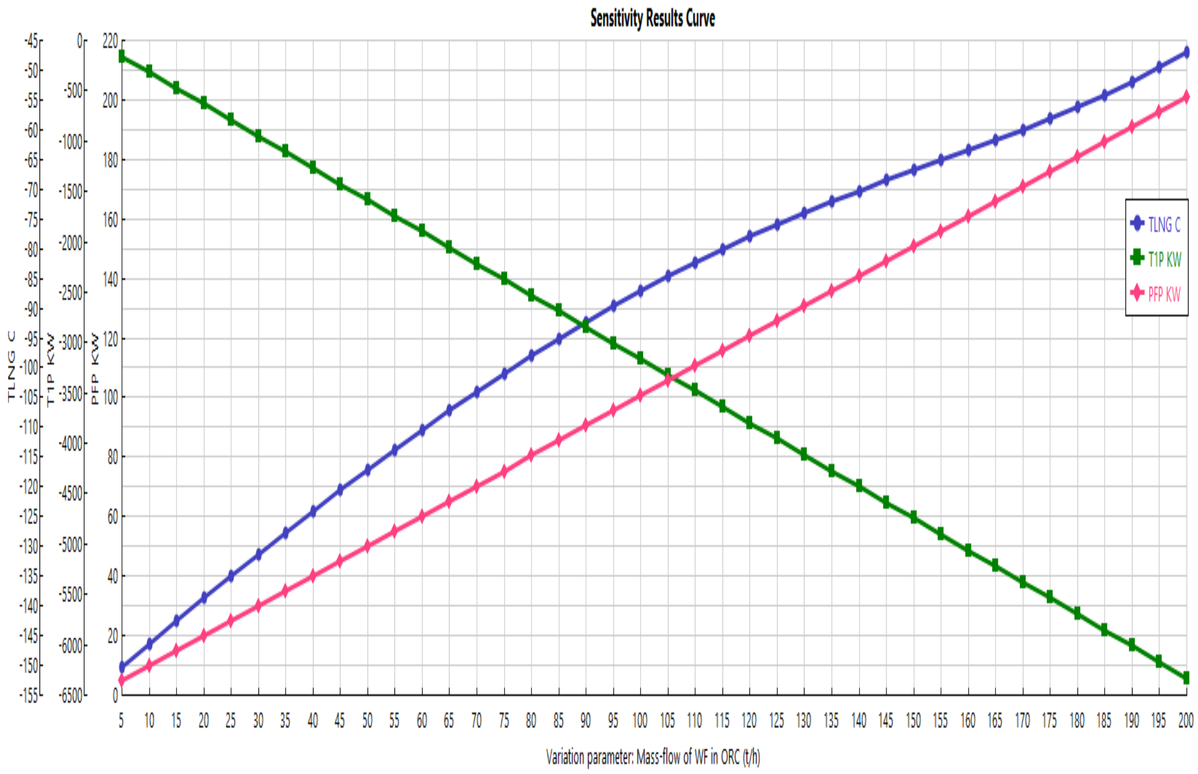


Figure 46: Sensitivity analysis for mass flow of WF - propane

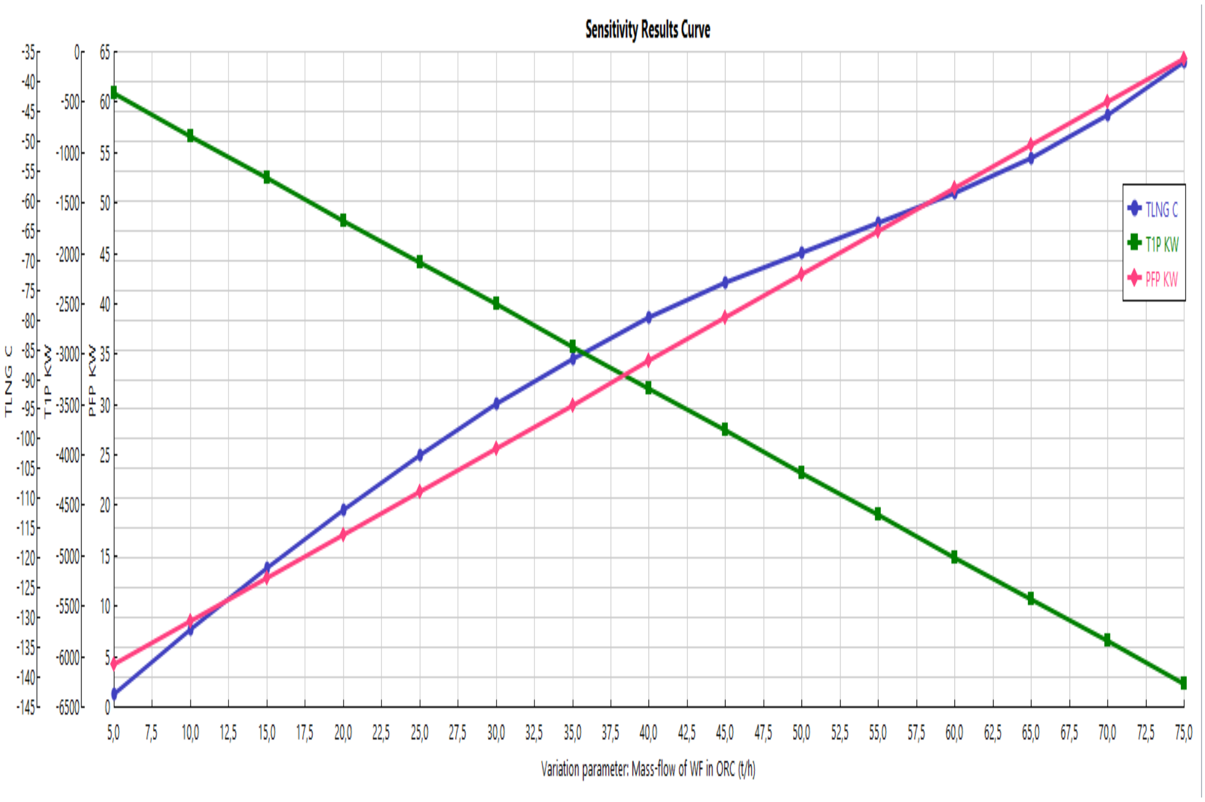


Figure 47: Sensitivity analysis for mass flow of WF - ammonia

The increase of LNG temperature is dependent on higher flow of WF. Higher flow of WF means higher temperature of LNG at the exit of the heat exchanger. This is limited to a point at which the temperature difference between the two streams (5 °C) has to be respected. The sensitivity analysis of mass flow of WF is displayed in Figures 46, 47 and 48.

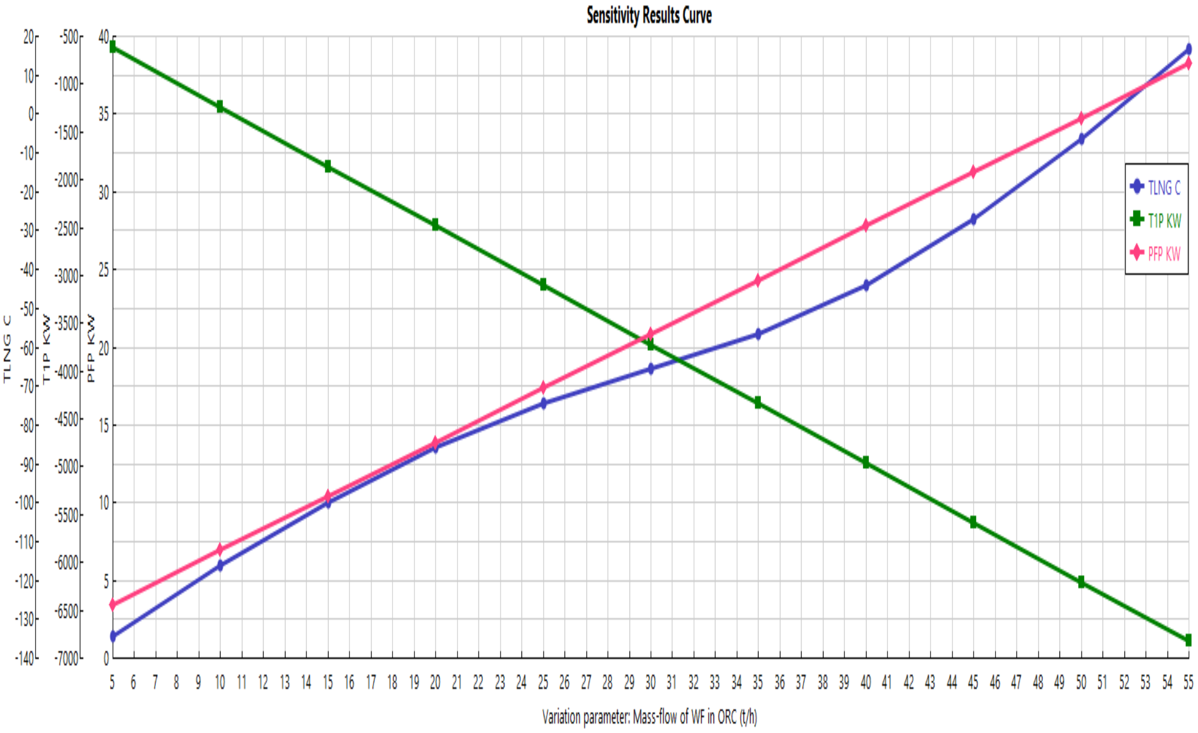


Figure 48: Sensitivity analysis for mass flow of WF – NH_3-H_2O mixture

6.4 Special case evaluation ORC + DE

Since the effects of the ORC scheme were explained above, here emphasize will be on its integration with DE cycle. This cycle makes use of both thermal and mechanical energy of LNG. The scheme is displayed in Figure.

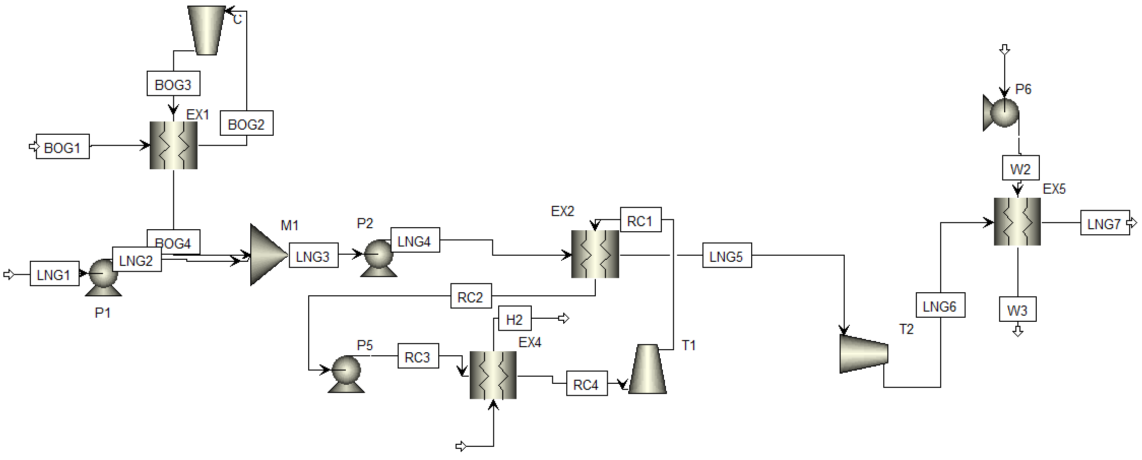


Figure 49: Scheme for ORC+DE combination

It will be run for the four specified pressures in the part for DE. Ammonia-water as fluid will be used for all four cases, while propane and ammonia will be tried just for the high pressure transport (80 bar). The reason for this is to evaluate in details the possibilities for this scenario (80 bar) as most feasible for the gas system in Portugal. The other cases are regarded as special cases.

Table 22: Results for ORC+DE, with NH3-H2O

Description	Pnet (MW)	Seawater (t/h)	Enthalpy lost (kJ/kg)	Thermal efficiency (%)
Gases ORC+DE 80bar	-7.09	102	14.90	17.37
Gases ORC+DE 9 bar	-14.34	1850	273.65	17.37
Gases ORC+DE 25 bar	-11.43	1250	185.58	17.37
Gases ORC+DE 30 bar	-10.84	1130	165.34	17.37

Table 23: Results for ORC+DE, 80 bar, 3 working fluids

Description	Pnet (MW)	Seawater (t/h)	Enthalpy lost (kJ/kg)	Thermal efficiency (%)
Gases ORC+DE propane	-4.37	2000	293.06	21.13
Gases ORC+DE ammonia	-4.62	1700	252.70	19.99
Gases ORC+DE NH_3-H_20	-7.09	102	14.90	17.37

6.5 Cycles comparison

Starting from the basic scheme, additional elements were added to the scheme in order to evaluate the pre-defined parameters. All results are summarized in Table 24.

Table 24: Simulation results summary

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

These results are related on the case for conditions specified for Portugal. The special cases indicated in scheme 2 and 10, are not displayed here because their conditions (lower sendout pressure of NG) does not apply to Portugal.

The first and most important conclusion from this work is that all the ORC schemes make positive net balance for electricity. This means that the terminal can sell this electricity.

The integration with ORC has additional benefits – decrease of the quantity of seawater needed and losses of LNG enthalpy.

The thermic efficiency is very low in all the cases. However, this shouldn't be seen as some big disadvantage. The low coefficient is due to the low temperature heat source used in combinations. Since there are no direct GHG emissions, even with low thermal efficiency this integration makes a positive contribution into utilizing waste heat or synchronization with other utility, in order to produce electricity.

Based on this evaluation the best integration comes with ORC cycle and ORC with additional DE. In the case for ORC, the higher the available heat source, the higher the power output and with that better net balance of power.

6.5.1 Improvement with ORC on basic case

Table 24 summarized all the results from the different schemes simulation. It is notable that we have wide variation of the obtained results. The improvements are represented on Figure 50. For better appearance of the graph, only here the positive net balance is presented without the sign "-", contrary to the previous displaying of results.

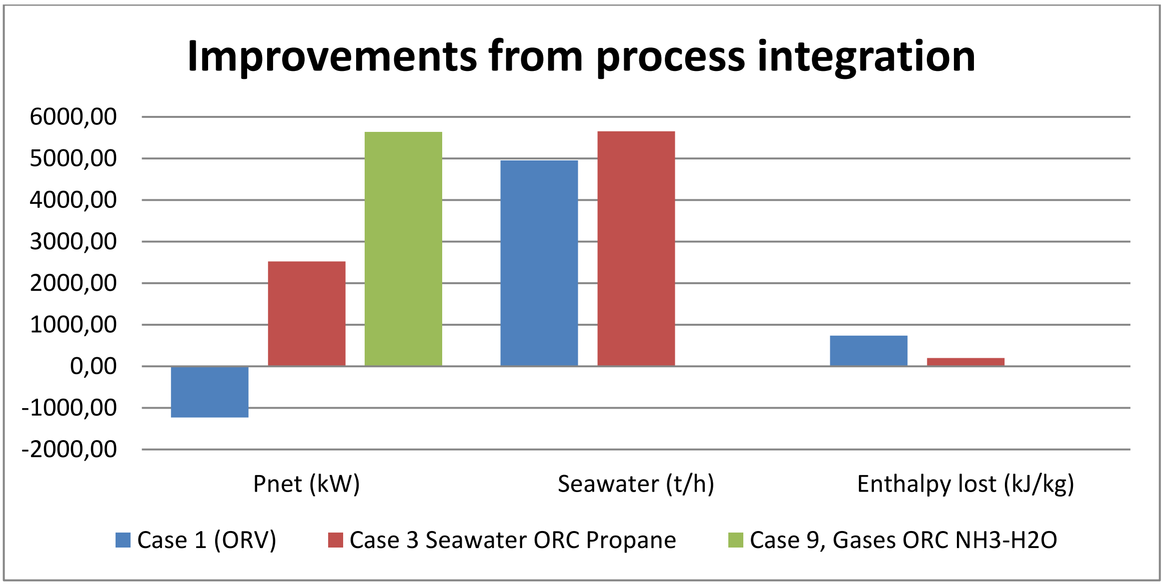


Figure 50: Comparison of effects from process integration

When using case 9, the starting situation is totally changed. The net power balance is turned from negative to positive, and the need for seawater use and enthalpy lost are eliminated.

When using Case 3, which is most often implemented in practice, the seawater consumption increases compared to case 1. This is due to the fact that seawater here is used as a heat source and for regasification of LNG. However, the net balance power is positive, and the enthalpy lost decreased.

Further addition of DE cycle on case 9, will additionally improve the net power balance, but will also require input of seawater to get NG to the required temperature for further distribution. The feasibility of this combination will depend on the price of the equipment and on economic analysis.

7. Economical assessment for feasibility of installation

After the technical analysis, the economics is the 2nd most important factor in projects.

Unfortunately, unlike the data for the cycles, the information on economic feasibility of this type of systems is very scarce. The main reason behind this is that only a very small number of companies have implemented this type of projects.

As displayed in previous Chapters, most of the implemented projects are done in Japan, mostly from Osaka and Tokyo Gas companies. Beside some of the schemes, and some operational data, to the best of knowledge, is not published.

As discussed in [4], primary contenders are terminals with minimal fluctuation of the sendout gas. Most of the terminals in Western Europe have strong developed distribution and storage network, so any incoming LNG can be regasified and distributed.

On the economics side, the expenses will be divided between CAPEX and OPEX. For the CAPEX part it is of huge importance, if the process integration is planned in the terminal construction or afterwards. For the OPEX part the variation is minimal.

The OPEX costs consist of [67]:

- Operation Labor
- Utilities
- Maintenance and repair
- Operating supplies
- Local taxes
- Insurance
- Plant overhead costs

The terminal has to recover these expenses by the positive net power balance. The previously expense for seawater pumps will be minimized or even eliminated, and additional power generated. Although this power can’t be classified as a renewable one, it comes from a cycle with no direct GHG emissions, and depending on the country legislative, if there are some feed-in tariffs for it or subsidies will make the project even more attractive.

From the scarce data available worth mentioning is the one related to Enagas and AMEC Foster Wheeler. According to [4], the most recent project at Huelva Terminal operated by Enagas, is estimated as an investment of 13 million euros for a 4.5 MW plant using propane as working fluid. The same report also states that there is a plan for a plant in Barcelona Terminal with power of 5.5 MW utilizing direct expansion of NG. AMEC Foster Wheeler is a company with vast experience and large list of references in LNG industry. In a publication [80] they suggest a payback period of 5-6 years for a terminal with capacity of 5 MTPA.

7.1 Economic approximation of project feasibility

Due to the very scarce data on this problematic, the economic assessment will be based on many assumptions, which means that the obtained results can vary significantly.

As a base case for reference is used Huelva terminal in Spain. This project has set a CAPEX cost of 13 million euros for the whole project.

The OPEX expenses are assumed to be 100.000 euros per year.

Retail price index RPI, also known as inflation, is assumed 2% yearly.

The corporate tax is assumed to be 30%.

The asset depreciation is assumed to be 4% per year, for a lifetime of 25 years.

Since the market price of electricity varies, there are two values considered for the electricity sold, 40 and 50 euros/MWh. These values are based on electricity market report [82]

Net Present Value (NPV) will be calculated to evaluate the economic feasibility of the project.

The rate of return is assumed to 8%.

In Annex is provided the table for calculation of the basic case.

Since the obtained values in the simulation differ from the basic case, and there is lack of data about price of equipment, approximate value for other power plants will be obtained from [83]:

$$CAPEX_{plant} = \left(\frac{Power_{plant}}{Power_{reference}}\right)^{0.6} CAPEX_{reference} \tag{22}$$

Equation 22 is used to obtain CAPEX value for different powers, while the other factors remain the same.

Table 25: NPV calculation

Case no.	Total power (MW)	CAPEX M€	NPV 40 €/MWh	NPV 50 €/MWh
3	3.8	11.8	-3.26	-1.25
4	3.5	11.1	-3.40	-1.59
5	5.1	14.0	-2.58	0.09
6	5.0	13.8	-2.66	-0.07
7	6.3	16.0	-1.72	1.59
8	6.3	15.9	-1.78	1.50
9	6.8	16.7	-1.36	2.22
10	6.2	15.7	-1.84	1.40
11	6.3	15.9	-1.74	1.57
12	8.7	19.4	0.28	4.86

The total power is obtained after gathering the values for t1 and t2 from Annex Table 45. This value differs from the Net Power Balance, used for previous comparisons.

The results show that for the defined conditions, electricity price of 40 €/MWh is not feasible for this type of systems. For a price of 50 €/MWh, the major part of the systems have positive NPV, and due to that, are economically feasible.

As factors which have key influence on the NPV and the economic feasibility of the project are identified installed power, electricity price and rate of return.

Higher power for the plant gives better results for NPV, the electricity price can improve the feasibility of the project and lower discount rates used will make more projects to be feasible.

Results from an Excel sheet used to calculate the base case are provided in Annex. The values that were presented for the evaluated cases in Table 25 used the same methodology.

Conclusions and Further Work Recommendation

The conclusions of this work will start with brief overview of the work done here, will go through results evaluation and will finalize with recommendations for further work on the topic.

Work overview

This work was devoted on evaluation of the potential of utilization of LNG cold energy. After the introduction and description of the motivation for it, the evaluation of the most relevant factors began.

The characteristics of natural gas make it very attractive for multiple uses. This combined with the already developed market, which in addition is predicted to additionally grow, makes natural gas a very important factor in the future energy mix. The market analysis and future energy scenarios have shown that the capacity of LNG terminals will continue to increase, making these terminals a very important point for evaluation.

The evaluation of the LNG supply chain shows that there are many processes which are energy intensive. In order to improve the energy balance, the regasification part must be done in a way which allows LNG cold energy utilization.

The most employed options for cryogenic power generation are ORC and DE cycles which make use of the thermal and mechanical energy of LNG, respectively.

Results evaluation

In the simulation part, ORC and DE combinations were evaluated into details. For the DE application, it was noted that the overall balance will depend on the sendout pressure. Lower pressures are favorable for power generation with DE. For the ORC, the hot gases utilization as highest temperature heat source, show highest power generation potential. Among the working fluids, the mixture of NH_3-H_2O shows best performance.

From the energy balance, increasing the heat source temperature allows greater operating pressures, yielding higher power output from the turbine. Regarding the fluids, propane and ammonia can heat LNG to certain degree, but still additional seawater input is required to meet the required delivery temperature. When using NH_3-H_2O mixture, the need for seawater heat input is eliminated. However, NH_3-H_2O mixture can run only with higher temperature heat source, due to the higher boiling point of this mixture.

The economic analysis shows that the most important factors regarding project feasibility are plant power, electricity price and the required rate of return.

When the simulation results are compared with the implemented projects, the doubt appears why the best combinations in the simulation part, are not yet implemented in a feasible practical project.

Until now, all the data about the operating plants shows that only implemented cycle is ORC with propane as WF and seawater as heat source.

Further Work Recommendation

The doubts mentioned above and in Chapter 7 are the first contenders for further work. The lack of data for economic feasibility of projects, demands more focus on this part. However due to the scarce data on the limited number of projects, this is not an easy task.

Technical analysis and construction of the needed equipment for process integration is also an interesting idea. Most of the proposed applications come in as unique innovative projects, so research can be done on the construction of the elements where process integrations occur – heat exchangers – evaporators and condensers.

Additional possibility is analysis of the pattern of use of the terminal and its effect on the efficiency of integration.

Although there are limited possibility for other working fluids (due to phase-out of refrigerants), potentially interesting further research is using a mixture of two or more elements as working fluid.

References of Used Literature

[1] BP Statistical Review For World in 2016

[2] BP Outlook to 2035

[3] David A. Wood, Competition is driving significant change in natural gas LNG and pipeline export markets, Journal of Natural Gas Science and Engineering 33 (2016) A1-A5

[4] M. Romero Gómez, R.Ferreiro Garcia, J.Romero Gómez, J.Carbia Carril, Review of thermal cycles exploiting the exergy of liquefied natural gas in the regasification process, Renewable and Sustainable Energy Reviews 38 (2014)781–795

[5] Alireza Bahadori, Natural Gas Processing – Technology and Engineer Design, Gulf Professional Publishing, 2014

[6] S.Faramawy, T.Zaki, A.A.-E. Sakr, Natural gas origin, composition, and processing: A review, Journal of Natural Gas Science and Engineering 34 (2016) 34-54

[7] Hamid A. Al-Megren (editor) – Advances in Natural Gas Technology, InTech, 2012

[8] GIIGNL, LNG Information Paper No.1

[9] Boyun Guo, Ali Ghalambor, Natural Gas Engineering Handbook, Gulf Publishing Company, 2005

[10] GIIGNL, Annual Report 2017

[11] Saeid Mokhatab, John Mak, Jaleel Valappil, Handbook of Liquefied Natural Gas, Gulf Professional Publishing, 2014

[12] Bruce Poling, John Prausnitz, John O'Connell, The Properties of Gasses and Fluids, Fifth Edition, McGRAW-HILL, 2001

[13] https://www.e-education.psu.edu/png520/m11_p2.html (Accessed on 31.10.2017)

[14] http://www.engineeringtoolbox.com/critical-point-d_997.html (Accessed on 31.10.2017)

[15] http://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng.html (Accessed on 31.10.2017)

[16] Natural Gas Conversion Pocketbook, available at http://agnatural.pt/documentos/ver/natural-gas-conversion-pocketbook_fec0aeed1d2e6a84b27445ef096963a7eebab0a2.pdf (Accessed on 31.10.2017)

[17] https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php (Accessed on 31.10.2017)

[18] Department of Energy USA, LNG: Understanding the basic facts

[19] British Chamber of Commerce in Singapore report, LNG 50 – A celebration of the first commercial shipment of LNG

[20] GIIGNL Vincent Demoury, The State of the LNG Industry, FLAME Conference, 09.05.2016

[21] Dr. Himadri Banergi, Risk Management in LNG FSRU, FSRU Conference 11.2013, Singapore

[22] IGU (International Gas Union) 2017 World LNG Report

[23] GIIGNL, Rollover in LNG Storage Tanks

[24] www.cbi.com LNG Storage (Accessed on 31.10.2017)

[25] Yajun Li, Yue Li, Dynamic optimization of the Boil-Off Gas (BOG) fluctuations at an LNG receiving terminal, Journal of Natural Gas Science and Engineering 30 (2016) 322-330

[26] Association Technique de l'industrie du Gaz en France, Aide-Mémoire de L'industrie du Gaz, Paris: ATG Edition, 1990.

[27] Shinji EGASHIRA, Takasago Equipment Plant, Energy & Nuclear Equipment Div., Machinery Business, LNG Vaporizer for LNG Re-gasification Terminal

[28] Dhirav Patel, John Mak, Daniel Rivera, Joanne Angtuaco, Fluor, LNG VAPORIZER SELECTION BASED ON SITE AMBIENT CONDITIONS

[29] S. Hirakawa and K. Kosugi, Utilization of LNG cold, International Journal of Refrigeration, Volume 4 Number 1 January 1981

[30] Takayuki Yamamoto, Yukio Fujiwara, The accomplishment of 100% utilization of LNG cold energy, Challenges in Osaka Gas Senboku LNG Regasification Terminals, World Gas Conference 2012 Kuala Lumpur

[31] Tatiana Morosuk, George Tsatsaronis, Comparison of novel concepts of cogeneration systems used to regasify liquefied natural gas (LNG), Journal of Natural Gas Science and Engineering 34 (2016) 1434-1445

[32] Stefanie Tesch, Tatiana Morosuk, George Tsatsaronis, Advanced exergy analysis applied to the process of regasification of LNG (liquefied natural gas) integrated into an air separation process, Energy 117 (2016) 550-561

[33] Armin Ebrahimi, Masoud Ziabasharhagh, Optimal design and integration of a cryogenic Air Separation Unit (ASU) with Liquefied Natural Gas (LNG) as heat sink, Thermodynamic and Economic analyses Energy 126 (2017) 868-885

[34] Antonio Messineo, Giuseppe Panno, LNG cold energy use in agro-food industry: A case study in Sicily, Journal of Natural Gas Science and Engineering 3 (2011) 356-363

[35] Vincenzo La Rocca, Cold recovery during regasification of LNG part one: Cold utilization far from the regasification facility, Energy 35 (2010) 2049–2058

[36] Vincenzo La Rocca, Cold recovery during regasification of LNG part two: Applications in an Agro Food Industry and a Hypermarket, Energy 36 (2011) 4897-4908

[37] Wensheng Lin, Meibin Huang, Anzhong Gu, A seawater freeze desalination prototype system utilizing LNG cold energy, International Journal of Hydrogen Energy 42 (2017) 18691-18698

[38] Hongbo Tan, Yanzhong Li, Hanfei Tuo, Man Zhou, Baocong Tian, Experimental study on liquid/solid phase change for cold energy storage of Liquefied Natural Gas (LNG) refrigerated vehicle, Energy 35 (2010) 1927–1935

[39] Young Kyong Jo, Jin-Kyeong Kim, Soon Geul Lee, Yong Tae Kang, Development of type 2 solution transportation absorption system for utilizing LNG cold energy, International Journal of Refrigeration 30 (2007) 978-985

[40] Phatthi Punyasukhananda, Athikom Bangviwat, Utilization of LNG Cold Energy at Maptaput LNG Receiving Terminal, 4th International Conference on Sustainable Energy and Environment (SEE 2011), Bangkok, Thailand

[41] Guan-Bang Wang, Xin-Rong Zhang, Thermodynamic analysis of a novel pumped thermal energy storage system utilizing ambient thermal energy and LNG cold energy, Energy Conversion and Management 148 (2017) 1248–1264

[42] Xiaojun Shi, Brian Agnewb, Defu Che, Jianmin Gao, Performance enhancement of conventional combined cycle power plant by inlet air cooling, inter-cooling and LNG cold energy utilization Applied Thermal Engineering 30 (2010) 2003-2010

[43] Diogo Angelo Stradioto, Marina Fonseca Seelig, Paulo Smith Schneider, Performance analysis of a CCGT power plant integrated to a LNG regasification process Journal of Natural Gas Science and Engineering 23 (2015) 112-117

[44] Guoqiang Zhang, Jiongzhi Zheng, Yongping Yang, Wenyi Liu, A novel LNG cryogenic energy utilization method for inlet air cooling to improve the performance of combined cycle, Applied Energy 179 (2016) 638–649

[45] Baris Burak Kanbur, Liming Xiang, Swapnil Dubey, Fook Hoong Choo, Fei Duan, Thermoeconomic assessment of a micro cogeneration system with LNG cold utilization, Energy 129 (2017) 171-184

[46] Yanni Liu, Kaihua Guo, A novel cryogenic power cycle for LNG cold energy recovery, Energy 36 (2011) 2828-2833

[47] G. Tsatsaronis, T. Morosuk, Advanced exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas, Energy 35 (2010) 820–829

[48] Manuel Romero Gomez, Javier Romero Gomez, Luis M. Lopez-Gonzalez, Luis M. Lopez-Ochoa, Thermodynamic analysis of a novel power plant with LNG (liquefied natural gas) cold exergy exploitation and CO2 capture Energy 105 (2016) 32-44

[49] T. Lu, K.S. Wang, Analysis and optimization of a cascading power cycle with liquefied natural gas (LNG) cold energy recovery, Applied Thermal Engineering 29 (2009) 1478–1484

[50] M.H. Taheri, A.H. Mosaffa, L. Garousi Farshi, Energy, exergy and economic assessments of a novel integrated biomass based multi generation energy system with hydrogen production and LNG regasification cycle, Energy 125 (2017) 162-177

[51] Huan Wang, Xiaojun Shi, Defu Che, Thermodynamic optimization of the operating parameters for a combined power cycle utilizing low-temperature waste heat and LNG cold energy, Applied Thermal Engineering 59 (2013) 490-497

[52] A.H. Mosaffaa, N. Hasani Mokarrama, L. Garousi Farshi, Thermo-economic analysis of combined different ORCs geothermal power plants and LNG cold energy, Geothermics 65 (2017) 113-125

[53] Wen-Ji Rao, Liang-Ju Zhao, Chao Liu, Mo-Geng Zhang, A combined cycle utilizing LNG and low-temperature solar energy, Applied Thermal Engineering 60 (2013) 51-60

[54] Mehdi Mehrpooya, Mohammad Mehdi, Moftakhari Sharifzadeh, Marc A. Rosen, Energy and exergy analyses of a novel power cycle using the cold of LNG (liquefied natural gas) and low-temperature solar energy, Energy 95 (2016) 324-345

[55] Pan Zhao, Jiangfeng Wang, Yiping Dai, Lin Gao, Thermodynamic analysis of a hybrid energy system based on CAES system and CO2 transcritical power cycle with LNG cold energy utilization, Applied Thermal Engineering 91 (2015) 718-730

[56] Guan-Bang Wang, Xin-Rong Zhang, Thermodynamic analysis of a novel pumped thermal energy storage system utilizing ambient thermal energy and LNG cold energy, Energy Conversion and Management 148 (2017) 1248–1264

[57] Chin Wu, Thermodynamics and Heat Powered Cycles, Nova Science Publishers 2007

[58] T.C. Hung, S.K. Wang, C.H. Kuo, B.S. Pei, K.F. Tsai, A study of organic working fluids on system efficiency of an ORC using low-grade energy sources, Energy 35 (2010) 1403–1411

[59] Junjiang Bao, LiZhao, A review of working fluid and expander selections for organic Rankine cycle, Renewable and Sustainable Energy Reviews 24 (2013) 325–342

[60] T. Miyazaki, Y.T. Kang, A. Akisawa, T. Kashiwagi, A combined power cycle using refuse incineration and LNG cold energy, Energy 25 (2000) 639–655

[61] T. Lu, K.S. Wang, Analysis and optimization of a cascading power cycle with liquefied natural gas (LNG) cold energy recovery, Applied Thermal Engineering 29 (2009) 1478–1484

[62] Xiaojun Shi, Defu Che, A combined power cycle utilizing low-temperature waste heat and LNG cold energy, Energy Conversion and Management 50 (2009) 567–575

[63] Huan Wang, Xiaojun Shi, Defu Che, Thermodynamic optimization of the operating parameters for a combined power cycle utilizing low-temperature waste heat and LNG cold energy, Applied Thermal Engineering 59 (2013) 490-497

[64] Kyoung Hoon Kim, Kyung Chun Kim, Thermodynamic performance analysis of a combined power cycle using low grade heat source and LNG cold energy, Applied Thermal Engineering 70 (2014) 50-60

[65] Kyung Chun Kim, Jong Man Ha, Kyoung Hoon Kim, Exergy analysis of a combined power cycle using low-grade heat source and LNG cold energy, Int. J. Exergy, Vol. 17, No. 3, 2015

[66] Jan Szargut, Ireneusz Szczygiel, Utilization of the cryogenic exergy of liquid natural gas (LNG) for the production of electricity, Energy 34 (2009) 827–837

[67] In-Hwan Choi, Sangick Lee, Yutaek Seo, Daejun Chang, Analysis and optimization of cascade Rankine cycle for liquefied natural gas cold energy recovery, Energy 61 (2013) 179-195

[68] Xue F, Chen Y, Ju Y, Design and optimization of a novel cryogenic Rankine power generation system employing binary and ternary mixtures as working fluids based on the cold exergy utilization of liquefied natural gas (LNG), Energy (2017),

[69] Xiaodi Xue, Cong Guo, Xiaoze Du, Lijun Yang, Yongping Yang, Thermodynamic analysis and optimization of a two-stage organic Rankine cycle for liquefied natural gas cryogenic exergy recovery, Energy 83 (2015) 778-787

[70] Kyeongsu Kim, Ung Lee, Changsoo Kim, Chonghun Han, Design and optimization of cascade organic Rankine cycle for recovering cryogenic energy from liquefied natural gas using binary working fluid, Energy 88 (2015) 304-313

[71] Sangick Lee, Multi-parameter optimization of cold energy recovery in cascade Rankine cycle for LNG regasification using genetic algorithm, Energy 118 (2017) 776-782

[72] Ung Lee, Jeongwoo Jeon, Chonghun Han, Youngsub Lim, Superstructure based techno-economic optimization of the organic rankine cycle using LNG cryogenic energy, Energy 137 (2017) 83-94

[73] P.A. Ferreira, I. Catarino, D. Vaz, Thermodynamic analysis for working fluids comparison in Rankine-type cycles exploiting the cryogenic exergy in Liquefied Natural Gas (LNG) regasification, Applied Thermal Engineering 121 (2017) 887–896

[74] Kyoung Hoon Kim, Hyung Jong Ko, Kyoungjin Kim, Assessment of pinch point characteristics in heat exchangers and condensers of ammonia–water based power cycles, Applied Energy 113 (2014) 970–981

[75] Jiangfeng Wang, Zhequan Yan, Man Wang, Yiping Dai, Thermodynamic analysis and optimization of an ammonia-water power system with LNG (liquefied natural gas) as its heat sink, Energy 50 (2013) 513-522

[76] Alessandro Franco, Claudio Casarosa, Thermodynamic analysis of direct expansion configurations for electricity production by LNG cold energy recovery, Applied Thermal Engineering 78 (2015) 649-657

[77] Ramon Ferreiro Garcia, Jose Carbia Carril, Javier Romero Gomez, Manuel Romero Gomez, Power plant based on three series Rankine cycles combined with a direct expander using LNG cold as heat sink, Energy Conversion and Management 101 (2015) 285–294

[78] Feier XUE, Yu CHEN, Yonglin JU, A review of cryogenic power generation cycles with liquefied natural gas cold energy utilization Front. Energy 2016, 10(3): 363–374

[79] Baris Burak Kanbura, Liming Xiang, Swapnil Dubeya, Fook Hoong Chooa, Fei Duanb, Cold utilization systems of LNG: A review, Renewable and Sustainable, Energy Reviews 79 (2017) 1171–1188

[80] Chris Sharratt, Manager, Midstream, Business Solutions Group, Foster Wheeler, UK, LNG terminal cold energy integration opportunities offered by contractors

[81] NPL Report MATC (A) 95, Steam Turbine Operating Conditions, Chemistry of Condensates, and Environment Assisted Cracking – A Critical Review

[82] Relatorio dos precos 2016, http://www.omel.es/files/informe_precios_port_navegable.pdf (Accessed on 31.10.2017)

[83] Max S. Peters, Klaus D. Timmerhaus, Ronald E. West, Plant Design and Economics for Chemical Engineers (Chemical Engineering), McGraw-Hill Education; 5 edition (16 Jan. 2003)

Annex

Table 26: Results for case 1

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-40	1.2	1	3.65
BOG3	111.8	8	1	3.65
BOG4	11.3	8	1	3.65
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.1	8	0	153.65
LNG4	-154	80	0	153.65
LNG5	10	80	1	153.65
W1	15	1	0	4950
W2	15	1.5	0	4950
W3	10	1.5	0	4950

Table 27: Results for Case 2, 80 bar

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-40	1.2	1	3.65
BOG3	111.8	8	1	3.65
BOG4	11.3	8	1	3.65
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.1	8	0	153.65
LNG4	-152.3	120	0	153.65
LNG5	10	120	1	153.65
LNG6	-17	80	1	153.65
LNG7	10	80	1	153.65
W1	15	1	0	4600
W2	15	1.5	0	4600
W3	10	1.5	0	4600
W4	15	1	0	1500
W5	15	1.5	0	1500
W6	13.1	1.5	0	1500

Table 28: Results for Case 2, 9 bar

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-40	1.2	1	3.65
BOG3	111.8	8	1	3.65
BOG4	11.3	8	1	3.65
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.1	8	0	153.65
LNG4	-152.3	120	0	153.65
LNG5	10	120	1	153.65
LNG6	-126.6	9	0.983	153.65
LNG7	10	9	1	153.65
W1	15	1	0	4600
W2	15	1.5	0	4600
W3	10	1.5	0	4600
W4	15	1	0	1500
W5	15	1.5	0	1500
W6	7.9	1.5	0	1500

Table 29: Results for Case 2, 25 bar

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-40	1.2	1	3.65
BOG3	111.8	8	1	3.65
BOG4	11.3	8	1	3.65
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.1	8	0	153.65
LNG4	-152.3	120	0	153.65
LNG5	10	120	1	153.65
LNG6	-85.1	25	1	153.65
LNG7	10	25	1	153.65
W1	15	1	0	4600
W2	15	1.5	0	4600
W3	10	1.5	0	4600
W4	15	1	0	1500
W5	15	1.5	0	1500
W6	9.6	1.5	0	1500

Table 30: Results for Case 2, 30 bar

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-40	1.2	1	3.65
BOG3	111.8	8	1	3.65
BOG4	11.3	8	1	3.65
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.1	8	0	153.65
LNG4	-152.3	120	0	153.65
LNG5	10	120	1	153.65
LNG6	-75.7	30	1	153.65
LNG7	10	30	1	153.65
W1	15	1	0	4600
W2	15	1.5	0	4600
W3	10	1.5	0	4600
W4	15	1	0	1500
W5	15	1.5	0	1500
W6	10	1.5	0	1500

Table 31: Results for Case 3 (Seawater ORC Propane)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	15	1.5	0	4300
H2	10	1.5	0	4300
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-154.1	80	0	153.65
LNG5	-46.1	80	1	153.65
LNG6	10	80	1	153.65
RC1	-40.3	1.1	0.982	200
RC2	-40.3	1.1	0	200
RC3	-40	6.3	0	200
RC4	9.7	6.3	1	200
W1	15	1	0	1350
W2	15	1.5	0	1350
W3	10	1.5	0	1350
W4	15	1	0	4300

Table 32: Results for Case 4 (Seawater ORC Ammonia)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	15	1.5	0	4550
H2	10.1	1.5	0	4550
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-154.1	80	0	153.65
LNG5	-37	80	1	153.65
LNG6	10	80	1	153.65
RC1	-31.3	1.1	0.919	70
RC2	-31.3	1.1	0	70
RC3	-31.3	6	0	70
RC4	9.6	6	1	70
W1	15	1	0	1100
W2	15	1.5	0	1100
W3	10.2	1.5	0	1100
W4	15	1	0	4550

Table 33: Results for Case 5 (Steam ORC Propane)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	36	0.05	0.9	42
H2	4.7	0.05	0	42
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-154.1	80	0	153.65
LNG5	-45.7	80	1	153.65
LNG6	10	80	1	153.65
RC1	-40.3	1.1	0.981	201
RC2	-40.3	1.1	0	201
RC3	-39.9	11	0	201
RC4	30.7	11	1	201
W1	15	1	0	1350
W2	15	1.5	0	1350
W3	10.1	1.5	0	1350

Table 34: Results for Case 6 (Steam ORC Ammonia)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	36	0.05	0.9	45
H2	15.3	0.05	0	45
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-154.1	80	0	153.65
LNG5	-38.1	80	1	153.65
LNG6	10	80	1	153.65
RC1	-31.3	1.1	0.886	72
RC2	-31.3	1.1	0	72
RC3	-31.2	11.75	0	72
RC4	30.5	11.75	1	72
W1	15	1	0	1100
W2	15	1.5	0	1100
W3	10	1.5	0	1100

Table 35: Results for Case 7 (Gases ORC Propane)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	148.6	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-154.1	80	0	153.65
LNG5	-46.9	80	1	153.65
LNG6	10	80	1	153.65
RC1	-40.3	1.1	0.975	200
RC2	-40.3	1.1	0	200
RC3	-39.4	20	0	200
RC4	57	20	1	200
W1	15	1	0	1350
W2	15	1.5	0	1350
W3	10	1.5	0	1350

Table 36: Results for Case 8 (Gases ORC Ammonia)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	145	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-154.1	80	0	153.65
LNG5	-36.8	80	1	153.65
LNG6	10	80	1	153.65
RC1	-31.3	1.1	0.859	75
RC2	-31.3	1.1	0	75
RC3	-31.1	20	0	75
RC4	49.6	20	1	75
W1	15	1	0	1050
W2	15	1.5	0	1050
W3	10	1.5	0	1050

Table 37: Results for Case 9 (Gases ORC NH_3-H_2O)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	130.5	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-154.1	80	0	153.65
LNG5	16.7	80	1	153.65
RC1	88.8	1.1	0.879	55
RC2	5.6	1.1	0	55
RC3	5.7	20	0	55
RC4	189.8	20	1	55

Table 38: Results for Case 10 (Gases ORC+DE Propane)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	156.6	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-152.4	120	0	153.65
LNG5	-45.6	120	1	153.65
LNG6	-61.5	80	1	153.65
LNG7	10	80	1	153.65
RC1	-40.3	1.1	0.975	169
RC2	-40.3	1.1	0	169
RC3	-39.4	20	0	169
RC4	57	20	1	169
W1	15	1	0	2000
W2	15	1.5	0	2000
W3	10	1.5	0	2000

Table 39: Results for Case 11 (Gases ORC+DE Ammonia)

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	153.1	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-152.4	120	0	153.65
LNG5	-37	120	1	153.65

LNG6	-55.9	80	1	153.65
LNG7	10	80	1	153.65
RC1	-31.3	1.1	0.859	64
RC2	-31.3	1.1	0	64
RC3	-31.1	20	0	64
RC4	49.6	20	1	64
W1	15	1	0	1700
W2	15	1.5	0	1700
W3	10	1.5	0	1700

Table 40: Results for Case 12 (Gases ORC+DE NH_3-H_2O), 80 bar

	Temperature C	**Pressure bar**	**Vapor Frac**	**Mass Flow tonne/hr**
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	130.5	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-152.4	120	0	153.65
LNG5	33.7	120	1	153.65
LNG6	4.9	80	1	153.65
LNG7	10	80	1	153.65
RC1	88.8	1.1	0.879	55
RC2	5.6	1.1	0	55
RC3	5.7	20	0	55
RC4	189.8	20	1	55
W1	15	1	0	102
W2	15	1.5	0	102
W3	10	1.5	0	102

Table 41: Results for Case 12 (Gases ORC+DE NH3-H2O), 9 bar

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	130.5	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-152.4	120	0	153.65
LNG5	33.7	120	1	153.65
LNG6	-112.4	9	1	153.65
LNG7	10	9	1	153.65
RC1	88.8	1.1	0.879	55
RC2	5.6	1.1	0	55
RC3	5.7	20	0	55
RC4	189.8	20	1	55
W1	15	1	0	102
W2	15	1.5	0	102
W3	-74.5	1.5	0	102

Table 42: Results for Case 12 (Gases ORC+DE NH3-H2O), 25 bar

	Temperature C	Pressure bar	Vapor Frac	Mass Flow tonne/hr
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	130.5	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-152.4	120	0	153.65
LNG5	33.7	120	1	153.65

LNG6	-66.3	25	1	153.65
LNG7	10	25	1	153.65
RC1	88.8	1.1	0.879	55
RC2	5.6	1.1	0	55
RC3	5.7	20	0	55
RC4	189.8	20	1	55
W1	15	1	0	102
W2	15	1.5	0	102
W3	-46.2	1.5	0	102

Table 43: Results for Case 12 (Gases ORC+DE NH3-H2O), 30 bar

	Temperature C	**Pressure bar**	**Vapor Frac**	**Mass Flow tonne/hr**
BOG1	-150	1.2	1	3.65
BOG2	-50	1.2	1	3.65
BOG3	97.1	8	1	3.65
BOG4	5	8	1	3.65
H1	200	1	1	2000
H2	130.5	1	1	2000
LNG1	-162	1.2	0	150
LNG2	-161.7	8	0	150
LNG3	-157.2	8	0	153.65
LNG4	-152.4	120	0	153.65
LNG5	33.7	120	1	153.65
LNG6	-56.5	30	1	153.65
LNG7	10	30	1	153.65
RC1	88.8	1.1	0.879	55
RC2	5.6	1.1	0	55
RC3	5.7	20	0	55
RC4	189.8	20	1	55
W1	15	1	0	102
W2	15	1.5	0	102
W3	-39.6	1.5	0	102

Table 44: Values used for calculating indicators of performance

No.	Description	p1 (kW)	p2 (kW)	c1 (kW)	p3 (kW)	p4 (kW)	p5 (kW)
1	Seawater (ORV)	74.44	818.30	265.16	76.12	/	/
2	Direct Expansion DE	74.44	1273.28	265.16	70.74	8.77	/
3	Seawater ORC propane	74.44	818.30	265.16	20.76	66.12	62.31
4	Seawater ORC ammonia	74.44	818.30	265.16	16.92	69.97	15.57
5	Steam ORC propane	74.44	818.30	265.16	20.76	/	105.93
6	Steam ORC ammonia	74.44	818.30	265.16	16.92	/	34.80
7	Gases ORC propane	74.44	818.30	265.16	20.76	/	201.22
8	Gases ORC ammonia	74.44	818.30	265.16	16.15	/	64.33
9	Gases ORC NH_3-H_20	74.44	818.30	265.16	/	/	38.26
10	Gases ORC+DE propane	74.44	1273.28	265.16	/	30.75	170.03
11	Gases ORC+DE ammonia	74.44	1273.28	265.16	/	26.14	54.90
12	Gases ORC+DE NH_3-H_20	74.44	1273.28	265.16	/	1.57	38.26

Table 45: Values used for calculating indicators of performance (continued)

No.	t1 (kW)	t2 (kW)	Qev (kW)	delta h1 (kJ/kg)	delta h2 (kJ/kg)	w1 (t/h)	w2 (t/h)
1	/	/	/	736.71	/	4950	/
2	-1631.12	/	/	680.89	83.38	4600	570
3	-3829.95	/	-26797.27	198.00	/	1350	4300
4	-3470.66	/	-28233.21	156.44	/	1100	4550
5	-5104.04	/	-28110.21	195.47	/	1350	/
6	-4963.43	/	-29515.88	160.90	/	1100	/
7	-6327.67	/	-28999.98	201.06	/	1350	/
8	-6264.68	/	-31019.11	155.48	/	1050	/
9	-6823.69	/	-39068.82	0.00	/	0	/
10	-5346.88	-835.70	-24504.98	293.06	/	2000	/
11	-5345.86	-963.18	-26469.64	252.70	/	1700	/
12	-6823.69	-1919.01	-39068.82	14.90	/	102	/

Table 46: Values used for calculating indicators of performance for special cases DE

No.	Description	p1 (kW)	p2 (kW)	c1 (kW)	p3 (kW)	p4 (kW)	p5 (kW)
1	de 80	74.44	1273.28	265.16	70.74	8.77	/
2	de 9	74.44	1273.28	265.16	70.74	33.06	/
3	de 25	74.44	1273.28	265.16	70.74	24.60	/
4	de 30	74.44	1273.28	265.16	70.74	23.07	/

Table 47: Values used for calculating indicators of performance for special cases DE (continued)

No.	t1 (kW)	t2 (kW)	Qev (kW)	delta h1 (kJ/kg)	delta h2 (kJ/kg)	w1 (t/h)	w2 (t/h)
1	-1631.12	/	/	680.89	83.38	4600	570
2	-7748.23	/	/	680.89	279.00	4600	2150
3	-5271.71	/	/	680.90	237.15	4600	1600
4	-4775.15	/	/	680.90	219.27	4600	1500

Table 48: Values used for calculating indicators of performance for special cases ORC+DE

No.	Description	p1 (kW)	p2 (kW)	c1 (kW)	p3 (kW)	p4 (kW)	p5 (kW)
1	ORC+DE 80 bar	74.44	1273.28	265.16	/	1.57	38.26
2	ORC+DE 9 bar	74.44	1273.28	265.16	/	28.45	38.26
3	ORC+DE 25 bar	74.44	1273.28	265.16	/	19.22	38.26
4	ORC+DE 30 bar	74.44	1273.28	265.16	/	17.38	38.26

Table 49: Values used for calculating indicators of performance for special cases ORC+DE (continued)

No.	t1 (kW)	t2 (kW)	Qev (kW)	delta h1 (kJ/kg)	delta h2 (kJ/kg)	w1 (t/h)	w2 (t/h)
1	-6823.69	-1919.01	-39068.82	14.90	/	102	/
2	-6823.69	-9195.39	-39068.82	273.65	/	1850	/
3	-6823.69	-6281.39	-39068.82	185.58	/	1250	/
4	-6823.69	-5684.00	-39068.82	165.34	/	1130	/

					FC	P [MW]					
RC	2				0.8	4.5	50		0.10		
n	RPI	RPI	Convert	Year	Production	Production	Electricity price	Revenue	Fixed Opex	Capex	Capital
	%	index	2015		hr/year	MWh	€/MWh mod	M€ mod	M€ mod	M€ mod	M€ mod
0	2.00	100.00	1.000	2017						13.00	
1	2.00	102.00	0.980	2018	7008	31536	51.00	1.61	0.10	0.00	12.48
2	2.00	104.04	0.961	2019	7008	31536	52.02	1.64	0.10	0.00	11.96
3	2.00	106.12	0.942	2020	7008	31536	53.06	1.67	0.11	0.00	11.44
4	2.00	108.24	0.924	2021	7008	31536	54.12	1.71	0.11	0.00	10.92
5	2.00	110.41	0.906	2022	7008	31536	55.20	1.74	0.11	0.00	10.40
6	2.00	112.62	0.888	2023	7008	31536	56.31	1.78	0.11	0.00	9.88
7	2.00	114.87	0.871	2024	7008	31536	57.43	1.81	0.11	0.00	9.36
8	2.00	117.17	0.853	2025	7008	31536	58.58	1.85	0.12	0.00	8.84
9	2.00	119.51	0.837	2026	7008	31536	59.75	1.88	0.12	0.00	8.32
10	2.00	121.90	0.820	2027	7008	31536	60.95	1.92	0.12	0.00	7.80
11	2.00	124.34	0.804	2028	7008	31536	62.17	1.96	0.12	0.00	7.28
12	2.00	126.82	0.788	2029	7008	31536	63.41	2.00	0.13	0.00	6.76
13	2.00	129.36	0.773	2030	7008	31536	64.68	2.04	0.13	0.00	6.24
14	2.00	131.95	0.758	2031	7008	31536	65.97	2.08	0.13	0.00	5.72
15	2.00	134.59	0.743	2032	7008	31536	67.29	2.12	0.13	0.00	5.20
16	2.00	137.28	0.728	2033	7008	31536	68.64	2.16	0.14	0.00	4.68
17	2.00	140.02	0.714	2034	7008	31536	70.01	2.21	0.14	0.00	4.16
18	2.00	142.82	0.700	2035	7008	31536	71.41	2.25	0.14	0.00	3.64
19	2.00	145.68	0.686	2036	7008	31536	72.84	2.30	0.15	0.00	3.12
20	2.00	148.59	0.673	2037	7008	31536	74.30	2.34	0.15	0.00	2.60
21	2.00	151.57	0.660	2038	7008	31536	75.78	2.39	0.15	0.00	2.08
22	2.00	154.60	0.647	2039	7008	31536	77.30	2.44	0.15	0.00	1.56
23	2.00	157.69	0.634	2040	7008	31536	78.84	2.49	0.16	0.00	1.04
24	2.00	160.84	0.622	2041	7008	31536	80.42	2.54	0.16	0.00	0.52
25	2.00	164.06	0.610	2042	7008	31536	82.03	2.59	0.16	0.00	0.00
										13.00	

Figure 51: Results for NPV analysis

0.04		0.3			DF	0.08	
Amortization	Taxable Amount	Corp. Tax	NCF	NCF	NCF Cum.	DCF	DCF Cum.
M€ mod	M€ mod	M€ mod	M€ mod	M€ 2017	M€ 2017	M€ 2017	M€ 2017
		0.00	-13.00	-13.00	-13.00	-13.00	-13.00
0.52	0.99	0.30	1.21	1.19	-11.81	1.10	-11.90
0.52	1.02	0.30	1.23	1.18	-10.63	1.01	-10.89
0.52	1.05	0.31	1.25	1.18	-9.45	0.94	-9.95
0.52	1.08	0.32	1.27	1.18	-8.27	0.87	-9.08
0.52	1.11	0.33	1.30	1.18	-7.10	0.80	-8.28
0.52	1.14	0.34	1.32	1.17	-5.92	0.74	-7.54
0.52	1.18	0.35	1.34	1.17	-4.75	0.68	-6.86
0.52	1.21	0.36	1.37	1.17	-3.59	0.63	-6.23
0.52	1.24	0.37	1.39	1.16	-2.42	0.58	-5.65
0.52	1.28	0.38	1.42	1.16	-1.26	0.54	-5.11
0.52	1.32	0.39	1.44	1.16	-0.10	0.50	-4.61
0.52	1.35	0.41	1.47	1.16	1.05	0.46	-4.15
0.52	1.39	0.42	1.49	1.15	2.21	0.42	-3.73
0.52	1.43	0.43	1.52	1.15	3.36	0.39	-3.34
0.52	1.47	0.44	1.55	1.15	4.51	0.36	-2.98
0.52	1.51	0.45	1.58	1.15	5.66	0.33	-2.64
0.52	1.55	0.46	1.60	1.15	6.80	0.31	-2.33
0.52	1.59	0.48	1.63	1.14	7.95	0.29	-2.05
0.52	1.63	0.49	1.66	1.14	9.09	0.26	-1.78
0.52	1.67	0.50	1.69	1.14	10.23	0.24	-1.54
0.52	1.72	0.52	1.72	1.14	11.36	0.23	-1.31
0.52	1.76	0.53	1.75	1.13	12.50	0.21	-1.10
0.52	1.81	0.54	1.79	1.13	13.63	0.19	-0.91
0.52	1.86	0.56	1.82	1.13	14.76	0.18	-0.73
0.52	1.90	0.57	1.85	1.13	15.89	0.16	-0.57
					NPV	-0.57	

Figure 52: Results for NPV calculation (continued)