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Analysis of Opportunities to Reduce Environmental Impacts from the Natural Gas Regasification Terminal

Abstract

Liquefied natural gas is imposed as an acceptable transitional solution that enables compliance with legislative environmental requirements. Transportation of gas is provided both to gas pipelines and to ships that have recently been witnessed by an increase in order numbers globally. This kind of interest is accompanied by an increase in the number of loading and unloading terminals which, when selecting the site, must meet both technological and environmental requirements. Environmental impact studies are mandatory, and are also of great interest to the local population.

Due to the planned location of the terminal for regasification of natural gas in the Rijeka Bay, this paper analyzes the most common adverse effects on the environment and local residents as well as the possibility of reducing its negative impacts, with special reference to the use of cryogenic energy in endothermic and exothermic technological processes and economic activities. At the same time, it can be shown that it is possible to reduce its adverse effects and produce useful energy, or products which may have significance in changing the perception of the local community.

Keywords: liquefied natural gas, regasification of natural gas, cryogenic energy

1. Introduction

Atmospheric warming and the resulting climate change have been the subject of a number of scientific studies that suggest a striking correlation between the increase in hydrocarbon consumption as a result of technological development and the increase in the greenhouse gas content of the atmosphere. Although greenhouse gases (carbon dioxide, nitrogen oxides, methane, water vapor, ...) are also generated from natural processes (breathing, plant rot, volcanic eruptions, naturally occurring forest fires, etc.), anthropological influence is recognized with a significant proportion (fossil fuel combustion, electricity or heat production, livestock breeding, etc.) especially in relation to carbon dioxide emissions.

The States Parties to the Kyoto Protocol (2005), including the EU Member States, have committed themselves to reducing their carbon footprint by 20% and to increasing their energy efficiency by 20% while increasing their share of renewable energy by 20%. The goals set in this way cannot be achieved unless the current levels of energy use change. Therefore, natural gas has become a transitional energy solution because of its more environmentally friendly characteristics. Basically, it is a mixture of methane (with a content of about 90%) and propane, butane, ethane, nitrogen and other gases in a smaller proportion. By combustion of natural gas, carbon dioxide emissions can be reduced by up to 60% compared to coal, and as sulfur-free, the requirements of regulations regarding sulfur oxide emissions have been met.

As gas deposits are at remote locations with respect to end users, technological solutions have been developed to process and transport them in a safe and environmentally friendly manner. Therefore, it is transported either in the compressed state via a pipeline or in the liquefied form by special types of ships. Transportation in liquefied state requires subcooling to $-162\text{ }^{\circ}\text{C}$, and arriving at the destination requires regasification, which requires a large investment in loading / unloading terminals and ships. The choice of location for the construction of the terminal, in addition to the economic and technological aspects, must include both environmental and social. It is the environmental and social aspects of implementation that cause the most difficulties at the local level. In this context, the planned construction of an FSRU (Floating Storage and Regasification Unit) terminal in the Bay of Rijeka is causing a lot of controversy. Therefore, a summary of the environmental impact of such a terminal will be presented below, as well as the potential to reduce its negative impact through the use of new technologies.

2. Basic properties of liquefied natural gas

In order to be able to objectively evaluate the environmental impact of Liquefied Natural Gas (LNG) terminals, some basic properties of methane as the gas with the largest share in natural gas composition need to be stated. (Table 1)

Table 1: Methane properties (CH_4), [3]

Ignition temperature	585 $^{\circ}\text{C}$
Boiling point	$-161,5\text{ }^{\circ}\text{C}$
Density of liquefied methane	425 kg/m^3
Critical temperature	$-82\text{ }^{\circ}\text{C}$
Critical pressure	46 bar
Lower explosive limit	5,24 %, 33 g/m^3
Upper explosive limit	14,02 %, 400 g/m^3

Methane (CH₄) gas is non-toxic, colorless and odorless and is not soluble in water. It is a highly flammable gas which, when mixed with air in a certain proportion, makes an explosive mixture, while in the liquefied state natural gas is not flammable. Indoors it can cause suffocation if oxygen concentration decreases (<17%). In the initial gasification phase, the density (specific mass) of methane is greater than the density of air, while this ratio changes as the methane is heated. By flushing liquid methane into the atmosphere, the cold gas condenses the water vapor present in the air and produces visible fog. It is a mixture of methane and water vapor that has a higher density than air, so it stays at ground level. With the help of wind, it spreads in the surrounding area, which increases the danger zone in which a flammable mixture is present. In case of fire, directly affected equipment and installations are protected by built-in systems with water spray and water curtain. However, water and air foam are not effective means of direct quenching because they have a much higher temperature. Better direct quenching effects are achieved by the use of powders or, more preferably, compressed carbon dioxide (indoors fires), which expands from liquid state to dry ice, which cools and reduces oxygen concentration and does not accelerate gasification, so that the explosive concentration occupies a small volume. [7]

Once gasified, methane becomes lighter than air and does not form explosive ground mixtures on open areas. In the atmosphere, its effect on the greenhouse effect is large, with far greater effects on heat retention than carbon dioxide, but its residence time in the atmosphere is much shorter.

Liquefied natural gas (LNG) is colorless, odorless, non-toxic and non-corrosive, with hazards such as flammability, freezing and the possibility of suffocation. The volume of liquefied natural gas is about 600 times smaller than the volume occupied in the gaseous state, and is liquefied in the LNG terminals. In the liquid state, it is at a temperature of about -162 ° C. Natural gas remains liquefied at "critical" temperature conditions of -82 ° C and a pressure of 46 bar. [1]

Natural gas (Table 2) is a mixture of lower hydrocarbons and inorganic compounds and gases, with the highest methane content (mostly higher than 70% and in the northern Adriatic as much as 99%). [2] In order for the gas to liquefy freely, it is necessary to first remove impurities from natural gas.

Table 2: Typical composition of natural gas, adapted from [2]

HYDROCARBONS	CH ₄	C ₂	C ₃	C ₄	C ₅
	>70%	< 15%	< 9%	< 4%	< 2%
Admixtures (noble gases)	He	Ar	Ne	Kr	Xe
	do 0,1%	do 0,1%	do 0,1%	do 0,1%	do 0,1%
Admixtures (others)	Natural gas also contains CO ₂ , H ₂ S, COS, H ₂ O, N ₂ , Hg, solids etc.				

3. Types of terminals and their impact on the environment and the local community

The basic division is based on the location of the terminal itself and they are divided into: land-based and offshore (floating). Land-based terminals have a firm connection with the shore and take up considerable space and require supporting infrastructure, while floating establish a flexible connection with the land. They differ in type of construction: Shore Regasification Unit – SRU, Gravity Base Structure – GBS, Floating Storage and Regasification Unit berthed – FSRU ship berthed, Floating Storage and Regasification Unit offshore anchored – FSRU ship anchored, Floating Storage and Regasification Unit offshore platform – FSRU platform. [8]

Considering the type of terminal, the following impacts are important:

- environmental impacts during construction, exploitation and decommissioning
- impacts on the local community

In the context of environmental impacts, specific impacts on the sea, air and soil can be observed at the observed location.

In the context of environmental impacts, specific impacts on the sea, air and soil at the observed site can be distinguished.

During construction and decommissioning impacts are mainly related to construction works (mining, machine excavation, demolition, etc.) that cause common side effects such as noise, vibration, turbidity of the sea and the like, and increased traffic related to logistics and work machines. In this regard, impacts in the form of habitat loss, marine pollution by discharges, changes in chemical or physical parameters in the sea, and the consequent impact on flora and fauna, air pollution, degradation or chemical pollution of the soil, etc. can be recognized in the environment.

During exploitation, impacts are mainly associated with an increase in maritime traffic, possible accidents caused by irregularities during operation or technical malfunctions of installed treatment systems such as wastewater or process water and discharges. The environment can recognize the effects of noise, light pollution, increased exhaust emissions, marine pollution (change in pH, surface oiling, turbidity, eutrophication, etc.). Such changes can cause changes in ecosystems: from changes in the chemical composition of the sea, the migration of indigenous organisms or their death or the settlement of allochthonous organisms, increased air pollution, light pollution, increased noise levels, impact on the quality of human life or aesthetic influence in the landscape and the like.

Table 3 shows the weighted value of the environmental impact of different terminals during the construction, operation and decommissioning and in Table 4 of the weighted value of the impact of the type terminal on the local community.

Table 3: Environmental impact of terminal type during construction, operation and decommissioning

Environmental impacts	Terminal type				
	SRU	GBS SRU	FSRU - berthed	FSRU - offshore	FSRU – offshore platform
Construction time	3	1	2	1	1
Operation time	3	2	2	1	1
Decommissioning time	3	1	2	1	1
TOTAL	9	4	6	3	3

Source: Authors

Table 4: Impact of terminal type on local community

Impact on local community	Terminal type				
	SRU	GBS SRU	FSRU - berthed	FSRU - offshore	FSRU – offshore platform
Population	3	2	3	1	1
Road traffic	2	1	1	1	1
Maritime transport	2	2	2	1	1
Land and property value	3	1	2	1	1
Aesthetic influence	3	3	3	1	1
Other activities (in ex. Tourism)	3	1	3	1	1
Noise effect	2	2	2	1	1
Local climate impact	2	2	2	1	1
Geological impact	3	2	3	1	1
TOTAL	23	16	21	9	9

Source: Authors

Legend:

Impact	Weighted value	Total environment	Total local community
Low	1	3-4	9-15
Medium	2	5-6	15-21
High	3	7-9	22 - 27

From the tables 3 and 4, it is clear that from the standpoint of environmental impact and the local community impact, the most acceptable solutions are those offshore and the onshore terminal in that sense is very unfavorable solution. Nevertheless, the land terminal is the most expensive but in a long-term most cost-effective solution.

4. Environmental impact of the regasification process

The LNG regasification is most often achieved by the energy obtained from the combustion of natural gas or the energy obtained from the environment. The terminals at which gas is gasified in this way create an additional burden on the environment, which is the basis for indignation of the locals when choosing their location.

One of the options for regasification is the combustion of natural gas, where about 1.5% of the amount of gas is burned for regasification purposes. Natural gas is burned in burners that are submerged in seawater, and the energy from combustion is transferred directly to seawater. The process takes place with continuously polluted seawater (Figure 1). Thus, the resulting industrial waste water is stored in the plant for waste water treatment. The plant operates at full capacity in all climatological conditions, but instead of exploiting energy imbalances with the environment, this process consumes additional quantities of natural gas.

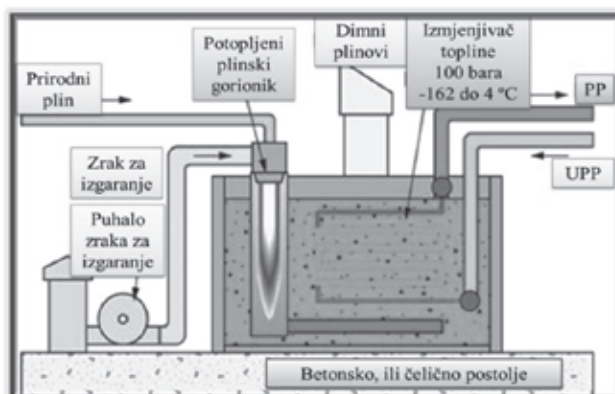


Figure 1: LNG regasification by submerged (immersed) burner in seawater, [6]

Regasification using energy from the environment is another option where seawater is mainly used because the energy contained in seawater is readily available and is practically in unlimited quantities (**Note!** The energy from air is not acceptable in this regard since it requires large exchangers and a considerable amount of electricity for fan startup).

The flow of seawater through the exchanger is achieved by means of pumps and the sub-cooled seawater is discharged into the environment (sea) with a temperature difference of about $\Delta t = 8$ °C. In winter, the consumption of natural gas is increased, and the seawater is colder, which requires a higher flow rate of seawater for regasification and consequently an increase in the cost of electricity. The regasification plant must be designed to meet the gas demand for the winter and the lowest sea temperature at the site observed.

Sea water systems are subject to fouling (shellfish, algae, ...) which reduces the effect of the plant. Electrochlorination, ultraviolet radiation and mechanical cleaning are most commonly used as protection against fouling.

Electrochlorination separates chlorine from salt in seawater, which destroys organisms in the system, but before it is released, chlorine must be neutralized to reduce its negative environmental impact.

Ultraviolet radiation is also installed on the intake chamber of the seawater system. Strong ultraviolet radiation destroys all living organisms sucked into the system, but the advantage is that it does not destroy living organisms on the discharge into the environment, but a large amount of sucked seawater carries significant quantities of plankton that feed larger organisms. Dead organisms accumulate on the walls of the exchanger that must be periodically cleaned.

Mechanical cleaning (Figure 2) consists of a filter which retains impurities larger than five millimeters and system for cleaning heat exchanger surface with calibrated balls. The filter clogging is proportional to the pressure difference at the inlet and outlet of the filter, and the cleaning is performed by a counter-current funnel. Polishing with calibrated balls lasts throughout operating time of the exchanger. The sponge balls last about four weeks and the system allows for change without stopping. This system is slightly more favorable than the previous two because it continuously cleans the walls of the exchanger, which maintains the capacity of the exchanger and prevents corrosion. The disadvantage of this system is that it does not remove the fouling in the intake and outlet chambers of seawater.

In addition to the technologies mentioned in the existing and new systems, the possibility of using ultrasonic antifouling systems is being explored.

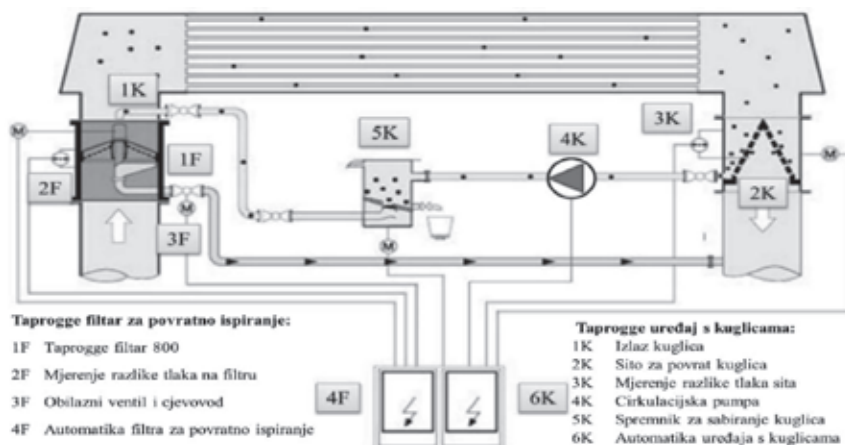


Figure 2: Mechanical cleaning of seawater systems (Taprogge), [11]

5. Opportunities to reduce the environmental impact of the regasification process

The environmental impact of the regasification process can be reduced by utilizing some of the cryogenic (“cold”) energy of the liquefied natural gas in the following ways:

- use of direct expansion and organic Rankine cycle process
- use of endothermic and exothermic processes
- application in other activities (avoiding energy conversion)

5.1. Use of direct expansion and organic Rankine cycle process

In direct expansion, the process starts by ‘pumping’ the LNG to a much higher pressure than required in the gas network. Propane, which warms the LNG to a higher temperature is introduced to protect the exchanger from freezing, followed by heating to a temperature of sea water. Due to the adiabatic expansion on the turbine, the natural gas is cooled and needs to be additionally heated, and by dividing it into more stages of expansion and heating, a greater efficiency is achieved. At the last stage of expansion, instead of heating the natural gas, it is possible to use ‘cold’ energy for air conditioning, cooling the storage space, etc. If there is a source of low energy value, here can be applied and thus increase efficiency.

With the phase change of propane in a closed organic Rankine cycle the LNG is heated. Seawater heat is used for the evaporation of propane, and for condensation the cryogenic energy of LNG. Liquid propane is pumped into the evaporator and gaseous propane is expanded at the turbine where potential energy is converted to mechanical work (Figure 3).

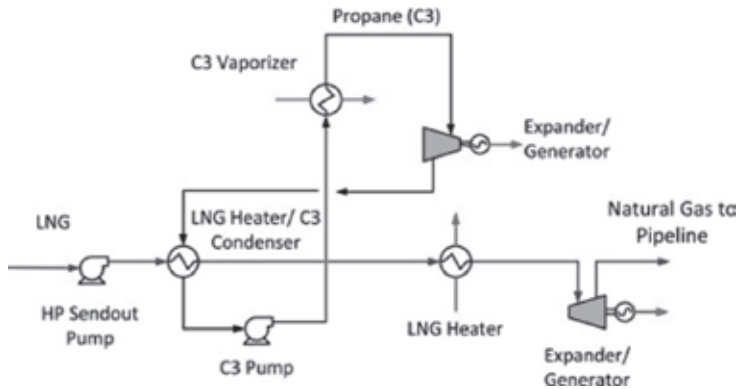


Figure 3: Use of direct LNG expansion and organic Rankine cycle process, [10]

5.2. Use of endothermic and exothermic processes

The system includes a gas turbine, utilization boiler and heat exchanger for regasification of LNG, and can be applied for the purpose of liquefaction of carbon dioxide in the exhaust gases to reduce emissions into the atmosphere and the possibility of its transport in a liquefied state for storage, for example in depleted well field of natural gas. Air cooled by the cryogenic energy of the LNG is sucked in by the gas turbine compressor thereby reducing the compression energy required (Figures 4, [4]). The gas turbine utilizes gas combustion energy at a temperature of 1600 to 600 °C, and the hot gases heat the CO₂ that expands on the turbine. The condenser combines an exothermic and endothermic regasification process whereby the still cooler natural gas is used to liquefy CO₂ and thereby heated to the required temperature. The energy required to drive an electricity generator is obtained from the turbine by cascading heating and expansion.

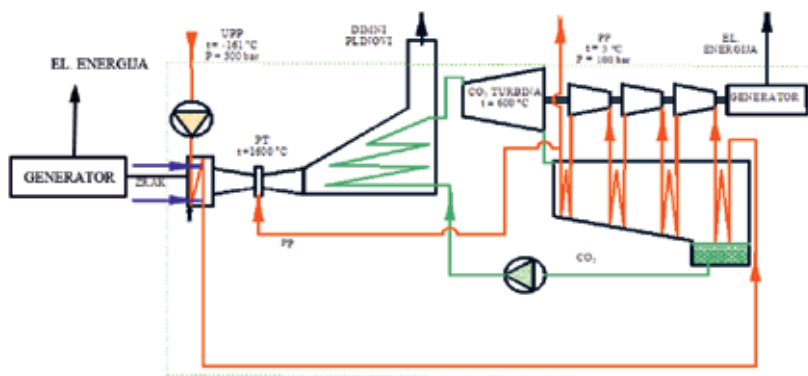


Figure 4: Schematic representation of the process
Source: Authors according to [4]

5.3. Application in other activities

The following examples show several possibilities of using cryogenic energy in a way that avoids its conversion.

A system that cryogenic energy of LNG is used for liquefaction of CO₂ for the production of methanol, and the transition of physical condition is used for electricity generation has been proposed for implementation in the manufacturing of magnesite in China. [9]

LNG regasification and CO₂ liquefaction takes place in two stages of heat exchange and through two Rankine cycle processes with different working media for exchanging the heat by changing the phase state (Figure 5).

Taking advantage of cryogenic energy for cooling instead of getting electricity avoids conversion losses of the process. Figure 6 shows the separation of air, which requires considerable amounts of energy, and which can extract liquid oxygen, nitrogen or argon, which are very important as technical gases.

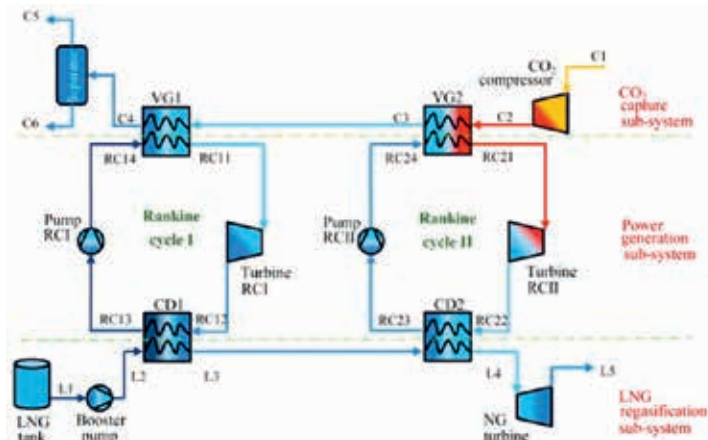


Figure 5: LNG regasification, and utilization of cryogenic energy to generate electricity and liquefy CO₂ from exhaust gases, [9]

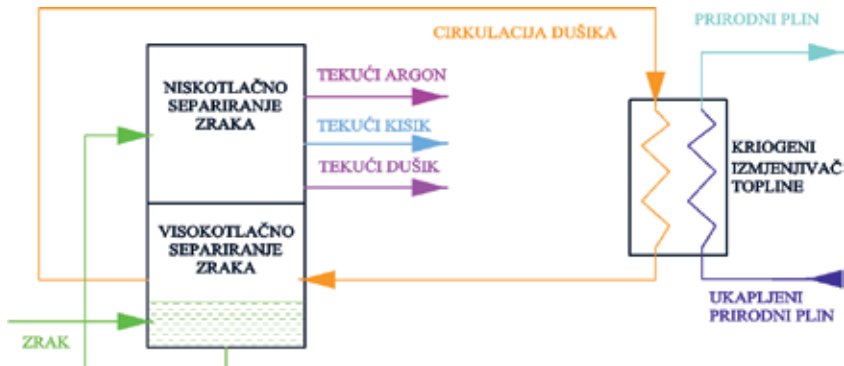


Figure 6: Production of oxygen, nitrogen and argon.
Source: Authors according to [5]

6. Conclusion

Concerning the environmental objectives in terms of preventing climate change and reducing emissions of carbon dioxide, natural gas has emerged as a transitional solution between periods of intensive use of solid and liquid fossil fuels and switching to renewable energy sources. Its sites are very often dislocated in relation to the end users, so it is supplied either compressed by pipelines or liquefied and transported by special ships.

When ships arrive at their destination before distribution, natural gas must be re-translated from liquid to gaseous state. Such conversion is carried out in facilities for regasification, which can be located in different locations where the offshore solutions showed the least influence on the environment. Land based and coastal floating solutions of the usual design to date (such as the FSRU ship foreseen in the Bay of Rijeka) have a more pronounced negative impact on the environment and consequently provoke local community resistance to their installation.

This paper presents some of the possibilities of reducing adverse effect of regasification plants by utilizing the cryogenic energy of liquefied natural gas before equalizing with ambient temperature in various thermal and technological processes. The conversion can be used to generate electricity, air-conditioning, carbon dioxide liquefaction or the separation of important process gases and the like.

Accordingly, it is concluded that appropriate communication and information, as well as proposing and applying appropriate technological solutions in the preparation and implementation of projects, can influence the change in the attitude of the public and the local population towards the plants whose construction is planned.

References

1. Bronzan, B., *LNG*, Energetika marketing, Zagreb, 1999.
2. Jenović, Z., *Naftni i petrokemijski procesi i proizvodi - 2. izd.*, Hrvatsko društvo za goriva i maziva, Zagreb, 2011., ISBN 978-953-97942-2-2 (str. 190)
3. Klobas, V., Bognolo, D., Kršulja, M., *Protupožarna zaštita kod LNG terminala*, str.: 29-42, Zagreb, 2017.
4. <http://advancedreheat.com/>, 1.10.2019.
5. <http://members.igu.org/html/wgc2006/pdf/paper/add11362.pdf>, 1.10.2019.
6. <http://www.oil-gasportal.com/lng-rd-for-the-liquefaction-and-regasification-processes/?print=pdf>, 1.10.2019.
7. [https://www.pfri.uniri.hr/knjiznica/download/Lghp\(sigcto\).pdf](https://www.pfri.uniri.hr/knjiznica/download/Lghp(sigcto).pdf), 1.10.2019.
8. <http://www.pfst.unist.hr/.../Planiranje%20luka%20i%20terminala%20-%20nastava%20XII.p>, 1.10.2019.
9. <https://www.sciencedirect.com/science/article/abs/pii/S0360544215011913>, 1.10.2019.
10. <https://www.sciencedirect.com/topics/engineering/organic-rankine-cycle>, 1.10.2019.
11. <http://www.taprogge.de/products-and-services/in-ta-ct/filtration/pr-bw-800/index.htm>, 1.10.2019.